Proactive Circular Design:
Data-Driven Selection System for Efficient Utilization in Circular Construction

Master Thesis

"This research proposes a circular resource selection system that supports circular decision-making by aligning future construction projects with available resources, thereby enabling more data-driven and environmentally conscious workflows and accelerating the transition towards a circular economy for the construction industry."

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Abstract

The construction sector is one of the most resource-intensive and carbon-emitting industries in the European Union, which highlights the need for a shift towards a circular economy. This thesis investigates how reusable construction elements can be integrated into design and construction workflows through a rule-based, data-driven selection system. Structured in three research phases—data foundation, system development, and validation—this study first identifies which construction elements are most suitable for reuse and proposes a material passport and environmental assessment method tailored to the reuse of circular construction materials. The second phase uses these insights to develop a functional web-based application that enables the registration, selection, and environmental evaluation of reusable elements. The final phase validates the system's performance and explores its integration into real-world workflows using expert feedback and process diagrams. While full-scale testing in live projects remains future work, the results show that combining structured data, lifecycle impact assessment, and rule-based selection logic can significantly enhance proactive reuse planning and support more circular decision-making in the construction industry.

keywords: circular construction, environmental impact assessment, resource selection system, data-driven design, material passport, lifecycle assessment, Django, GWP

Summary

The construction industry is one of the most resource-intensive, carbon emitting, and waste creating sectors of the European Union. The sector is globally responsible for approximately 40% of the total carbon dioxide emission, 50% of raw materials, and produce 35% of all waste. Because of this significant footprint, there is an urgent need to reduce this. Therefore, the Dutch government has set targets to tackle these critical challenges. They are aiming to reduce the use of primary raw materials by 50% by 2030, and by the year of 2050, they want to transition to a fully circular economy. However, the reuse of building materials is not done on a large scale because of fragmented data, lack of integration between supply and design, and limited decision-making support. This thesis addresses these challenges by developing a data-driven, rule-based workflow that enables designers and contractors to make proactive reuse decisions based on material availability and environmental performance. The research is structured into three research phases: (1) data foundation, (2) system design and engineering, and (3) validation and implementation.

The aim of the first research phase, data foundation, is to identify what kind of construction elements are most suitable for reuse and to define the data attributes that are necessary to support environmentally informed decisions. Based on literature and expert input from Van Gelder, ReCreate, and TAUW, six characteristics were identified that define reuse potential. These six characteristics include durability, ease of disassembly, environmental impact, standardization, transportation and storage, and availability of production. A reuse potential analysis was done on infrastructure components to identify frequently used elements that have a high potential. These elements include paving stones, curb stones, structural prefabricated elements, traffic signs, and foundation such as aggregate or sand. Additionally, an environmental impact assessment method was developed based on Global Warming Potential (GWP) that is in line with EN 15804 standards and the Nationale Milieu Database (NMD). This calculation method used the life-cycle stages of a product and calculates the total kgCO2 of all production, transportation, and (de)construction activities for a reusable element on a projected location. Based on the earlier defined data attributes and the calculation method, a structured material passport is proposed in this thesis that is tailored for circular reuse scenarios.

In the second research phase, the system design and engineering, the objective was to design and develop a circular resource selection system. Therefore, the system engineering approach is used consisting of the requirement analysis, functional definition, physical definition, and system validation. The functional, non-functional, and data requirements were defined and structured around three core functions: (1) database setup and element registration, (2) inventory and data management, and (3) material selection and environmental evaluation. These requirements were translated into a SQL-based data model based the material passport and environmental calculation logic. A web-based application was developed using the Model View Template architecture from Django and Python. MySQL was used to create the backend database. This application allows users to register circular elements manually or via reference types to the system, can calculate automatically the GWP for different reuse scenarios, and automatically generate reuse or hybrid strategies with available materials. The system supports informed trade-offs by comparing reuse with new production alternatives.

The third research phase, validation and implementation, evaluated the system against its requirements that were defined in the previous research phase. Also, it explored how the functionalities of the system could potentially be implemented in real-world workflows. The core functionalities that were defined in the previous research phase, including structured data input, automated environmental calculations, and reuse strategy generation, were validated through testing and expert feedback. With BPMN diagrams and a proposed integration into Van Gelder's CircuTool the potential implementation of the system in design and construction workflows was shown. Although the system was not evaluated in live projects, the findings show potential to shift reuse planning from static, post-design decisions to dynamic, data-informed processes that support earlier and more circular decision-making.

Despite that the system has not yet been fully evaluated or implemented in real-world projects, this research shows that structured data, environmental performance metrics, and rule-based logic can create a more proactive way of reusing construction elements. Future research and development can focus on deeper integration with BIM environments and validation through case studies and can focus on the exploration of algorithmic or machine-learning extensions to further optimize reuse configurations.

Samenvatting

De constructie industrie is een van de meest materiaal intensieve, koolstofdioxide, and afval producerende sectoren van de Europese Unie. De sector is verantwoordelijk voor ongeveer 40% van de wereldwijde koolstofdioxide uitstoot, 50% van het gebruik van primaire grondstoffen, en 35% voor al het afval. Vanwege deze grote voetafdruk is het belangrijk om hier maatregelen tegen te nemen. Daarom heeft de Nederlandse overheid als ambitie om in het jaar 2030 50% circulair te zijn, en bij het jaar 20250 volledig over te zijn gegaan in een circulaire economie. Echter worden constructie elementen nog niet op grote schaal hergebruikt. Dit komt door gefragmenteerde data, slechte integratie tussen aanbod en vraag en de beperkte ondersteuning bij besluitvorming. Deze thesis wil bijdragen een verbetering hiervan door een data-gedreven regel gebaseerd systeem te ontwikkelen dat ontwerpers en aannemers helpt in het actief hergebruiken van beschikbare materialen. Het onderzoek in gestructureerd in drie onderzoeksfasen: (1) datafundament, (2) systeemontwerp en -ontwikkeling, en (3) validatie en implementatie.

Het doel van de eerste onderzoeksfase, het datafundament, is om circulaire constructiematerialen te herkennen met een hoog hergebruik potentieel. Daarnaast is het doel om de data attributen te identificeren die nodig zijn om milieubewuste beslissingen te ondersteunen. Gebaseerd op literatuur en de input van experts van Van Gelder, ReCreate en TAUW, zijn er zes karaktereigenschappen opgesteld die materialen beschrijven met een hoog hergebruik potentieel. Deze zijn: gemakkelijkheid van deconstructie, milieu impact, transportatie en opslag, standaardisatie en beschikbaarheid. Een hergebruikspotentie-analyse werd uitgevoerd op infrastructurele componenten om elementen te identificeren die frequent gebruikt worden en een hoge potentie hebben. Deze elementen omvatten onder andere bestratingselementen, trottoirbanden, prefab-constructie-elementen, verkeersborden en funderingsmateriaal zoals zand en granulaat. Daarnaast werd er een methode ontwikkeld, gebaseerd op Global Warming Potential (GWP), om de milieu impact te kwalificeren. Deze methode is in lijn met de bepalingen in de EN 15804 standaard en de voorschriften van de Nationale Milieu Database (NMD). D Deze berekeningsmethode gebruikt de levenscyclusfasen van een product en berekent de totale kgCO2 van alle productie-, transport- en (de)constructieactiviteiten voor een herbruikbaar element op een projectlocatie. Op basis van de eerder gedefinieerde data-attributen en de berekeningsmethode wordt in deze thesis een gestructureerd materiaalpaspoort voorgesteld dat is toegespitst op circulaire hergebruikscenario's.

In de tweede onderzoeksfase, dat de systeemontwerp en -ontwikkeling betreft, is het doel om een circulair materiaalselectie systeem te ontwikkelen. Hiervoor is de systeem engineering methode gebruikt die bestaat uit de vereistenanalyse, functionele definitie, fysieke definitie en systeemvalidatie. De functionele, niet-functionele en data-eisen werden gedefinieerd en gestructureerd rond drie kerntaken: (1) opzet van de database en registratie van elementen, (2) beheer van voorraad en data, en (3) materiaalkeuze en milieuevaluatie. De systeemeisen zijn vertaald naar een SQL-data model gebaseerd op het materiaal paspoort en de milieu impact berekening gedefinieerd in de vorige onderzoeksfase. Een webapplicatie is ontwikkeld met de Model View Template systeemarchitectuur van Django en Python. MySQL werd gebruikt voor de backend-database. Deze applicatie stelt gebruikers in staat om circulaire elementen handmatig of via referentietypes te registreren, automatisch de GWP voor verschillende hergebruikscenario's te berekenen en automatisch hergebruik- of hybride strategieën te genereren met beschikbare materialen. Het systeem ondersteunt het maken

van onderbouwde afwegingen door hergebruik te vergelijken met alternatieven op basis van nieuwe productie.

De derde onderzoeksfase, die de validatie en implementatie betreft, evalueert het ontworpen systeem op de systeemeisen die opgesteld zijn in de vorige onderzoeksfase. Ook werd onderzocht hoe de functionaliteiten van het systeem mogelijk geïmplementeerd kunnen worden in de praktijk. De kernfunctionaliteiten, waaronder gestructureerde data-invoer, automatische milieuberekening en hergebruikstrategie-generatie, werden gevalideerd door middel van tests en feedback van experts. Door middel van BPMN-diagrammen en een voorstel voor integratie in de CircuTool van Van Gelder wordt getoond hoe de functionaliteiten in het echt kunnen worden geïmplementeerd. Hoewel het systeem nog niet in echte projecten getest is, tonen de bevindingen aan dat het potentieel heeft om hergebruikplanning te verschuiven van statische, post-ontwerpbeslissingen naar dynamische, data gedreven processen die hergebruik in een vroeg stadium van besluitvorming ondersteunen.

Hoewel het systeem nog niet volledig is getest of geïmplementeerd in de praktijk, laat het onderzoek wel zien dat gestructureerde data, milieuprestatie-indicatoren en systeem gebaseerd op regels kunnen bijdragen aan een proactieve manier van hergebruik van constructiematerialen. Toekomstige onderzoeken kunnen zich richten op diepere integratie met BIM-omgevingen, validatie aan de hand van praktijkcases en verkenning van algoritmische of machine learning extensies om hergebruik verder te optimaliseren.

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Preface

This thesis marks the end of my master's degree and is the result of several months of dedicated work. Despite that the journey was not always easy, I look back on valuable and enriching experience at the TU/e – both academically and personally. I now very much looking forward to starting my professional career.

I would like to express my gratitude to the employees of Van Gelder, the contributors to the ReCreate Project, and all the interviewees for their valuable input and collaboration. A special thanks to my supervisors Remco Kok and Nick van den Berg to make this collaboration with Van Gelder possible. Lastly, I would like to thank my TU/e supervisors – Pieter Pauwels, Claudia Fecarotti, and Simon Wijte – for their expertise, guidance, and involvement throughout this process.

Hugo Spaan

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List of acronyms and abbreviations

BIM	Building Information Modelling
CO2-eq.	Carbon Dioxide Equivalent
GD	Generative Design
GIS	Geographical Information System
GWP	Global Warming Potential
DfD	Design for Disassembly
EIA	Environmental Impact Assessment
EPD	Environmental Product Decleration
HTML	HyperText Markup Language
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MKI	Milieu Kosten Index
MP	Material Passport
MVT	Model View Template
NMD	Nationale Milieu Database
PLM	Product Lifecycle Management
SQL	Structured Query Language
UI	User Interface
UX	User Experience

Chapter 1: Introduction

1.1 Context and background

The construction industry is one of the most resource-intensive sectors of the European Union. They emit a lot of carbon and create a substantial amount of waste (European Commission, 2020). The construction industry is globally responsible for approximately 40% of the total carbon dioxide emissions. Furthermore, they use 50% of the raw materials, and they produce 35% of all waste (Elghaish et al., 2022). Because of this significant environmental footprint, there is an urgent need for the reduction of these emissions. The Dutch government has set, in response, ambitious targets to tackle these critical challenges. They are aiming to reduce the use of primary raw materials by 50% by 2030, and by the year of 2050, they want to transition to a fully circular economy (Ministerie van Infrastructuur en Waterstaat, 2024). The concept of the circular economy has gained significant attention, also within the construction industry. In a circular economy resources are efficiently used through strategies like material reuse, recycling and they aim for closed-loop lifecycles. Currently the construction industry is making efforts to integrate these circular economy principles. They work on technologies like decomposable buildings, Design for Disassembly (DfD) and modular construction. However, the full potential of reusing construction materials remains underutilized.

This thesis recognizes that the technologies of deconstructing, storing, and reusing modular elements is still in the beginning phase. There is fragmented data, inconsistent workflows, and a lack of integrated tools. Furthermore, recycling is currently often prioritised over reuse. This results in a loss of opportunities to maintain the high value of materials and reduce the consumption of resources. The research presented in this thesis is not only intended to address these limitations but also to function as a catalyst for change. It provides a framework and generative design tool that can enable practical insights and support for designers to reach the full potential of reusable materials.

The following sections give the research context by introducing circular economy, the reuse of construction materials, modular construction, and the shift from conventional to modular design. These topics highlight the need for innovative approaches that connect available resources with design processes to enhance circularity and efficiency in modular construction.

1.1.1 Circular Economy

A substantial amount of research has been conducted on the concept of circularity and the circular economy. These two terms are often used interchangeably. The circular economy can be categorized as an economic model that has the intention to be environmentally, economically, and socially more sustainable than current economies (Adan et al., 2023). The economic model is designed to minimize waste and to make the most efficient use of available resources. Instead of the traditional ‘take, make, dispose’ approach, the aim of the circular economy is to focus on a closed-loop system where materials are reused, recycled, and regenerated (Ghisellini et al., 2015), as explained in the closed-loop product lifecycle management (PLM) framework (Sillanpää & Ncibi, 2019). This PLM framework enables products, components, and materials to cycle through stages of reuse, refurbishment, and

recycling, which maximizes material utility and preserves the value of the materials throughout their lifecycle. This PLM system minimizes the need for raw resources while continuously reintroducing materials into the supply chain. Figure 1 illustrates how to close the loop in the PLM, where no waste is produced, and no new raw materials are introduced.

Principles of the circular economy can be translated as designing for longevity, keeping product and material value, and promoting sustainable consumption (Garusinghe et al., 2023). The definition of the circular economy of Ellen MacArthur Foundation is the most widely referenced among various studies circular economy (Charef et al., 2021; Ellen MacArthur Foundation, 2015; Kirchherr et al., 2017) and will therefore be adopted in this thesis: *"restorative and regenerative industrial system, by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."* (Ellen MacArthur Foundation, 2015).

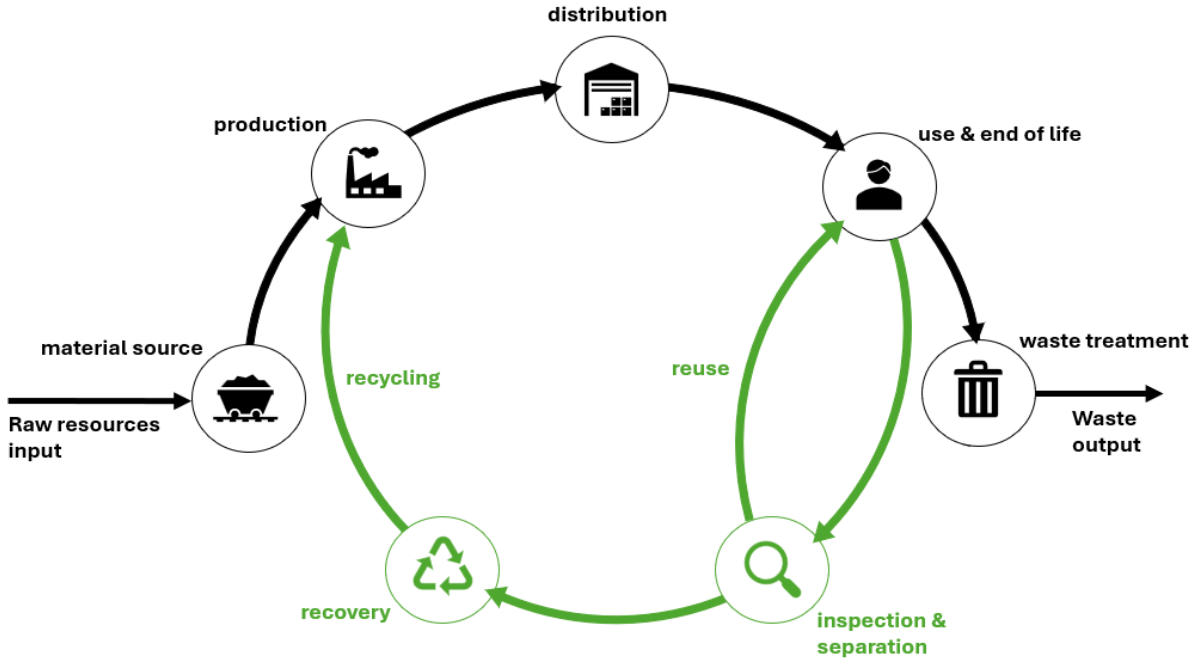


Figure 1: Closed loop of product lifecycle management with circular economy strategies.

However, the transition to a fully circular economy brings both challenges and opportunities for the construction industry. Despite the enormous efforts to implement modern technologies like decomposable building techniques, modular construction, and material databases, the full integration of available resources into practical design processes stays a challenge. The gap between these resources and their practical use in design is complex and will require continuous efforts to narrow over time.

To realize the goals of the circular economy it is important to actively collect and manage data about available resources. Tools, such as material databases, are designed to catalogue and store detailed information about construction materials, such as their physical characteristics, lifespan, and potential for reuse (Miu, 2020; Munaor & Tavares, 2021). One of the key aspects

of enabling effective reuse of materials lies in the collection and management of data through material passports. Material passports are specific types of digital records that offer a comprehensive overview of each material's characteristics and can be evaluated when considering the reuse of products, as they contain critical information like durability, compliance with technical standards, and any potential hazardous materials (Bellini et al., 2024). Material information can be collected and stored manually, for example in Excel files. However, integrating this data into the design process through, for example Building Information Management (BIM), enhances connectivity and accessibility for future projects. BIM is a digital framework that allows for the creation and management of detailed building information models. The models provide a shared knowledge resource for all stakeholders throughout the building's lifecycle. By embedding material data directly into a digital BIM model, designers and contractors again gain easy access to critical information at every project phase.

1.1.2 Reuse of construction materials

Construction materials are not being reused on large scale in the construction industry (Van Stijn et al., 2023). Munaro and Tavares (2021) highlight several key barriers that contribute to inefficiencies in assessing and integrating reusable circular materials into modern designs:

1. Inconsistent and incomplete data: a lot of "databases" do not contain comprehensive data on the characteristics and performance of materials. They are often not standardized and not accurate. Because of this fragmented information, it is difficult for architects and engineers to make informed decisions during the design process.
2. Accessibility and usability: databases are not always correctly structured. Therefore, they are not always accessible and user-friendly. The data may be difficult to retrieve and require specific expertise of the software.
3. Uncertainty about reuse potential: there exist uncertainties related to the physical condition, availability, and long-term performance of reused materials. There is often no clear guidance on how these materials can be used in unique design contexts.
4. Economic considerations: designers do not have a clear overview or insights to see the financial benefits of choosing circular elements over new materials.
5. Lack of integration with digital design tools: current databases are not integrated into design tools that are commonly used, like BIM platforms. Because of this disconnection, material data is often not accessible directly within the design workflow, even when relevant data is available. This limits the impact that reusable materials could have on the design process.

Despite these challenges, it is widely recognised that there are potentially a lot of sustainable benefits of reusing construction materials. A very promising strategy for reusing materials is modular construction. This is also shown in the 10-R ladder of circularity (Rijksdienst voor Ondernemend Nederland, 2020), shown in Figure 2. The 10R ladder builds upon the foundational principles of the 4R strategy—Reduce, Reuse, Recycle, recover—by expanding the framework to offer a more detailed hierarchy of circularity strategies, including Refuse, Rethink, and Repurpose.

Hence, strategies incorporating reuse into design and/or reusable materials can enhance circular economy in a more productive and valuable manner than recycling (Charytonowicz & Skowroński, 2015). Effective reuse can elevate circular economy strategies beyond recycling by maintaining higher material value and reducing resource consumption. Bridging the gap between material databases and the design process is essential for realizing these benefits.

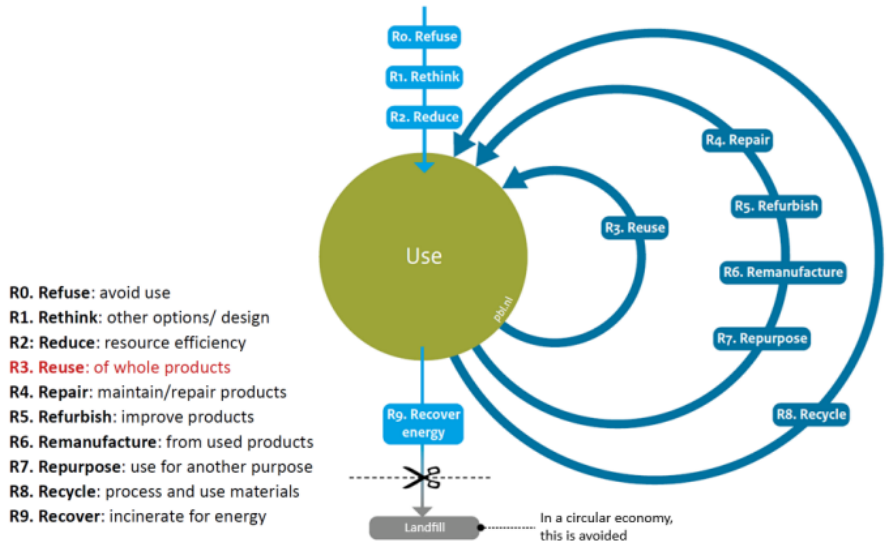


Figure 2: 10-R ladder of priorities for circularity strategies (Rijksdienst voor Ondernemend Nederland, 2020)

1.1.3 Modular construction

Modular construction refers to the assembly, disassembly, and reconfiguration of prefabricated construction elements and components which are designed for reuse in multiple life cycles. In this thesis, elements are defined as singular construction parts such as walls or doors, whereas components are assemblies of multiple elements, such as a wall with an integrated door. These types of elements can be deconstructed and transported to a new project. On this new location they can be reconfigured into a new structure. Key principles of modular construction include Design for Disassembly (DfD), which allows components to be taken apart without loss of quality or excessive waste; reusability across multiple life cycles, where elements are intentionally designed for future application in new projects; and configurability, which enables components to be reassembled into various structural forms, supporting adaptive reuse (Taghaddos et al., 2018; Hong, 2020; Fivet & Brutting, 2020).The concept of modular construction in this thesis can be explained in multiple levels of prefabrication, what is outlined in Figure 3.

Level 0: Material – Basic raw materials used primarily in site-intensive construction.
Level 1: Element – Prefabricated construction parts made from materials.
Level 2: Component – Assemblies of elements that form more complex prefabricated construction parts.
Level 3: Module – Configurations of components that constitute larger construction sections, such as entire rooms.

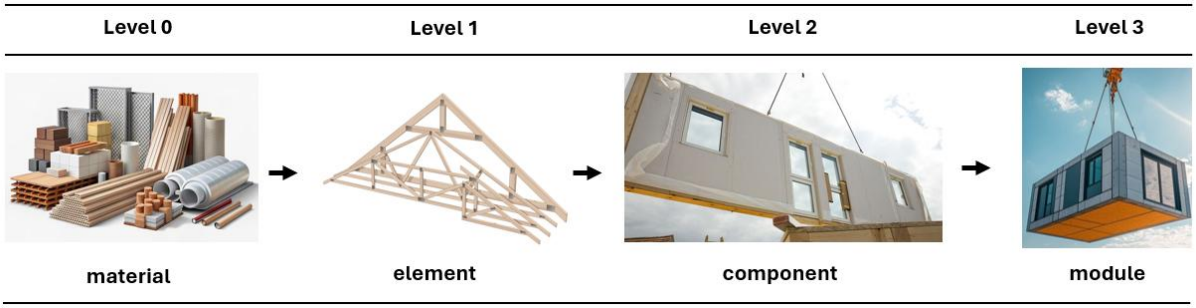


Figure 3: Four levels of prefabrication where Levels 1, 2 and 3 refers to modular construction.

These prefabrication levels enable varying scales of modularity and reuse. Prefabrication is characterized by standardized geometries, systems, and materials using topological interlocking systems (Zhuang et al., 2023). Standardized dimension and connections enhance interoperability across different projects which makes modular construction suitable for permanent, long-term, and temporary structures due to the possibility of relocating entire modules or configure new structures from available elements and components (Hořínková, 2021). These principles not only support efficient reuse but also allow for the creation of flexible and adaptable design tailored to specific project requirements (Minnuno et al., 2018).

While modular construction deals with the physical process of the disassembly and assembly of structures, modular design involves the conceptualization and arrangement of these prefabricated construction parts into cohesive systems that fulfil the design requirements. Importantly, the assembly highlights the creation of functional structures through the integration of smaller prefabricated construction parts, while disassembly emphasizes the potential for deconstruction and reuse of these construction parts without material loss.

Modular construction is often associated with buildings, however, the principles of reuse, DfD, and configurability is also applicable to other domains of the built environment. In collaboration with Van Gelder, an infrastructure company in the Netherlands, this thesis will demonstrate that modular construction strategies can, next to building structures, also be adopted for infrastructure and urban landscaping. Examples include (1) infrastructure roads, bridges, and (underground) utilities, where modular sections or components can be disassembled, stored, and reused, and (2) urban landscape modular street furniture, paving systems, and retaining walls, which can be prefabricated in a factory setting, where controlled conditions improve quality and efficiency, and transported to the construction site for assembly (Minnuno et al., 2018). Therefore, in this thesis modular construction elements and components refers to not only building elements and components but those from the whole construction industry, including infrastructure and (urban) landscaping.

Unlike traditional modular definitions that focus solely on prefabricated volumetric units, this thesis highlights modular construction as a circular design strategy that goes beyond the levels of prefabrication. Modular elements and components can originate from resource hubs - facilities that store disassembled elements from end-of-life structures - or from factories that produce prefabricated components under controlled conditions, although the focus in this thesis lays on deconstructed elements. Modular construction emphasizes the strategies of the circular economy by allowing construction elements and components to be reconfigured for new purpose or projects (Adan et al., 2023).

1.1.4 Traditional design vs. circular design

When designers shift from traditional to circular design, the open-ended design approach becomes a more constraint-driven design process. In traditional design workflows, designers have a high degree of freedom at the start of the design process. This means that they can choose materials and their configuration based on the project goals and their creativity. Constraints are introduced gradually as structural, functional, and regulatory standards need to be considered. This approach allows for iterative adjustments throughout the design process where the design can be refined until it reaches a finalized stage (Suwa et al., 2000). In circular design workflows the designers start with elements that have already specific identities, geometries, and structural and functional attributes (Mudge, 2024). These predefined

attributes limit the flexibility of the design and results into a design process that works with established parameters, instead generating entirely new forms (Dokter et al., 2021). In contrast to the open-ended approach of traditional design, circular design restricts choices to fit the predefined attributes. This transition makes circular design more complex, as the configurations must be designed with all the geometry, structural and functional constraints inherent to the construction elements (Kilian, 2006).

This difference between traditional and circular design becomes especially evident when examining the concepts of 'problem space' and 'solution space.' In traditional design, the problem space is loosely defined which allows designers to explore and redefine a broad range of potential solutions. This exploration of the large solutions space is characterized by flexibility and has fewer constraints on geometry, materials, location, configuration, structural, and functional requirements, enabling iterative design modifications based on the evolving design goals (Dorst & Cross, 2001). In contrast, circular design limits this flexibility as the problem space is determined by the characteristics and the predefined attributes of the available resources. Designers must identify the properties by performing an 'inventory' to map out viable configurations that meet the design requirements within the constraints (Kilian, 2006).

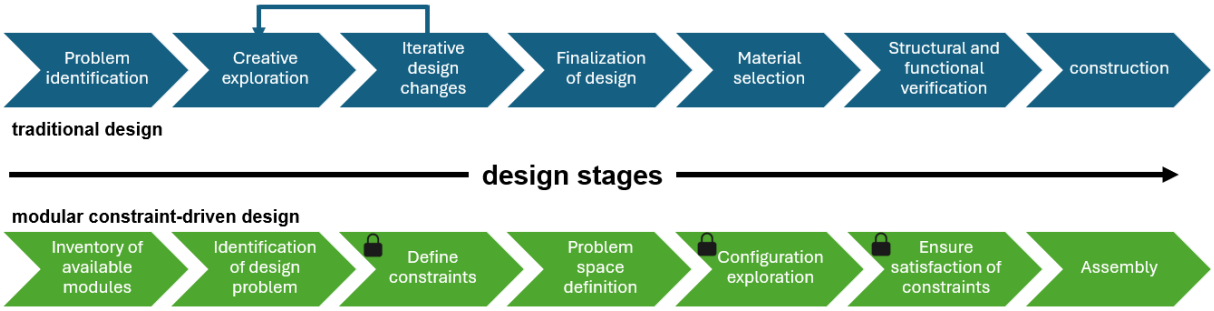


Figure 4: Flowchart of conventional design vs. modular design.

One critical factor in circular design is the uncertainty surrounding the availability of construction resources, which can vary widely between projects. At the outset of a design, the designer is dependent on what is accessible at that time, introducing an element of unpredictability. Because of this variability, designers need to remain flexible within the constrained framework. The role of the designer shifts from unrestricted creativity to one which needs to optimize within a predefined set of boundaries (Mudge, 2024).

Digital tools have become essential to support designers and offer detailed insights into the availability and attributes or available resources together with their constraints (Sanches et al., 2022). Computational methods allow designers to navigate complex constraint sets and identify valid configurations. These tools are essential to bring efficiency and circularity into modular construction workflows (Sanches et al., 2022).

1.1.5 Computational design

To support designers in navigating constrained design spaces, computational design methods, including parametric, algorithmic, and generative design (GD), have emerged as valuable tools. These methods automate part of the design process and help identify valid solutions

within strict predefined boundaries (Dervishaj & Gudmundsson, 2023; Caetano et al., 2020). According to Caetano et al. (2020), the three main computational approaches are:

1. Parametric design: is a process that uses algorithmic thinking to create relations between design parameters and the constraints. It works good with BIM workflows because it can create a wide range of geometries and configurations based on the parameters within a predefined set of boundaries.
2. Generative design (GD): GD takes the parametric design further and can automatically explore a wide range of design solutions based on predefined rules and constraints. GD is a powerful tool for modular design that require flexible but controlled design exploration.
3. Algorithmic design: is a subset of GD. It provides more predictability because it allows designers to trace the logic of the design process.

Among these, GD is particularly promising for circular design as it can automatically generate spatial or material configurations that match predefined constraints. GD can support designers in creating solutions that align with the availability of materials (Wei et al., 2021; Zhang & Li, 2024; Sanches et al., 2022).

GD knows a lot of different approaches and can variate from rule-bases systems to machine-learning models. Rule-based GD creates predictability and control over the process with more traceability (Wei et al., 2021). Machine-learning driven GD offers the potential to identify hidden patterns in complex datasets but often require extensive training data (Ma et al., 2021). In this thesis, a rule-based generative design approach is applied to develop a circular resource selection system that supports designers in making informed material reuse decisions within the constraints of circular and modular construction.

1.2 Problem description

The introduction explained the importance of reusing existing building elements to transition towards a circular economy to reduce environmental impact. However, in current design processes the available reusable building elements are rarely considered from the beginning. Design decisions are often made without insights into what elements and components are already accessible. This results in missed opportunities to reduce material use and environmental footprint. Although various material databases and passport now exist, they are not yet effective in informing or guiding design choices. A critical gap exists there is no structured method for matching available reusable elements to project-specific requirements, nor for evaluating which combinations results in the lowest environmental impact.

This thesis addressed this gap by developing a tool-supported process that helps designers and contractors in identifying and selecting suitable reusable elements from existing inventories. The tool matches supply and demand based on element type, geometric fit, quantity, and environmental performance. The system provides designers and contractors with decision support by calculating and comparing the environmental impact of different reuse scenarios. This allows them to make design choices on actual available resources and their environmental consequences. By proving this matching process and the integration of environmental data, the research contributes to a reuse-oriented design workflow that can support the transition toward circular construction.

1.3 Research objectives and scope

This research aims to support circular design in construction by developing a generative selection system that matches reusable construction elements with project-specific needs based on environmental performance. The research is addressed by the following main research question:

> *"How can a generative selection system match reusable construction elements from a database with project-specific demands, based on environmental impact, to support circular design in modular construction?"*

The objectives and scope are divided into three consecutive phases that structure the research: (1) data foundation, (2) system design and engineering, and (3) validation and implementation.

Phase 1: Data foundation
Objective 1: Identify the types of building elements that are suitable for reuse, determine the key data that is needed to support reuse decision-making, propose a structured material passport that is tailored for reuse, and define a method for environmental impact assessment of reusable materials.

- RQ1.1: What types of construction elements are typically suitable for reuse in modular construction and how can they be described?
- RQ1.2: What environmental assessment methods are suitable to evaluate the environmental impact of reusing the available elements?
- RQ1.3: What for data is needed to describe and evaluate the reuse potential, functional characteristics, and environmental performance of these elements?
- RQ1.4: How can that data be effectively integrated into early-stage design workflows?

The information for the data foundation is gathered from the review of academic literature and expert insights from stakeholders at Van Gelder and ReCreate (see Section 1.5). Only direct reuse scenarios (R3 on the 10R ladder) are considered. This means that this research focuses on building elements that can be reused without substantial transformation. The scope does not include recycled or remanufactured materials. The environmental assessment is based on globally recognized standards, primarily the European EN and Dutch NEN standards. These standards ensure compatibility with the Dutch Nationale Database (NMD) which is publicly available and used for environmental performance data. No project-specific LCAs or custom datasets are created. Furthermore, the study does not evaluate the full environmental impact of specific projects or companies but instead uses generic data to structure the decision-making process. The material and component data are structured around the needs and practices of Van Gelder and ReCreate but is formulated in a way that stays generalisable for other circular construction contexts.

Phase 2: System design and engineering
Objective 2: Define and develop a prototype system that can register reusable elements to a database and that automates the selection of reusable elements based on environmental performance calculations, and project requirements.

- RQ2.1: What are the functional and non-functional requirements for a system that register reusable elements and enables the automated selection process?
- RQ2.2: How should the system store and retrieve the data needed to fulfil the functional and non-functional requirements?

- RQ2.3: How can a computational algorithm be developed that automates the selection of elements based on environmental impact, quantity, geometry, and type?
- RQ2.4: How can such a user interface be developed that allow users to interact with the system to register reusable elements and configure reuse-based designs?

The focus in the second phase is on defining the system's structure and building the prototype. The requirements of the system are collected from literature insights, interviews with experts from Van Gelder and ReCreate, and analyses of their existing reuse workflows and tools (see Section 1.5). The system is developed locally using Python and Django, and it includes a basic relational database. The prototype does not connect directly to external sources or databases such as the NMD but uses the data from it to perform environmental impact calculations internally. These calculations follow the methodology provided by the NMD. The system is designed to provide logical selections of available reusable elements, but it does not generate complete architectural forms or spatial designs. Furthermore, although the system will give logical output, the system does not include compliance checks with building codes, safety standards, or structural calculations. All selected elements will require further engineering, validation, and regulatory checks by qualified professionals.

Phase 3: Validation and implementation
Objective 3: Validate whether the developed system meets the defined functional requirements and theoretically explore how its functionalities could be integrated into construction and design workflows, along with the potential effects on project outcomes.

- RQ3.1: Does the developed system meet the functional and non-functional requirements that are defined in the system engineering phase?
- RQ3.2: How can the system's functionalities be conceptually integrated into existing design and construction workflows to enhance circularity?
- RQ3.3: What are the potential effects of the system's functionalities on project outcomes such as decision-making efficiency, environmental performance, and resource?

In the final phase, the focus is on validating whether the system performs according to the defined functional requirements. The system behaviour is evaluated on the requirements described in phase 2. The system is not evaluated in a real-world construction project or integrated into an existing BIM environment. Instead, the validation proves how the system could function in future workflows by mapping the prototype functionalities onto typical design and construction processes. This is done with a theoretical scenario-based evaluation and discussion on how the tool could support in decision-making, improve resource reuse and support in environmentally beneficial solutions. These are conceptual explored, and no empirical environmental or economic outcomes are measured or compared with real world projects. The prototype serves as a proof of concept which shows what is technically feasible and how such a tool could support circular design processes.

1.4 Deliverables

This research produces the following deliverables:

1. Reuse potential analysis framework.
   A multi-criteria assessment method to evaluate the reuse potential of construction elements. This assessment combines qualitative and quantitative criteria bases on the characteristics of reusable construction elements.

2. Material passport structure for reuse
   A proposed data structure that is tailored to the reuse of construction elements. It defines the key attributes needed for reuse and environmental assessment.
3. Environmental impact assessment method
   A method for calculating the environmental impact (Global Warming Potential) for different reuse scenarios bases on data available in the NMD.
4. System requirements
   An overview of the functional, non-functional and data requirements for a generative selection system based on the principles of system engineering.
5. Database design
   A relational SQL database structure that is designed to store reusable elements data and support environmental impact calculation and selection logic.
6. Generative selection system
   A python and Django based web application that enables the registration and selection of reusable elements bases on environmental performance, geometry, quantity, and type.
7. Validation of functionalities
   A validation of the system's functionalities against the requirements defined in the system engineering process.
8. Theoretical integration
   A conceptual exploration of how the functionalities of the system could be implemented into real-world design and construction workflows and what potential benefits the functionalities of the system offer.

1.5 Building on existing initiatives: Van Gelder and ReCreate

This thesis builds upon foundational work conducted by Van Gelder and the ReCreate project:

ReCreate[1] is an EU-funded project focused on deconstructing and the reuse of precast concrete elements, with the goal of innovating technological solutions for the circular economy in construction. The aim of the company is to prove the technical and economic viability of reusing precast concrete components. The goal of the project is to reduce the emission of carbon and improve the sustainability in the industry. A pilot project has been done where a building is being deconstructed and prefabricated concrete elements are reclaimed. These elements were catalogued in a digital material database that stores their attributes. These attributes include the dimensions, structural properties, and condition. Additionally, a Revit plug-in was developed. With this plug-in, designers can select the elements from the database for reuse in their modern design.

Van Gelder[2] is a large infrastructure company specialized in the design, construction and maintenance of asphalt, roads and streets, sewers, street furniture, and cables, pipes and distribution networks for gas, water, electricity, telecom, and sustainable energy sources. Their focus is on the sustainable design and maintenance of public space by finding smart, sustainable solutions, professional environmental management, and emission-free working. The goal is to focus on circularity by reusing locally available materials and experience in developing circularity tools for infrastructure projects. Van Gelder developed the CircuTool, a

[1] https://recreate-project.eu/
[2] https://www.vangelder.com/van-gelder-groep

tool designed to enhance material reuse in the transition from demolition to new construction. The CircuTool matches materials from a deconstruction site to a new construction site. The CircuTool finds which materials become available during deconstruction, in what quantities, and matches them to material demands in upcoming construction projects.

The collaboration with Van Gelder and the ReCreate project shaped the starting point of this thesis. This thesis aims to advance their efforts by automating and optimizing resource registration, selection, environmental impact performance, and develop an intuitive user interface.

1.6 Reader guide

Chapter 1 – Introduction – In the first chapter the context and background about the subject is given. In addition, the problem description is stated, together with the research objectives and questions. Lastly the scope and limitations of the research is described.

Chapter 2 – Theoretical background – This chapter gives a theoretical background with a literature review, giving a foundation for the following chapters.

Chapter 3 – Methodology – In this chapter the methodology regarding the data collection is described, including the overview of how this thesis research is conducted.

Chapter 4 – Resource data and environmental impact – This chapter defines elements with high reuse potential, their data requirements and environmental impact metrics necessary to facilitate circular design and introduces a method for cataloguing reusable construction elements.

Chapter 5 – System design and engineering – This chapter presents the design of the circular resource selection system. It follows the system engineering principles and defines the functional and non-functional requirements, how data is being processed, and outlines the system architecture that enables automated selection and configuration of reusable element.

Chapter 6 – Desing validation and implementation – This chapter validates developed system both from a stakeholder perspective and against the technical requirements from the previous chapters. It explores how the system can integrate into design can construction workflows. It evaluates the system's impact on decision-making, environmental performance, and resource optimization.

Chapter 7 – Conclusion, discussion, and reflection – The closing chapter concludes the research by answering the main research question. It discussed the key findings, implications for practice, and reflects on the limitations of the research and suggestions for future development and research.

Chapter 2: Theoretical background

2.1 Introduction

As the construction sector transitions toward circular economy principles, assessing environmental impacts becomes a critical factor in the adoption of sustainable practices. This chapter gives a theoretical background based on twenty-three research papers, focusing on environmental impact assessments and their relevance to modular construction. It explores the commonly used assessment methods and shows the types of data typically needed to support these evaluations. Additionally, this chapter gives general foundation for understanding how data collection, management, and accessibility can support more circular design decisions. These insights are later compared with stakeholder needs and current industry practices. This comparison finds gaps and opportunities for improvement.

2.1.1 Search strategy

The following keywords were used to search for articles in the database of ScienceDirect:

“environmental impact assessment” / "environmental impact" / "assessment methodology"
“modular construction” / “modular design”
“circular” / "circular economy"
"material data" / “material properties”
"life cycle assessment"

Inclusion and exclusion criteria were used to filter the findings to ensure relevance and quality of the articles included in the literature review. These criteria were selected to align with research objectives and ensure that the reviewed articles provide meaningful insights into the application of EIAs within modular construction. The articles will be assessed by four yes or no statements. If any of these statements are not answered with “yes,” then the article will not be included in the review. The four statements are as follows:

1. The article was published in 2014 or later.
2. The article is written in English.
3. The article is a research article.
4. The article applies to the field of engineering.

By excluding articles published before the year 2014, the findings are not outdated and describe the state-of-the-art. As the circular economy is gaining momentum and new legislation and regulations are being rolled out globally and nationally, the state-of-the-art within the EIAs must be clearly identified. The second criterion is included because of potential language barriers that might affect the analysis of the publication through misinterpretation or inaccuracies in translation. Therefore, it is preferable to only include publications originally written in English. To guarantee academic rigor and reliability of the finding, only research articles with clear methodological foundation are included. Because EIAs are commonly used

in different field and domains, the fourth criterion is included to only focus on the field of engineering.

Using the keywords and inclusion and exclusion criteria, a total of 141 articles were found. These 141 articles were then further screened to analyse their applicability to modular construction workflows and their contribution to advance circular economy objectives.

2.1.2 Screening

The 141 articles found through the search strategy were systematically screened based on their title, abstract, and conclusion to evaluate their relevance for modular construction and modular design, as well as their alignment with circular economy principles. The screening process aimed to identify articles that directly or indirectly contribute to the understanding and integration of EIAs within the construction industry focussing on circular workflows. The articles were first assessed based on their titles to find a clear focus on environmental impact of circular construction materials in the construction industry. Titles that lack direct references to the construction industry were excluded. Secondly the abstracts of the remaining articles were reviewed to verify whether the research explicitly addressed EIAs or provided insights into methodologies and data needed for assessing environmental impact in the construction industry. Additionally, the articles are being screened if they are representative for the global construction industry and if they are not solely applicable to a specific (local) scenario or use case. Articles that were not directly applicable to the construction industry, were too specific for one case, or did not have enough common ground with the principles of the circular economy were excluded. Finally, the conclusions of the articles were analysed to decide whether the findings offered good insights or best practices that could inform the integration of EIAs in the resource selection process where elements are selected automatically based on their environmental impact.

The screening process resulted in a total of thirty-two articles that remained for further in-depth analysis. Removing duplicates among these articles resulted in a total of twenty-three relevant articles to review, focusing on the following five specific points:

1. Existing EIAs and their applicability to modular construction.
2. How environmental impacts are assessed.
3. Types of data needed for EIAs in the construction industry.
4. Best practices for integrating environmental data into modular design.
5. Data collection, structuring, management, and accessibility throughout the process.

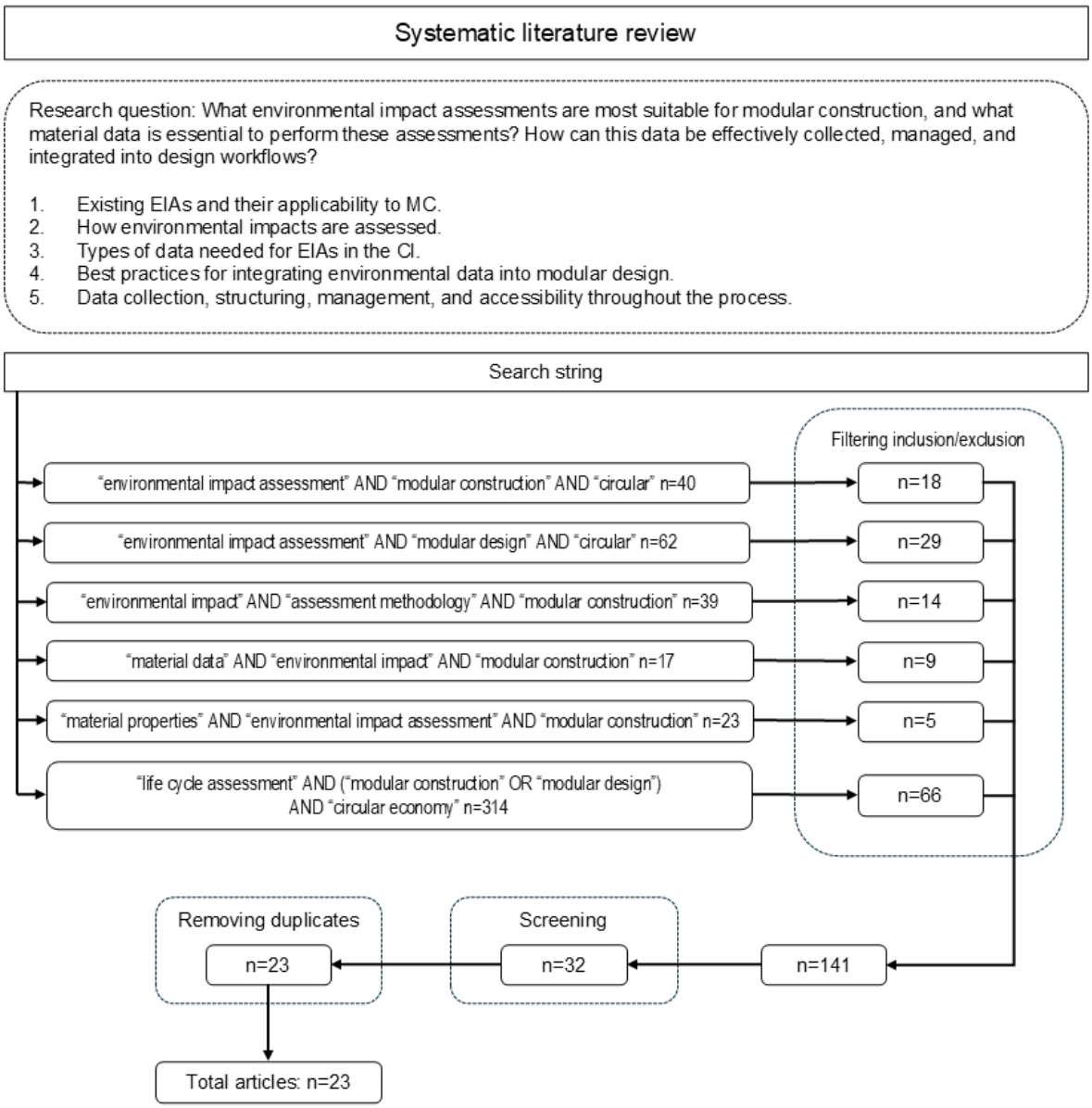


Figure 5: Systematic literature review overview.

2.2 Existing environmental impact assessment

To transition to a fully circular economy in the built environment, the application of EIAs in the construction industry is of enormous relevance. EIAs provide a structured framework for evaluating the environmental impacts of various construction projects. With the help of these assessments, informed decision about materials, designs and construction processes could be made. In modular construction, digital tools such as BIM and Life Cycle Assessments (LCA) lay the foundation in enhancing environmental performance of construction projects. They ease the reuse of existing resources by giving information about the environmental performance and by managing designs and materials.

Olumo and Haas (2024) had done a study to propose a framework that evaluates the environmental impacts of new construction materials and that of reusable construction materials. The method that they propose integrates LCA within BIM. With this integration, life

cycle impacts can be linked to digital models to enhance the decision-making process during the design phase. The authors discuss that there should be a good connection between the real environment and the model environment. In this real environment it must be carefully decided which materials are present. The model environment consists out of BIM software and LCA tooling. Within this model environment, material data can be stored, and EIA can be performed with the use of LCA.

The research by Andersen et al. (2022) compared the environmental sustainability of conventional and modular buildings. They proved that even though modular construction typically exhibits lower environmental impacts, they still exceed thresholds of sustainability. This underscores the need for both reducing embodied and operational environmental impacts in modular design.

Another key aspect in modular construction is the implementation of circular economy principles. These principles are already discussed in the introduction of this thesis. However, they can be further promoted through policies like extended producer responsibilities. Tong et al. (2024) explore that extended producer responsibilities can encourage producers to design products with their end-of-life in mind. This makes sure that materials are being reused and recycled. These are important points of the 10-R ladder (Rijksdienst voor Ondernemend Nederland, 2020) and can influence the EIA of modular construction.

The development of MPs also plays an important role in enhancing sustainability in modular construction. MPs store detailed data on materials. This information includes their origin, reuse potential, and their environmental impact. Atta et al. (2021) argue that the integration of MPs with BIM can automates the analysis of environmental performance. This can improve the selection processes of elements in circular design.

The research of Jansen et al. (2022) finds that a mixed approach offers the best sustainable performance. This approach suggest that modular construction can achieve great environmental benefits when reusing diverse types of material. This is done by carefully selecting and combining materials based on their lifecycle impacts.

2.3 Assessment of environmental impact

The assessment of environmental impacts in the construction industry is conducted with LCA. LCA is a widely accepted method for evaluating the environmental effects of products and systems across their entire life. An LCA the whole life cycle: from raw materials extraction to end-of-life disposal. LCA can find environmental impact through for example greenhouse gas emissions, energy use, waste generation, and resource depletion (Barbhuiya and Das, 2023).

LCA is the starting point in evaluating the environmental performance of modular elements and components. Antwi-Afari et al. (2023a) confirm this by emphasizing that LCA is essential for assessing the environmental impacts of these elements. Barbhuiya and Das (2023) also give insight into the methodologies of LCA which are applied to construction materials. They explain that LCA results can support the circular economy in identifying low-impact material alternatives and the assessment of their reuse potential.

In line with this, Yang et al. (2024) underscores how important LCA is for understanding the environmental credits and burdens of reusing materials over multiple life cycles. Their research

shows that increasing the reusability of recyclability of materials significantly reduce the environmental impact, especially for CO2 emissions. Additionally, the study emphasises the need for LCA to account for multiple-life cycles. This is essential in evaluating the full environmental benefits of modular construction as materials are reused in multiple projects. Yang et al. (2024) presented a multi-use cycle framework. This framework assesses the environmental impacts of reusable resources. The results show that modular components show significant environmental benefits in terms of reduced CO2 emissions when reused across multiple life cycles. This multi-use cycle framework shows the importance of incorporating LCA methodologies that can account for long-term environmental benefits of modular elements and components. Additionally, this research shows that it is important to catalogue environmental data in material databases or MPs to retrieve information of the materials over multiple life cycles.

Lastly, the integration of multi-criteria decision-making with LCA can be another important strategy. To decide the optimal partition system for a modular building, Antwi-Afari et al. (2023b) highlighted how this multi-criteria decision-making can be combined with LCA. The multi-criteria decision-making helps stakeholders to make informed decisions because they can evaluate the environmental, economic, and social impacts of different modular designs.
When multiple criteria can be considered at the same time, final designs can be optimized for sustainability, cost, and functionality.

LCA is a critical tool for assessing the environmental impacts of modular construction. It incorporates the principles of circular economy, multi-use cycle assessments, and multi-criterial decision-making.

2.4 Types of data needed for environmental impact assessment

The accuracy of an environmental impact assessment depends on the quality of the data and if the data is complete. To perform a reliable EIA, diverse types of data are needed.

An important type of data needed for EIAs in modular construction is the data on material recovery, disassembly, and reusability. Li et al. (2024) tell that it is needed to have correct data on the ease of disassembly and material recovery for building. For example, timber modular buildings. Automated connections and interlocking designs enable easy disassembly in timber constructions. This approach promotes the reuse of materials. This type of data is crucial for assessing the environmental benefits of reusing the materials. Furthermore, it ensures that materials can be easily recovered at a structures end-of-life. Additionally, strength, durability, and performance, which is data related to material specification are essential. Li et al. (2024) point out that in timber construction, material performance data must be integrated into EIAs. In this way it can be ensured that these materials are fit for reuse. With this data it can be ensured that reclaimed materials meet the necessary safety and performance standard.

Van Stijn et al. (2021) propose a new model: the Circular Economy Life Cycle Assessment (CE-LCA) model. This model requires data on multiple life-cycle cycles of modular elements and components. The CE-LCA model assessed the environmental impact of materials during their first use and assesses their potential for reuse and recycling across several life cycles. Within modular construction this data is important to determine how materials can be reused in future construction without compromising their environmental performance.

Another important data type for EIAs in modular construction is greenhouse gas-emissions data. Greenhouse gas emissions are emitted in various stages of the building's lifecycle. Such as production, transportation, and construction. Jayawardana et al. (2023) highlight that detailed LCA data on greenhouse gas emissions is necessary to evaluate the environmental performance. Their study finds that prefabrication, which is often used in modular construction, can reduce greenhouse gas emissions by 8.06% compared to traditional construction methods. Next to greenhouse gas emissions, data om embodied energy, embodied carbon, and embodied water is of high importance, highlighted by Dixit & Kumar (2024). Accurate data on emissions of varied materials is thus necessary for a comprehensive EIA. This data helps to decide the environmental footprint of both new and reclaimed materials.

To conclude this part, the types of data needed for a thorough EIA are diverse but are mostly concentrated on the material characteristics, lifecycle impacts, environmental performance metrics, and digital management systems.

2.5 Integrating environmental impact assessments in modular construction

The integration of EIAs into modular construction requires careful considerations of best practices that perfect material reuse, environmental performance and are in line with the principles of the circular economy. Different design and construction strategies that enhance the integration of EIA in modular construction have appeared.

An upcoming approach in LCA for modular construction is the integration of DfD principles. Vandervaeren et al. (2021) demonstrate that buildings designed with the DfD principles can lead to big environmental benefits by enhancing material flows and reusability. DfD is a relevant technique for modular construction where buildings need to be deconstructed a reconstructed in different forms. Kręt-Grześkowiak and Baborska-Narożny (2023) also discuss the principles of DfD. They say that this is a key practice for integrating EIAs. By designing buildings for disassembly, the construction industry can significantly reduce waste and enhance sustainability of construction projects. Nex tot DfD, there is also design for adaptability. This is closely related to DfD. This strategy focuses on creating flexible buildings that can be easily adapted to future changes or needs. Shahi et al. (2021) say that design for adaptability is an important technique for modular construction because it allows buildings to evolve over time. This minimizes waste and promotes long-term sustainability.

Besides these construction strategies there are more design strategies. Kunic et al. (2024) do research in how automated construction methods can promote circularity by enabling material reuse. These methods use data tracking. This data tracking can enhance material reuse and help assess environmental impacts. Kumi and Jeong (2023) present an optimization model that balances impacts and cost. In this way it selects the best design for prefabricated columns. The model makes it decisions based on environmental performance and costs. The optimization of material selection with these algorithms enhances sustainability because they enable the selection of materials that minimize the environmental impact.

2.6 Data collection, structuring, and accessibility throughout the process

To perform a comprehensive EIA, it is important to have good and structured data that is well accessible. The success of the EIA depends on the quality of the data and on how well it is structured, managed, and made accessible to all relevant stakeholders through the lifecycle.

Material passports and digital product passports have an important role in structuring and managing material data. Li et al. (2024) emphasize in their research that these passports ease tracking and management of material data. Within these passports, environmental performance from production through end-of-life can be stored together with all relevant information. This information is essential for assessing the environmental impact. Integrating these passports with BIM is an effective way to give different stakeholders access to relevant environmental data (Olumo and Haas, 2024).

In the research of Kebede et al. (2024) a modular ontology model for DPP is proposed. This ontology makes the interoperability and reusability of data possible, across the lifecycle. When cloud-based platforms are being used, sharing and management of data can be easily done and ensures that all stakeholders have access to relevant and up to date data. Kebede et al. (2024) also underscores that cloud-based platforms are important for data access and up-to-date decision making based on the latest available information.

In addition to the tools that are mentioned above, automation and machine learning algorithms can enhance the data management and accessibility. Large volumes of environmental data can be processed by these technologies, and they can identify patterns and offer predictive insights. Shahi et al. (2021) propose the use of computational methodologies to optimize modular design for building extensions. These building extensions are designed in a sustainable and cost-effective way.

Next to these tools and platforms that make the data accessible, it also important to structure the data to make it accessible and actionable. Standardization of data in standard formats ensures that the data can be shared seamlessly between different platforms and stakeholders. Vandervaeren et al. (2021) propose a bottom-up approach to structure material flow data during the disassembly of buildings. It is important to systematically collect data on the material properties, potential for reuse, and environmental impact to ensure that this valuable information can be accessed and used in future projects.

Tools and platforms such as BIM, GIS and cloud-based platforms help to make the necessary information about materials available for different stakeholders and create a place to manage this information. Material passports and digital product passports create a framework to store information about materials. This can then be shared on the different tools and platforms. To effectively use the data, it is important that it is structured in a standardized way to be used between different software platforms and stakeholders.

Chapter 3: Methodology

3.1 Introduction

The research methodology adopted in this thesis, illustrated in Figure 6, includes the three research phases of the research objective and scope. The methodology provides a structured approach to explore, develop, and validate the resource selection process that generate reusable material options that fulfil the design criteria while minimizing environmental impacts.

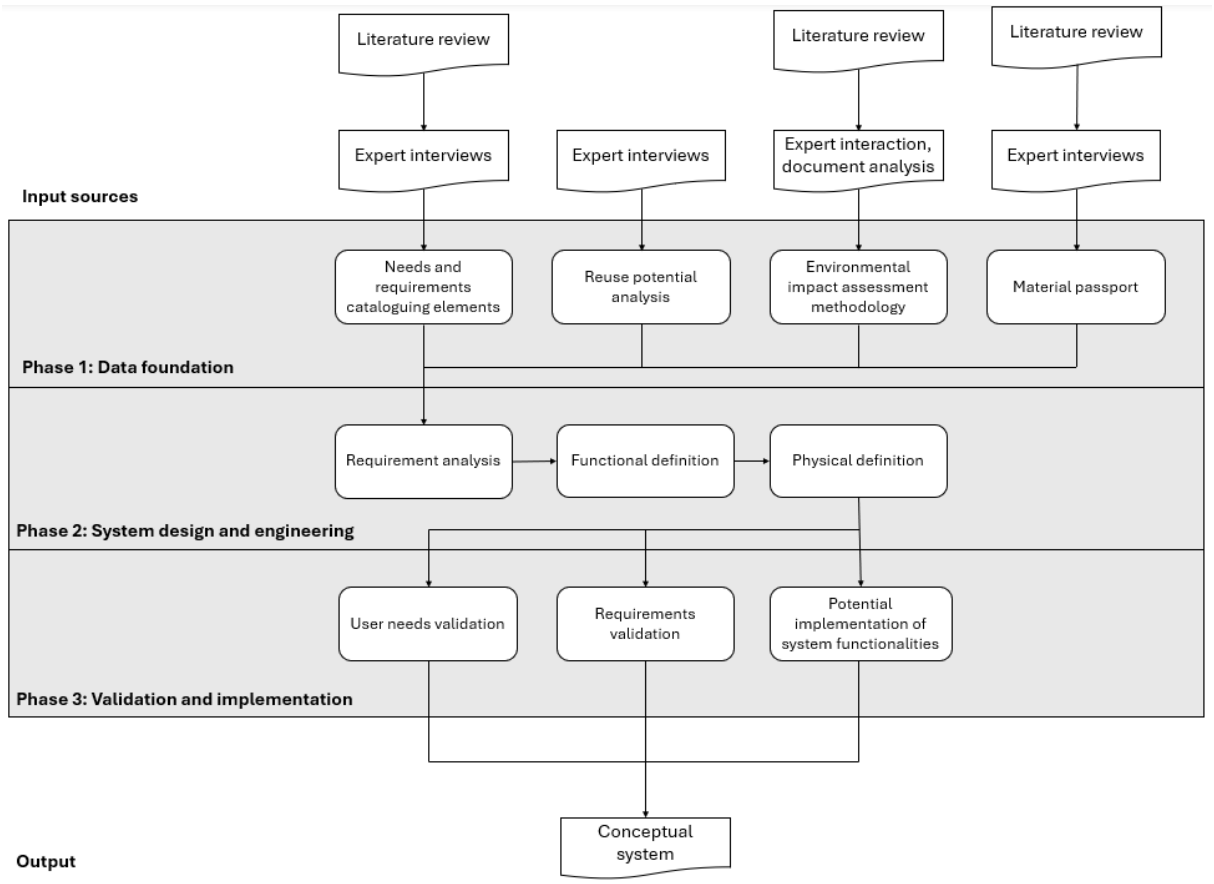


Figure 6: overview of research methodology and all activities in three main research phases.

3.2 Resource data and environmental impact

The first research phase, information gathering, addresses Objective 1 and Research Question RQ1.1 to RQ1.4. The purpose of this phase is to understand how reusable elements can be catalogued, what data is needed, and how the environmental performance of reusing these elements can be calculated. The information is gathered both from the literature from Chapter 2 and expert interviews with Van Gelder and ReCreate. The information in this phase forms

the conceptual foundation for the system design and engineering of chapter 4 and includes four key methodological steps:

1. Needs and challenges of cataloguing reusable construction elements
   Based on the literature and expert interviews, this step explores the role and value of systematically cataloguing reusable construction elements. This step gives the key challenges that the experts and researchers face. Furthermore, it gives the functional needs of database and the organizational conditions for such a system.
2. Identification of reusable elements and multi-criteria analysis
   This step defines the characteristics that make elements suitable for reuse. With these characteristics, a multi-criteria analysis has been conducted on often used elements from Van Gelder to determine what kind of elements are suitable to be pre-populated in the system.
3. Environmental impact assessment methodology
   This step developed a method to assess environmental impact. The methodology includes different formulas for the different reuse scenarios.
4. The final step of this phase synthesized the findings and gives a material passport that is tailored for reuse. This passport includes the data needed for both environmental performance calculations and reuse decision-making. This forms the basis of the system that will be developed in the next chapter.

3.2.1 Expert interviews

The expert interviews are designed to explore the current circular practices in the construction industry. The aim of the interviews is to gather information on the type of data needed in a circular design workflow by identifying the current gaps that hinder the adoption of circular design. Furthermore, the interview will give information about the functional and non-functional requirements of the circular resource selection system.

Interview set-up

The interviews will be held with industry experts of Van Gelder, as well as other relevant professionals and contributors of the ReCreate project. The interview questions are semi-structured which allows flexibility to explore certain topics in more depth, while maintaining a consistent structure. In addition, follow-up questions can be asked to elaborate more on specific subject when more detail is needed.

Interview objectives

The objectives of the expert interviews are as follows:

1. Understand the current practices: This consist of understanding the existing workflows for designing environmentally optimizes structures. The types of material data and EIAs currently used in the design process will be identified, and an evaluation how resource databases are being employed currently.
2. Discuss future aspirations: These questions will gather expert opinions on what best practices should look like in a circular design workflow. Innovative ideas for improving material choice, configuration, and environmental impact evaluation during the design phase will be explored to understand what role digital technologies could play in enhancing these workflows.
3. Identify gaps, challenges, and limitations: What do experts face in implementing reusable materials in their designs. The lack in tools, data, or technical barriers will give the functional and non-functional requirements for the circular resource selection system.

Interview themes

The discussion will focus on the following themes:

1. Material Data Requirements: What types of data are currently collected, and how is this data used in the design process?
2. Workflow Integration: How are material databases and BIM tools incorporated into current workflows?
3. Environmental Impact Assessment: What methods or tools are used to evaluate environmental performance?
4. Barriers and Challenges: What are obstacles or barriers in creating more sustainable designs?
5. Vision for the Future: What would the ideal workflow or tool look like to support circular and modular design?

Expected outcomes

The findings from the interviews will provide critical insights into:

1. Current strengths and limitations in workflows for circular modular construction.
2. Key functional and data requirements for an improved circular selection framework.
3. Specific recommendations for bridging existing gaps through tool integration and data enhancement.

Quality assurance

Interviews are conducted in person and audio or via Microsoft Teams and the audio is recorded. The recordings are used to transcribe the interviews. Intelligent verbatim transcription is the chosen method for transcribing the interviews to filter out grammatical errors, distracting filler words, and repetitions. This will result in a more readable transcript, which is still true to the speaker's intended meaning. After the interview are transcribed, they are sent to the interviewees to assess if they agree with the transcriptions, and they have the chance to make any alterations on the final transcription.

Data management and privacy

This research includes human participants and is therefore ethically reviewed by the Ethical Review Board (ERB) from Eindhoven University of Technology. Before the start of the data collection, the online form for ethical review of the research project is filled out by the principal researcher, the graduate student Hugo Spaan. Additionally, any participant will be informed about their collaboration and data collection and management with a consent form which will be signed by both parties. For the thesis the graduate student, and any other person involved in the research, will adhere to the guidelines for Research Data Management (RDM) developed by the department of the Built Environment of Eindhoven University of Technology.

3.3 System design and engineering

The second research phase, the system design and engineering, addresses Objective 2 and Research Question RQ2.1 to RQ2.4. This phase focuses on the definition and development of a circular resource selection system that supports reuse-based decision making. The goal is to create a system that can match available resources with the demand bases on project goals and a system that match the needs and requirements of their intended users.

The methodology in this phase follows the System Engineering principles (Kossiakoff et al., 2011). This methodology uses an iterative approach, which will ensure that the system is

logically structured, responsive to the user needs, and technically feasible. The process is based on the spiral model of system development (Boehm, 1986). This spiral emphasizes progressive refinement through multiple stages (see Figure 7).

This research phase consists out of three key steps:

1. Requirements Analysis – The system's objective and scope, together with the user needs are defined from the findings in Phase 1. The functional, non-functional, and data requirements are established. To structure the list of requirements and constraint the MoSCoW framework will be used.
2. Functional definition – This step maps the system's internal logic and functions which consist out of three components: data structure, application processing, data presentation. These components define the database structure, how the data is stored and accessed, and how the data is transformed and shown to the user. UML diagrams are used to formalize the system's functions and lay the basis for the system's architecture.
3. Physical definition – This step first defines the system's architecture that meet the requirements and functional definition. The conceptual model is translated into a functional system, using a Python and Django web application. This step includes the implementation of the database, backend logic, and creates a user interface to enable element selection and environmental impact calculations.

The final step of the spiral model, design validation, is conducted in the third research phase.

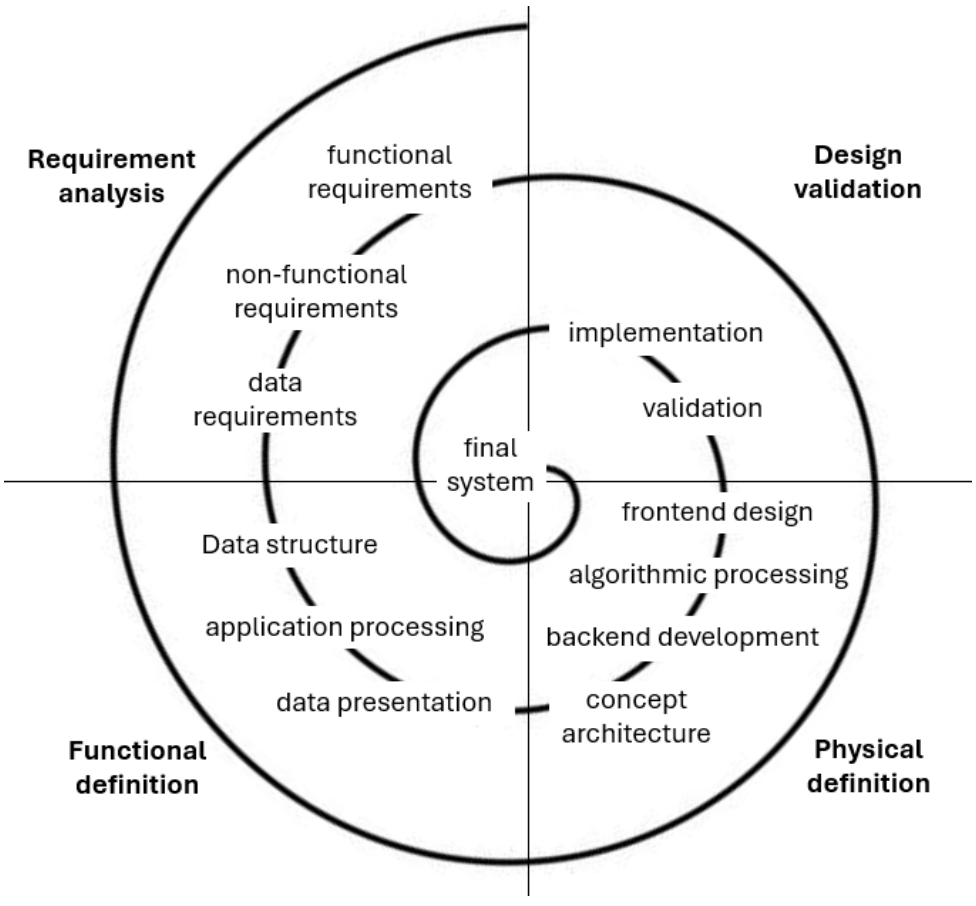


Figure 7: Spiral model of the system engineering process used to develop the generative design selection system.

3.4 Validation and implementation

The third research phase, validation, and implementation, covers the last step of the system engineering methodology. This phase addresses Objective 3 and Research Questions RQ3.1 tot RQ3.3. The goas is this phase it validates if the developed system meet the defined requirements and user needs. Furthermore, it explores how the functionalities of the developed system could be implemented in design and construction workflows to support circularity.

The validation assessed the system against the stakeholder needs and the defined requirements in the second research phase. It verifies is the system behaves as intended and if the core functionalities, reuse-bases element selection and environmental impact calculation, are correctly implemented.

In addition, this phase present how the system's functionalities could potentially be implemented in typical construction and design workflows. BPMN diagrams are used to show how the functionalities could fit in the workflows. Together with system engineers of Van Gelder, the implementation of the system functionalities in their existing tooling is analysed. Lastly, although not evaluated in a real-world project, a scenario-based evaluation is done to evaluate the potential impact of the system on decision-making support, environmental performance, and resource optimization.

Chapter 4: Resource data and environmental impact

4.1 Introduction

This chapter presents the results of the first research phase, data foundation, addresses Research Objective 1 and RQ1.1 to RQ1.4. Based on the literature and the expert interviews, this chapter outlines the challenges of data management, it defines suitable elements for reuse and develops a method for environmental impact assessment. At the end, the chapter proposes a structured material passport designed to support data-driven reuse decisions and is the direct input for the system engineering of Chapter 5.

4.2 Cataloguing reusable construction elements

When structures are designed with reusable construction elements, these elements may either still be embedded in existing structures or stored in dedicated storage locations, also known as resource hubs. According to literature, enabling reuse requires structured data collection and digital cataloguing of available elements. In this research, an internal digital database is proposed. However, this database could potentially be extended towards a shared platform, a marketplace, where stakeholders offer and access reusable construction elements.

4.2.1 Purpose cataloguing reusable construction elements

Cataloguing reusable construction elements in a database aims to address several challenges in circular construction. Summarizing the insights from the literature and expert interviews, the key purposes of cataloguing elements are:

1. Facilitating the transition to circular construction:
   Cataloguing elements enables efficient reuse of circular construction elements. The platform can bridge the gap between material availability and project needs. Centralized platforms are essential for realizing circular construction goals. They reduce reliance on virgin materials and promote resource efficiency (Ghisellini et al., 2015; Kirchherr et al., 2017; Olumo & Haas, 2024; Kebede et al., 2024). Experts in Appendix A emphasized that without a centralised place, designers overlook reusable materials due to the difficulty of finding reliable and accessible options.
2. Promoting environmental sustainability:
   Cataloguing the elements supports informed decision making. The database includes environmental impact data of the elements as described in the literature in Section 3.2. Based on this data, designers and the circular resource selection system can calculate environmental impact and make informed decisions. Interviewees also explained that you need to get an overview of what elements on which location at what time are available. The database can provide that information to strategically buy reusable resources.

3. Enhancing collaboration across stakeholders:
   Experts pointed out that the database or marketplace fosters collaboration between the different stakeholders, for example: demolition contractors, material suppliers, designers, and general contractors, can trade available resources with each other on a marketplace. The findings from Leising et al. (2018) also highlight that effective stakeholder collaboration is key to achieving circularity in the construction industry.
4. Economic opportunities for asset owners:
   Interviewees highlighted that asset owners can generate additional revenues by offering reusable materials on the marketplace. This can create an economic incentive for proper deconstruction and willingness to offer their assets for reuse.

4.2.2 Functionalities of the database

While specific functionalities of the circular resource selection system will be discussed in Chapter 5, insights from expert interviews provide information on what stakeholders expect such a system where circular resources are catalogued:

1. Comprehensive search capabilities:
   Designers want to automatically search for the right materials based on project-specific criteria. Experts remarked that when this database takes on a large form, automatic searching for the right element should become available. Otherwise, it will be a time intensive task for the designer.
2. Variety in options and supported decision-making:
   Experts expressed that they want to explore different options and possibilities. Additionally, the system to be developed, should support the designer in making informed design decisions, such as alternations to reduce the impact the modern design makes on the environment.

4.2.3 Data requirements

To efficiently and effectively reuse the elements offered in the database, it is essential to have a robust data structure to make sure the system meets it intended functionalities. Both the literature and expert feedback provide guidance on what data should be included:

1. Material Passports:
   To bundle all the necessary information needed to assess if the element can be reused in a project, MPs can be used. As described in the literature study in Chapter 2, the MP needs to bundle all the necessary information. Several factors influence the suitability of construction elements for reuse. Therefore, they should include:
   a. Identity and geometry
      General information such as the special ID, general name, type, description, and geometry should be included to identify the elements.
   b. Environmental Impact:
      The motivation for reusing construction elements is to reduce the environmental impact. It is therefore important to calculate the environmental impact of reusing elements and compare it to the impact of using similar new components (Mudge, 2024). Furthermore, elements with high embodied carbon or energy (e.g., concrete and steel) provide greater environmental savings when reused (Yang et al., 2024).

c. Condition and Quality:
   MPs must document the condition and remaining lifespan of components to facilitate reuse. Experts emphasized the need for standardized quality assurance to clients (Appendix A). The remaining lifespan is important when assessing whether elements can be used for a full use-cycle, and if not, if they could be used for temporary structures.
d. Aesthetic and Functional Compatibility:
   While the goal of this research is to optimize and proactively use reusable elements, there will still be clients that demands pristine aesthetics. This can limit the reuse of visibly worn elements (Appendix A). Including this information is therefore important to assess which materials are suitable for what kind of projects and clients.

2. Real-time availability and geolocation:
   Both the literature and expert interviews emphasized the need for real-time updates on material availability and geolocation (Olumo & Haas, 2024; Kebede et al., 2024). When this data is available, it is possible for the circular resource selection system to prioritize local materials. This reduces transportation costs and emissions. To match demand and supply, experts explained that it crucial to know the location where the materials are stored and when they are available. Furthermore, experts noted that timing mismatches between material availability and project schedules pose challenges for best reuse.
3. Standardized formats and interoperability:
   To systematically catalogue resources and ensure compatibility with digital tools, it is important to use standardized data and classification systems. NL-SfB[3] is in the Netherlands the standards for classification of elements, materials, and details in the building sector. For the infrastructure sector the NLCS[4] classification is the industry standard. NL-SfB and NLCS is relevant when using digital systems for processing construction information, from the design to realization, to the management of constructions. The NL-SfB and NLCS classification ensures that information is clearly available in every phase and therefore suitable to use as classification system in the database.

Interviewees highlighted that inaccurate or incomplete data discourage reuse. It is necessary to evaluate the reusable resources against the requirements set for the new project. Experts underscore the need for asset owners to take responsibility for providing correct data, they noted: “Without reliable data, it’s impossible to convince designers and clients to use second-hand materials.” Section 4.6 proposes a full MP tailored to the reuse of construction elements and the calculation of environmental performance.

4.2.4 Social and organizational considerations

The expert interviews also highlighted several non-technical factors that influence the success of cataloguing the elements in a database or marketplace:

1. Stakeholder responsibility and engagement:
   The owners of the assets must ensure correct and complete data on their materials, collected in MPs. Designers and contractors must collaborate early in projects to

[3] Source: https://ketenstandaard.nl/nl-sfb-facts/viewer/
[4] Source: https://www.infracad.nl/nlcs-structuur

identify opportunities for reuse. Experts explained a shift in the way we should think about the design of a circular structure. Instead of first creating a volume and later adding materials, we can start with the available materials and try different possibilities for the arrangement to create a volume that meets the criteria. Furthermore, design principles such as DfD can help to keep the value of elements after they served their purpose in the current structure.

2. Education and training:
   Interviewees pointed out a lack of awareness about circular construction principles. The construction industry is very traditional, and cost driven. Providing workshops, technical guidelines, and case studies can inform the industry of circular principles.
3. Governance and business models:
   The marketplace could run as a public platform, funded by government initiatives. This is especially relevant for infrastructure elements, as often Rijkswaterstaat or the province is the owner and buyer of the assets. For buildings this could either be a public platform or a private enterprise. Experts noted that public platforms could promote accessibility, while private platforms might ensure higher quality and innovation.
4. Client perception:
   Experts often noted that not only the designer and contractor are responsible for circularity but also the client must overcome resistance to the use of second-hand materials, particularly in aesthetic applications. Importantly, in many cases, especially in public projects, is the client not the end-user, but rather a municipality or governmental body that acts on behalf of the public. As such, public perception influences the client decision significantly. The public must accept visible signs of prior use. Increasing public awareness of environmental benefits and quality assurance of reused materials is essential and could lower the resistance for clients and end users. Additionally, it is expected that soon, clients will also be driven towards circular reuse by legislation and regulations.

4.3 Types of construction elements suitable for reuse

To advance circular construction principles, it is critical to find construction elements suitable for direct reuse, R3 on the 10-R ladder of Figure 2. From both literature and expert interviews, this section gives the characteristics that make specific elements ideal for reuse.

4.3.1 Characteristics of reusable elements

Construction elements that are suitable for reuse can be characterized as follows:

1. Durability and longevity:
   Elements suitable for reuse need to be designed with durability in mind and be capable of withstanding multiple use cycles without significant degradation. Prefabricated elements, such as concrete components, are prime candidates due to their robustness and long service life (Fivet & Brutting, 2020). Experts noted that elements with great residual life are interesting for clients to use in their design. Furthermore, it is important that materials are clean from any toxic materials to reuse them again. Moreover, when the first impact a material makes on the environment for production can be divided over multiple-use cycles, it drastically lowers the environmental impact of the current design. Relevant data for the durability and longevity are material type, strength class, technical lifespan, condition.

2. Ease of disassembly:
   Elements constructed according to the principles of DfD are highly suitable for reuse. DfD principles ensure that materials can be removed without damage and that the elements preserve their structural and functional integrity (Vandervaeren et al., 2021). Freestanding elements such as street furniture, railroad construction, traffic engineering, and telecommunication are more straightforward to reclaim and reuse when comparing it to elements that are integrated into compound structures, such as road structures or casted concrete, according to experts. Relevant data includes the assembly method, element type, geometry complexity and deconstruction damage.
3. Standardization:
   Standardized dimensions, connections, and modular building practices ease reuse across multiple projects. When elements adhere to industry standards, they are more versatile (Zhuang et al., 2023). Relevant data for standardization includes certifications and geometry.
4. High environmental impact during production:
   Elements with high embodied carbon or energy during production offer significant environmental benefits when reused compared to replacing them. Examples are precast concrete slabs or steel components (Yang et al., 2024). Relevant data is the environmental impact of an element and material type.
5. Frequent use and availability:
   Another strong candidate for reuse is elements that are widely used and frequently available, such as street paving. The environmental impact of a single component may be low, but the collective impact of reusing a material with high volumes is significant. Furthermore, frequent use in construction means that they can often be reclaimed and reintroduced into new projects. Relevant data is the available quantity and previous use application.
6. Transportation and storage
   To reuse elements in an effective way, they should be easily movable between the donor location and new projected location. Experts noted that often elements first go to a material or storage hub where they will be inspected and prepared for future use. Elements can be transported and stored in an efficient way are therefore more suitable for reuse. Relevant data is the weight and the geometry.

4.3.2 Database pre-population of database

To support the circular resource selection process with realistic, reusable options, best practice is to pre-populate material databases with elements that are often used in the industry and demonstrate that they have a high reuse potential. To create a selection of construction elements with reuse potential, two complementary sources: (1) an internal analysis of often used infrastructure materials by Van Gelder, and (2) academic and industry insights from the ReCreate project are used.

Reuse potential analysis – Van Gelder

In collaboration with industry experts from Van Gelder, a structured analysis was performed to evaluate the reuse potential of infrastructure elements that are often used in their projects. The objective of the assessment is to gain insights in which elements are technically and practically suitable for reuse and should therefore be included as reference elements in the to be developed tool.

The analysis was conducted using a multicriteria evaluation framework, see Appendix B2. Six key criteria were defined based of the characteristics defined in Section 4.3.1:

1. Durability / technical lifespan
2. Ease of disassembly
3. Standardization
4. Environmental impact
5. Availability and volume
6. Transport and storage feasibility.

Each element was assessed with a score of 1-5 per criterion and weighted according to its importance for reuse. For each of the six criteria, an explanation is given what a specific score means for that specific criteria to make sure that all the different elements are scored in the same methodology. The complete assessment of all elements (e.g. paving stones, curbs,

ReCreate insights

In addition to the assessment done with Van Gelder, relevant findings from ReCreate have been considered. ReCreate has investigated the reuse of prefabricated concrete structural elements such as floors slabs, façade panels, columns, and beams. The project highlights that these elements often retain their structural integrity long after a building is deconstructed and are therefore excellent for being reused in new projects (Wijte et al., 2023). The pilot project in the Netherlands, The Prinsenhof building, showed successful recovery and reuse of these prefabricated concrete elements.

Selected elements for pre-population

Based on both sources, the following materials are often used and have a high reuse potential and are therefore suitable to be pre-populated in the database as reference elements:

- Concrete paving stones
- Clay and concrete pavers
- Concrete curb stones
- Crushed stones
- Traffic signs
- Soil, sand, and clay
- Prefabricated concrete walls
- Prefabricated concrete slabs
- Prefabricated concrete beams
- Prefabricated concrete columns

A copy of GWP and MKI scores can be found in appendix B4.

4.4 Analysis of environmental impact assessments and their matrices

The literature and experts clearly state that the reason for reusing construction elements is to reduce the environmental impact of the construction industry. To know if reusing construction elements make a difference compared to using new products, it is important to calculate it. This ensures that environmental benefits are achieved in all cases and prevents reusing elements in cases where newly manufactured elements would have smaller environmental impact (Mudge, 2024). This Section describes the existing frameworks, and their matrices identified in the literature and interviews (Appendix A) to select the right metrices and calculation method for the database and circular resource selection system, respectively.

4.4.1 Key frameworks and their matrices

EIA rely on structured frameworks and standardized methods to ensure their accuracy and comparability for informed decision-making. The literature and experts (Appendix A) stated the fundamental frameworks and standards for EIA: ISO 14040 (LCA), ISO 14042 (LCIA), EN 15804+A2 (EPD), and MKI. These frameworks form the EIA in the construction industry and are therefore explored and discussed in order to find the best suitable metrices for (1) calculating and comparing environmental impact in order to make automatic selection by the selection system possible, and (2) in order to find the best suitable metric to express the environmental performance of a design and communication to stakeholders (Stichting Nationale Milieudatabase, 2020).

Life-Cycle-Assessment (LCA) and Life-Cycle-Impact-Assessment (LCIA)

The LCA is defined in ISO 14040. This is an international standard that explains the principles of the LCA and explains how to conduct an LCA. The International Organization for Standardization (ISO) gives a framework on how to conduct an LCA. It sets out the methodology for assessing environmental impact of a product in the entire life cycle. An important property about the LCA, and highlighted by the experts in Appendix A, is that an LCA often includes proprietary or sensitive data, such as exact material composition, production processes, and energy consumption. This means that a LCA is typically intended for internal use or academic/technical purposes and thus not always suitable for public distribution.

The LCA that is described in ISO 14040 provides the guidelines and methodology for analysing environmental performance. It does not describe any impact categories on which the assessment is being done. Instead, ISO 14040 leaves the choice of impact categories to the practitioner. They can choose the right impact categories bases on the goal, scope, and context of the study. That means that LCAs under ISO 14040 can be customized and can include fewer or more impact categories. Therefore, an LCA can go deep into areas of interest or concerns for the product being assessed (Stichting Nationale Milieudatabase, 2020).

Although the purpose of ISO 14040 is to provide a general framework for conducting an LCA, and therefore does not prescribe specific impact categories, it refers to ISO 14042 for details on Life-Cycle Impact Assessment (LCIA), which is one of the four key phases. These four key phases are shown in Figure 9 and consists of out (European Commission, n.d.):

1. Goals and scope definition: determine the purpose of the study and the system boundaries.
2. Life cycle inventory (LCI): collect data about all inputs and outputs.
3. Life cycle impact assessment (LCIA) assesses the potential environmental impacts based on the inventory data (ISO 14042).
4. Interpretation: analyse and draw conclusions based on the results.

As described in Figure 8, LCIA is a subcomponent of the LCA framework. The LCIA focuses, specifically on the impact. LCIA translate the inventory done in the LCI (step 2 of the LCA framework) in meaningful environments impact categories. As discussed earlier, the impact categories are not prescribed and can be chosen based on the type of material that is assessed.

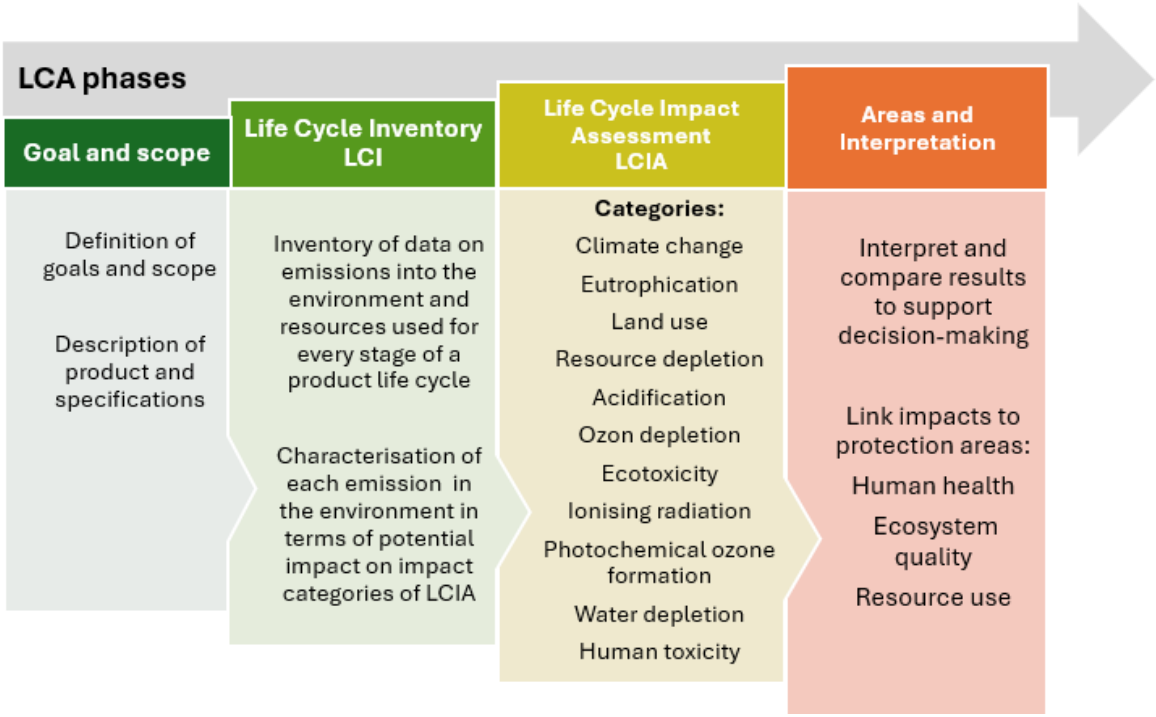


Figure 8: Four key phases of life cycle assessment.

Environmental Product Declaration (EPD)

In the European Union it is mandatory to provide environmental data in EPDs. The European standard for creating EPDs for construction products is described in EN 15804+A2, which is the successor of the EN 15804+A1. It aligns with the LCA methodologies but focuses on providing detailed, standardised information about product's environmental impact in different life stages. An EPD is a publicly accessible document that summarises the findings of an LCA with predefined impact categories, aligned with unique environmental concerns of the construction industry. It uses a standardised format, meaning that EPDs does not include sensitive information and can be compared with each other. Table 1 gives an overview of the nineteen prescribed impact categories of an EPD summarised by The Dutch National Environmental Database[5] (Stichting Nationale Milieudatabase, 2020).

[5] https://milieudatabase.nl/en/

Table 1: Environmental impact categories (Nationale Milieudatabase)

Milieu-impactcategorie	Indicator	Eenheid
Klimaatverandering - totaal	GWP-totaal	kg CO2-eq.
Klimaatverandering – fossiel	GWP-fossiel	kg CO2-eq.
Klimaatverandering – biogeen	GWP-biogeen	kg CO2-eq.
Klimaatverandering - landgebruik en verandering in landgebruik	GWP-luluc	kg CO2-eq.
Ozonlaagaantasting	ODP	kg CFC11-eq.
Verzuring	AP	mol H+-eq.
Vermesting zoetwater	EP-zoetwater	Kg P-eq.
Vermesting zeewater	EP-zeewater	kg N-eq.
Vermesting land	EP-land	mol N-eq.
Smogvorming	POCP	kg NMVOC-eq.
Uitputting van abiotische grondstoffen mineralen en metalen	ADP-mineralen&metalen	kg Sb-eq.
Uitputting van abiotische grondstoffen fossiele brandstoffen	ADP-fossiel	MJ, net cal. val.
Watergebruik	WDP	m3 world eq. deprived
Fijnstof emissie	Ziekte door PM	Ziekte-incidentie
Ioniserende straling	Humane blootstelling	kBq U235-eq.
Ecotoxiciteit (zoetwater)	CTU ecosysteem	CTUe
Humane toxiciteit, carcinogeen	CTU humaan	CTUh
Humane toxiciteit, non-carcinogeen	CTU humaan	CTUh
Landgebruik gerelateerde impact / bodemkwaliteit	Bodemkwaliteitsindex	Dimensieloos

From the 19 impact categories described in the EN 15804+A2, The Nationale Milieudatabase identifies several indicators that describe distinct categories of environmental impact resulting from construction works. From these impact categories, the Global Warming Potential Total (GWP-total), measured in kgCO2-eq. is considered as the metric to be used to quantify the total climate change from construction works.

The EN 15804+A2 also specifies the life-cycle stages of construction elements, shown in Figure 9. It is mandatory to provide information on the product stage (A1-A3) and the end-of-life stage (C1-C4). With the GWP metric it is possible to calculate the environmental impact of both new and reused elements (Stichting Nationale Milieudatabase, 2020).

Figure 9: Life-cycle stages on construction works (Nationale Milieudatabase, 2025)

Milieu-Kosten-Index (MKI)

The MKI is a Dutch metric used for expressing environmental impact in terms of money. It combines multiple impact categories into a single cost value which reflects the environmental burden. Experts (Appendix A) highlight that this simplifies complex environmental data into an easily understood figure and streamlines communication towards stakeholders. The MKI is preferred for client communication due to its simplicity compared to LCA and EPD and aligns with Dutch policy frameworks. It enables straightforward comparison and justifies design decisions.

To calculate the MKI, the shadow price is used, which is the societal costs of environmental damage. Each of the nineteen impact categories shown in Table 1 are multiplied by the respective shadow costs. Summing up, all these values produce a single value expressed in money, MKI. To calculate the MKI the following formula can be used:

$$\text{MKI} = \sum_{i=1}^{19} (Impact\ Category\ Value_i * Shadow\ Cost_i) \quad (4.1)$$

In addition to the calculation method there also exist databases that collect the MKI information of a variety of construction elements such as The Nationale Milieudatabase (Stichting Nationale Milieudatabase, 2020).

4.4.2 Environmental impact metrics for calculation and communication

To support data-driven material selection and transparent communication, the material passport must include environmental impact metrics that serves the following key purposes:

1. Automated selection of materials in the circular resource selection system based on environmental impact.
2. Comparison between new and reused materials based on environmental performance.
3. Transparent communication of environmental impact to clients and stakeholders.

The GWP is the standard metric for assessing embodied carbon in construction materials, expresses in CO2-eq. It enables the comparison between reusable materials among themselves and new materials. GWP values can be extracted from EPDs per life-cycle stage for detailed calculations.

While the GWP will be used for calculations, MKI provides a monetary representation of the environmental impact. This serves as an effective communication metric by translating environmental impacts into tangible costs for stakeholders. MKI values can be sources from the NMD, EPDs, or calculated with formula 4.1.

Table 2 summarises the key environmental impact metrics that must be included in MPs and stored in the material database.

Table 2: Overview of environmental impact metrics

Category	Metric	Unit	Purpose	Data source
Calculation	GWP	Kg CO2-eq.	Rank selection in system	EPDs (A1-A3, A4-A5, C1, C2)
Communication	MKI	€-eq.	Stakeholder communication	NMD, EPDs

4.5 Calculation of environmental impact assessment

This section presents the formulas for calculating the GWP of different scenarios in circular construction. The scenarios are distinguished between new materials and reused materials under different conditions. The following three scenarios are covered in this section:

1. New material on a site
2. Reused material on the same site
3. Reused material on a new site

In Table 2 the different scenarios are described (Nationale Milieu Database, 2022; Mudge, 2024), and the formula names are given.

Table 3: Scenarios of calculating GWP.

Scenario	Formula name	Description
New material on a site	GWP_NewMaterial	Covers A1-A3 (production) + A4 (transport) for a new material being produced and transported to the site location + A5 for the construction process.
Reused material on the same site	GWP_ReusedSameSite	Covers factored previous use-cycle (A1-A3) + C1 (deconstruction), as material is deconstructed, and no transport is involved.
Reused material on a new site	GWP_ReusedNewSite	Covers factored previous use-cycle (A1-A3) + C1 (deconstruction) + C2 (transport) for deconstructed materials to a material or storage hub + A4 (transport) for transportation of materials from storage hub to projected location.

4.5.1 Calculation of new material on a site

The environmental impact of new materials transported to a site consists out of the production stage (A1-A3), transportation (A4), and construction (A5) see Figure 9. The total GWP can be based on whether a material is unit based (point object), line based (line object), Area based (plane object) volume-based (m^3), or weight-based (kg or tons).

Production impact calculation (A1-A3):

$$GWP_{production} = GWP_{A1-A3} * Q \quad (4.2)$$

Where:
Q = functional quantity of the element (m, m^2, m^3, kg, pc)
GWP_{A1-A3} = impact per unit of Q

Transport impact calculation (A4):

$$GWP_{transport_A4} = GWP_{A4} * ((Q \times CF) / 1000) * Distance(km) \quad (4.3)$$

Where:
CF = conversion factor (kg/m, kg/m^2, kg/m^3, 1, kg/pc)

Construction impact calculation (A5):
The construction impact is calculated by summing up all the different construction activities required for total construction:

$$GWP_{construction\ total} = GWP_{A5} = \sum_{i=1}^{n}(GWP_{construction,i} * Time_i) \quad (4.4)$$

Where:
$GWP_{construction\ total}$ = total kgCO2-eq from al construction activities
$GWP_{construction,i}$ = kgCO2-eq per hour for activity i
$Time_i$ = hours spent on activity i

Total impact of new material:

$$GWP_NewMaterial = GWP_{production} + GWP_{transport_A4} + GWP_{construction} \quad (4.5)$$

4.5.2 Calculation of reused material on the same site

For reused elements remaining on the same site the environmental impact includes the factored previous use-cycle (A1-A3), the deconstruction phase (C1), and new construction (A5). The previous use-cycle is included with a reuse factor as this aligns with the principles of designing for multiple use-cycles and accounts for the environmental burden of reuse in a fair way, as prescribed by the calculation methods of NMD (Nationale Milieu Database, 2020). This approach ensures that materials are not treated as zero-impact when reused but distributes the impact of the production phase over multiple use-cycles. For some materials you can include the use phase (B1-B7) when materials experienced a lot of maintenance during their previous use-cycle, however for materials that do not need (a lot of) maintenance, which is according to the characteristics of reusable materials described in Section 3.3 the case, the use phase does not have a lot of environmental impact and is therefore not included in the calculation.

Deconstruction impact calculation (C1):
The deconstruction impact is calculated by summing up all the different deconstruction activities required for total deconstruction:

$$GWP_{deconstruction\ total} = GWP_{C1} = \sum_{i=1}^{n}(GWP_{deconstruction,i} * Time_i) \quad (4.6)$$

Where:
$GWP_{deconstruction\ total}$ = total kgCO2-eq from al deconstruction activities
$GWP_{deconstruction,i}$ = kgCO2-eq per hour for activity i
$Time_i$ = hours spent on activity i

Factored previous use-cycle:

$$GWP_{previous\ use} = GWP_{production} * RF \quad (4.7)$$

Where:
RF = Reuse Factor
$GWP_{production}$ = formula 4.2

*GWP_{A4} is not added to this calculation while the transportation emissions need to be added to the environmental impact of the specific structure the materials were used for. Only initial impact (production) needs to be spread over all use cycles.

Total impact of reused element on same site:

$$GWP_ReusedSameSite = GWP_{previous\ use} + GWP_{deconstruction\ total} + GWP_{construction\ total} \quad (4.8)$$

Where:
$GWP_{Construction,\ =}$ formula 4.4
$GWP_{deconstruction\ total\ =}$ formula 4.6

4.5.3 Calculation of reused material on a new site

For elements that are deconstructed on site x and transported to site y for reuse, the environmental impact consists out of the deconstruction and factored previous use cycle together with the transportation phase to the new site (C2).

Transport impact calculation (C2):

$GWP_{transport_C2}$ is equal to the calculation of $GWP_{transport_A4}$ (4.9)

Where:
$GWP_{transport_A4}$ = formula 4.3

Total impact of reused element on new site:

$$GWP_ReusedNewSite = GWP_{previous\ use} + GWP_{deconstruction\ total} + GWP_{transport_C2} + GWP_{transport_A4} + GWP_{construction} \quad (4.10)$$

Where:
$GWP_{previous\ use}$ = formula 4.7
$GWP_{deconstruction\ total}$ = formula 4.6
$GWP_{construction\ total}$ = formula 4.4

*The formulas 4.10 and 4.5will be used in the tool to calculate reused materials and new materials. Scenarios where material will be reused on the same site, can be modelled by setting the location for the donor project, storage location, and new projected site to the same coordinates. In this way both transport distances C2 and A4 equals zero and are eliminated from the equation. In case that no storage location is being used, the storage location can be set on the same location as the projected site location, in this way transport A4 will be eliminated from the equation.

4.5.4 Base emission factors

NMD have set base emissions factor for transportation and (de)construction activities (Nationale Milieu Database et al., 2021). For example, for transportation: *0320-tra&Transport, vrachtwagen (>32 ton), Euro 5, diesel, per tkm 0.0854 kg CO_2 / ton·km,* or for example for construction: *Verplaatsen, Betonmixer-pompwagen combinatie, diesel H1-8000 processen, 0,050 uur.* This means that in most LCA/EPD results a single emission factor per unit for the whole transportation and (de)construction phase is given. However, these results are calculated with a flat rate distance and predefined (de)construction time. Within this thesis the no flat rate distance is being used but calculated through the distance between the donor location, storage location, and projected site. (De)construction activities, time, and their respective emissions are taken over from the NMD. Although due to the intensification of optimization and electrification of the (de)construction process the formulas 4.4 and 4.6 can be used for more tailored results.

4.6 Material Passport for cataloguing circular construction elements

This section proposes all data attributes that should be included in a MP, tailored for reusable elements, based on the findings of the previous sections. This MP is specifically designed to collect, structure, and store the essential data that is required to catalogue circular construction elements in a database. The MP serves as a product sheet that document key attributes of reusable elements and ensures that all relevant, technical, environmental, and logistical data is recorded for future selection and reuse. A simplified example of MP that currently is being used, is given in Appendix B1. While this format provides a solid foundation, this MP does not contain all relevant information and should be elaborated with the key data categories that are given in Table 4.

Table 4: Data necessary to include in MP.

Category	**Data fields**	**Unit / Format**	**Purpose**
Identification	Element type	Coded classification (NL-SfB)	Categorization and search method for digital tools
	Unique identifier (ID)	Alphanumeric code	Tracks and catalogues elements uniquely
	Element name	Text	Standardized name for identification
	Description	Text	Additional specification (optional)
	Quantity	Count / m2 / m3	Specifies how much is available
Geometry	Height	mm	Gives dimensions
	Length	mm	Gives dimensions
	Width	mm	Gives dimensions
	Weight	Kg or tons	Required for transport calculations
Material & certification	Material type	Concrete, steel, wood, etc	Identifies material characteristics
	Certification compliance	ISO, CE, EN – standards	Verifies technical acceptance
Physical / structural properties	Strength class (if applicable)	Class (e.g. C30/37)	Ensures safe reuse
	Load capacity (if applicable)	kN	Ensures safe reuse
Condition & quality	Damage	Scale (Clear, Minor, Major)	Determines structural suitability for reuse
	Aesthetic condition	Scale (good, moderate, poor)	Evaluates visual appearance for reuse
Previous use-cycle data	Number of use-cycles and duration	List	Tracks how many times the element has been reuses
	Remaining lifespan	Years	Determines suitability for new projects
Environmental impact metrics	GWP_A1	kg CO2-eq.	Production impact
	GWP_A2	kg CO2-eq.	Material transport
	GWP_A3	kg CO2-eq.	Processing
	GWP_A4	kg CO2-eq.	Logistics
	GWP_A5	kg CO2-eq.	Construction
	GWP_C1	kg CO2-eq.	Deconstruction
	GWP_C2	kg CO2-eq.	Transportation
	MKI	€-eq.	Reference value of NMD or EPD

Availability & logistics	Storage location / donor site	GIS coordinates	Determines where element is stored or donated from.
	Availability date	Date	Ensures materials are available
	Status	Available / unavailable	Check availability
Ownership & assessment	Current owner	Text	Identifies who owns the element(s)
	Assessment date	Date	Ensures up-to-date material condition data

4.7 Conclusion and outlook

This chapter established the foundation for enabling circular design through structured material data and environmental performance assessment. It defined which types of elements are most suitable for reuse, what data attributes are necessary to support reuse decisions, and how GWP-based environmental assessments can be calculated for different reuse scenarios. These insights formed the basis for the data structure and reuse logic used in the remainder of the thesis.

The findings from this chapter serve as critical input for Chapter 4, where these data requirements are translated into a conceptual system design. The goal is to define how a generative design model can operationalize the reuse of construction materials using the principles and data structures introduced here.

Chapter 5: System design and engineering

5.1 Introduction

This chapter presents the system design and development, the second phase of this research, and addresses Research Objective 2 and RQ2.1 to RQ2.4. The system has been developed following the system engineering methodology as described in the methodology in Chapter 3. This chapter builds upon the methodology and integrated contextual insights form ReCreate Studio and the CircuTool which both serve as a reference and practical example of a database-driven design tool. The system described in this chapter provides both a practical framework and a working prototype, and is developed through the following phases:

1. Introduction and scope
2. Requirement analysis
3. Functional definition
4. Physical definition

5.1.1 objective and scope of the system

The circular resource selection system that will be developed in this chapter has the objective to facilitate data-driven material selection for circular construction. The core functionalities include:

1. A structured database to catalogue reusable construction elements.
2. A registration interface for adding new elements to the database.
3. An automated selection algorithm that matches material demand to supply based on environmental performance, location, quantity, type, and geometry.
4. A user interface for designers and contractors to explore reuse and hybrid (reuse-new) scenarios.
5. Backend access for database managers.

5.1.2 Integration with existing workflow

The circular resource selection system needs to be developed in a way so that is possible to integrate it into existing design and construction workflows. From interviews and workflow analysis (Chapter 4), it became clear that material availability, location, and environmental performance are critical input for decision-making in preliminary design phases and construction workflows. Figure 13 gives a conceptual process to ensure that the developed system can potentially be implemented in real-world design and construction workflows:

1. A designer defines material needs based on conceptual designs.
2. The material needs are translated into searchable attributes.
3. The system queries the database and calculates GWP values for matching elements.
4. Material configurations are generated and could be exported for further use in the design process.
5. Designers can make decisions based on the data generated by the tool.

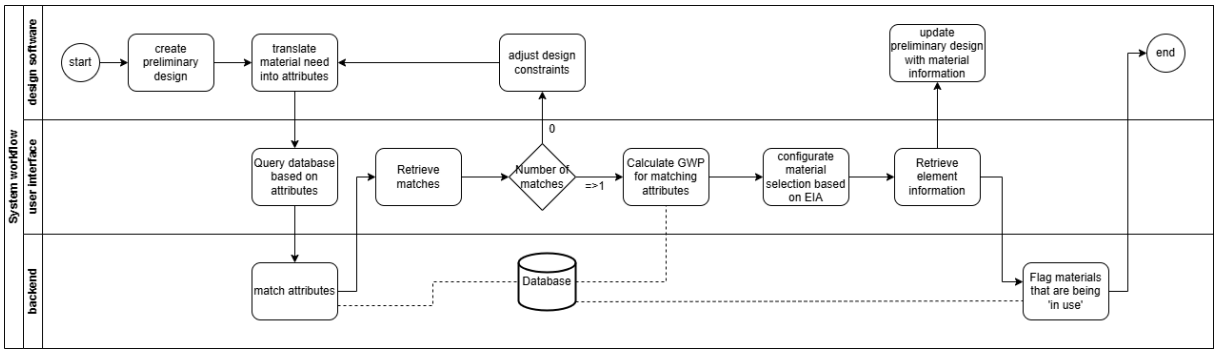


Figure 10: Conceptual integration of the circular resource selection system into the existing workflow.

While the system itself is standalone, it is designed and structured in a way that it supports integration with platforms like Autodesk Revit, Civil 3D, company specific tools like CircuTool and integrates in real-world design and construction workflows. The detailed implementation of the tool within actual workflows, including practical use cases and BPMN activity diagrams, is presented in Chapter 6.

The development of the system draws from existing industry tools like ReCreate Studio and CircuTool, as introduced in Section 1.6. While both tools provide valuable contribution to the reuse of material, each has limitations that restrict their broader application. The CircuTool, developed by Van Gelder, features a material matching mechanism but lacks a centralized database or structured schema. This prevents the tool to being directly integrated into design tools (Civil 3D). Although it includes a material registration form, it does not include any information on environmental performance and does not perform EIA.

ReCreate Studio, on the other hand, offers a structured database and is connected to the design software Revit via a plug-in. However, the database of ReCreate is limited to a fixed set of elements which are identified in the ReCreate Project. It lacks the ability to register new elements or update the dataset dynamically through a user interface. Additionally, it does not feature environmental performance calculations or a standalone interface for users to explore or manipulate the data.

The circular resource selection system designed and developed in this thesis builds upon these initiatives and aims to create one unified system that has:

- A flexible and scalable database that can store a wide variety of elements, structured according to industry experts' insights.
- Web interface for registration form to support the addition of new elements, enabling database growth and extensibility.
- Web interface for material overview for designers to get informed about all available reusable elements.
- Environmental impact assessment that automatically calculates the GWP and enables hybrid reuse material configurations.
- An architecture designed for future integration with BIM software.

By analysing existing initiatives in the industry and combining these capabilities, the system aims to support a more automated, transparent, and adaptable approach to circular material selection that can be implemented in workflows from the industry to fill the existing gap of the data driven reuse of materials.

5.1.4 Target audience/stakeholder analysis

The successful implementation of the tool relies on a diverse group of stakeholders who interact with the system throughout different lifecycle stages. This section identifies the different stakeholder groups who are involved in the tool. It defines their roles, expectations and interactions with the system as follows:

- Architects and Engineers
  Use Case: Select elements based on project design requirements
  Interaction: Query the database to find reusable materials; receive ranked suggestions based on environmental impact
  Need: Detailed geometry, performance data, environmental scores.

- Contractors
  Use Case: Plan and prepare construction using selected materials
  Interaction: Access material availability, condition, and logistics
  Need: Reliable and accurate information for procurement and scheduling.

- Project Managers / Sustainability Officers
  Use Case: Evaluate environmental impact of design options
  Interaction: View environmental impact assessments (GWP, MKI)
  Need: Metrics for sustainability reporting and decision-making.

- Database Owners
  Use Case: Populate the system with materials and manage records
  Interaction: Input, update, and manage reusable materials
  Need: Structured data management interface, quality control tools.

- Asset Owners / Clients
  Use Case: Offer elements for reuse and resell
  Interaction: Submit material information to the database
  Need: Validation and documentation of offered elements.

The interaction between the users and the system is captured in the Unified Modelling Language (UML) Use Case Diagram in Figure 14. The primary actor that interacts with the system is the Architect/Designer. This user will initiate the generative design process and configurate reusable materials based on predefined constraints. However, the tool also includes functionalities that can be accessed by other actors such as the environmental performance, history tracking or material information for construction planning.

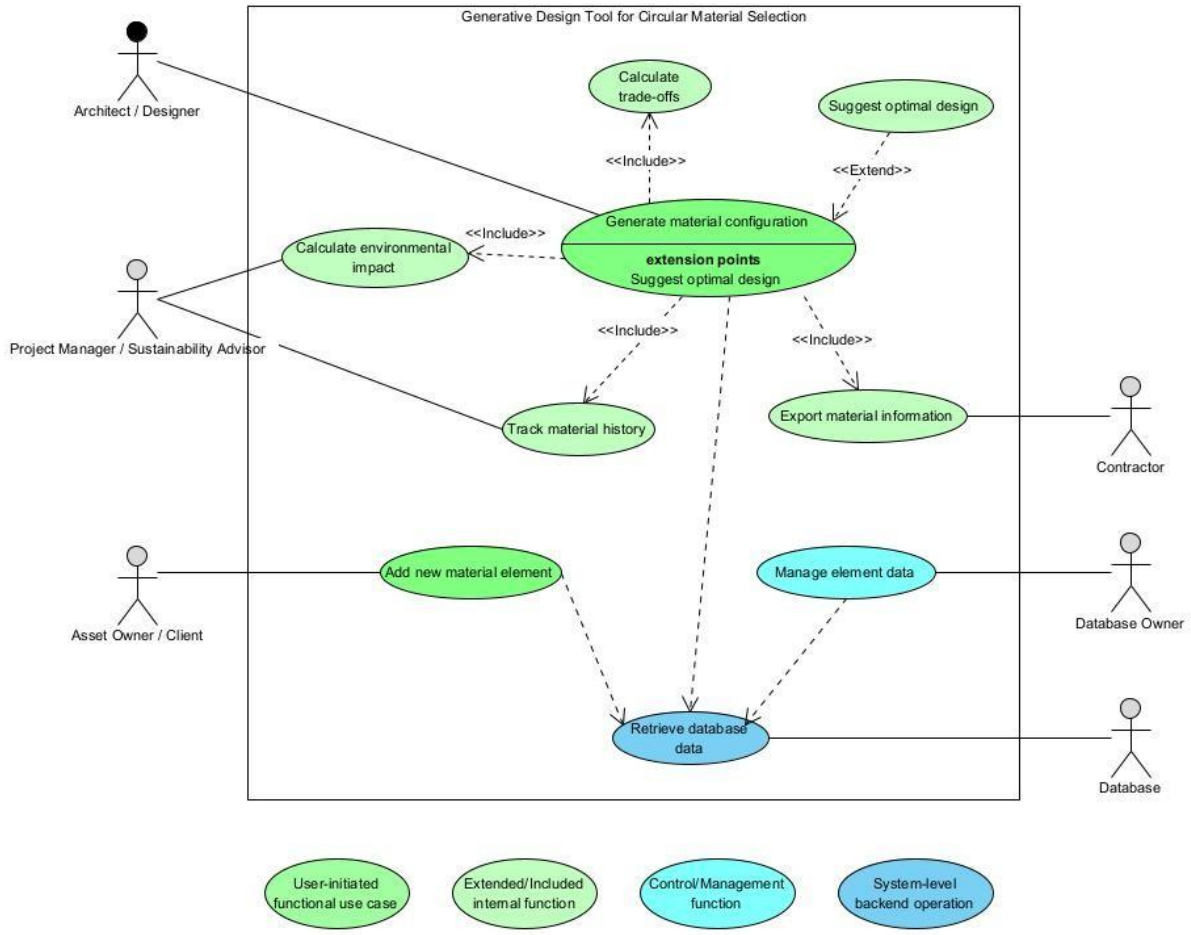


Figure 11: UML Use Case Diagram

5.2 Requirement analysis

This section breaks down the high-level requirements given in the introduction of this chapter into specific, actionable needs. While the structure of this chapter follows the system design phases defined by Kossiakoff et al. (2011), the requirements can be grouped into user requirements (functional and non-functional) and data requirements. The distinction between user and data requirements reflects the user-driven and data-oriented nature of the tool. The user requirements encompass both the functional and non-functional needs of the tool. They define what the system must do to support the users in selecting and configuring reusable elements and define how the system should perform. The data requirements define the type, structure and quality of the data needed to effectively operate the system.

5.2.1 Functional requirements

The functional requirements define the core conditions under which the tool must operate and ensure that it will deliver value and contribute to circular construction workflows. These requirements come from practical insights gathered from expert interviews (Appendix A), literature, and the analysis the existing tools of ReCreate and Van Gelder. The tool and therefore also the operational requirements are structured into three core functional clusters:

1. Database setup and maintaining the database.
2. Managing of existing elements and interacting with database.
3. Support for material selection and circular design decisions making.

This structure reflects the workflow progression which started with setting up a reusable materials environment which expands to an actively supporting data-driven design tool.

Setting up and maintaining the material database

The operational foundation of the tool is a structured, queryable material database. The database is locally hosted and built with MySQL, which is an open-source relational database management system. A relational database is a way of structuring information in tables, rows, and columns. It can create links, also known as relationships, between information by joining tables. This makes it easy to understand and gain insights about the relationship between various data points. Furthermore, the database is equipped with structured query language (SQL) which makes it possible to query and update the database. A database schema is used that is aligned with the material passports (Table 3) and is further explained in Section 5.3 Functional definition. The tool is pre-populated with material elements that has a high reuse potential identified by ReCreate and Van Gelder and with environmental reference values from the NMD.

To serve real-world applications, however, the tool must eventually allow users, such as contractors or asset owners to add their own elements using a standardized input format, based on the material passport for reusable construction elements identified in Chapter 4. The standardized format ensures interoperability, data quality, and comparability between projects. In future versions the database could evolve into a marketplace-like functionality that connects supply (owners of reusable materials) and demand (designers and contractors)

Table 5: MoSCoW table database setup

Database Setup		
Requirements	**Description**	**Priority**
Initial database setup	Enable storage of material passports in structured format	Must-have
Data pre-population	Populate prototype with reusable elements (ReCreate, Van Gelder)	Must-have
User input	Interface to add new reusable elements manually	Should-have
Data validation	Ensures entries include minimum required fields	Must-have
Marketplace functionality	External parties offer materials via shared interface	Could-have
Integration with external database	Real-time syncing with material database (e.g. NMD)	Could-have
Cloud-based shared access	Multi-user access to a cloud-hosted or centralized version of the database	Will not-have

Managing and interacting with existing elements

Once materials are in the system, the users must be able to interact with the existing elements to support evolving project needs. This includes searching and filtering the database, updating material statuses, editing metadata, and tracking historical changes. These operations enables the tool to support real-world logistics and planning. Furthermore, it aligns with stakeholder expectations (see Appendix A), where digital access accurate and up-to-date material information is a prerequisite for practical reuse.

Table 6: MoSCoW table material management

Material management		
Requirements	**Description**	**Priority**
Search and filter	Allow users to locate materials by filter such as type, location, conditions, etc	Must-have
Update materials status	Enable transitions such as “available” → “in use” → “reserved”	Must-have
Edit existing records	Provide ability to modify material properties post-upload	Should-have
Usage log/history tracking	View usage history and modifications of each material over time	Should-have
Export capabilities	Allow data export for material overview and reporting	Could-have

Material selection and design decision support

The primary value of the tool lies in its ability to support designers in selecting reusable materials for their project and align with circular design goals. Based on a predefined quantity (e.g. surface area, volume, or number of pieces), the system must generate material combinations that account for environmental performance, location, availability, quality, and compatibility with technical requirements such as dimensions and structural properties. When the reusable materials presented in the database are insufficient to meet the full design demand the tool should propose mixed solutions with new materials, suggest design adjustments to better fit available stock, and present the environmental trade-offs between reuse, hybrid, and conventional options.

Table 7: MoSCoW table material selection and decision support

Material selection and decision support		
Requirements	**Description**	**Priority**
Fill design space with reusable materials	Match available materials to required quantity (m3, m2, m, kg, pcs) based on environmental impact	Must-have
Filter design selection	Filter materials based on availability, location, dimensions, conditions, etc	Must-have
Suggest design adaptations	Suggest modifying the design (e.g. adjust the required quantity to available materials) to optimize reuse	Should-have

Mixed reuse-new material solutions	Suggest hybrid solutions combining reused and newly produced materials if needed	Should-have
Environmental impact assessment	Calculate and display the environmental impact (GWP and MKI) per configuration	Must-have
Compare alternative configurations	Present multiple reuse configurations to support decision-making	Should-have
Live design feedback	Provide real-time feedback as users adjust constraints or parameters	Could-have
Export selected configuration	Export final material selection to BIM environments (e.g. Revit, Civil 3D, IFC)	Should-have
Visual 3D preview in BIM	Direct 3D visualization or real-time BIM plug-in integration	Could-have
Structural analysis of design	Perform structural feasibility or load-bearing validation	Will not-have
Role-base access control	Different permission levels for modifying or viewing materials	Should-have

5.2.2 Non-functional requirements

The non-functional requirements describe how the system should perform and which technical qualities the system should possess. These are split into the performance requirements and the system requirements which both should support adaptability and long-term functionality. In terms of performance requirements, the system must maintain low latency under different user interactions. It must remain stable and responsive when the dataset grows. Furthermore, it could be capable of supporting batch operations and integration with external databases in the future, such as the NMD for environmental impact data, in the future. This will support smooth data exchange, reduce manual input, and enable dynamic environmental impact assessment. For the system requirements the application must be developed in a modular way. In that way each major function – material input, environmental impact assessment, and element selection – is isolated and can be independently maintained and when necessary, expanded with new functionalities. The database must support scalability and editable data structures to allow for continuous expansion. Additionally, the user interface must be intuitive, while the overall architecture is designed to support maintainability and prepare for future integration with other tools and platforms.

Table 8: MoSCoW table non-functional requirements

Performance and system requirements		
Requirements	**Description**	**Priority**
Query response time <3s	Searching for materials and configurate material selection under 3 seconds per query	Must-have
Batch operations	Elements added in batches instead of single entries.	Could-have
External databases	System connected with APIs of outside databases for environmental impact data	Should-have
Modular code architecture for data input	Independently maintainable and extensible code for data input.	Must-have

Modular code for environmental impact assessment	Independently maintainable and extensible code for environmental impact assessment.	Must-have
Modular code for element selection	Independently maintainable and extensible code for element selection.	Must-have
Scalable database	The schema must be designed to allow easy additions of new component types or data classes	Must-have
Queryable database	The database manages simple to complex queries over different data tables	Must-have
Editable component attributes	Option to update attributes without breaking existing data entries	Must-have
Extensible logic for rule integration	Adding new rules and selection algorithms without modifying the core system	Must-have
Cloud-deployable system	Running system on a remote server or cloud environment to allow future scalability and access	Should-have
Decouples frontend and backend	UI and logic separated to allow changes to interface without requiring changes to underlaying logic	Should-have

5.2.3 Data requirements

This section outlines the data and the requirements of the data to fulfil the system's functionalities that are described in Section 5.2.1. The data requirements are structured around the four core clusters of the tool: (1) structure data input, (2) validation and retrieval, (3) assessing environmental impact, and (4) generating material configurations and decision support. These cluster correspond with the use cases described in the UML Use Case diagram in Figure 12.

1. Structured data input and validation

To ensure reliable performance, the system must support consistent and structured data entry that is aligned with the material passport that is developed in Chapter 4. New entries must match the class structure defined in the UML Class Diagram (Figure 13).

System requirements:

- All mandatory fields must be completed.
- Data types must comply with predefined constraints (e.g. numbers, strings, enums).
- Units must be standardized to enable comparison and calculations (e.g. m², kg, €/eq).
- The system must allow modular extensions for future object types without disrupting current operations.

2. Data retrieval and processing

To perform operations such as environmental impact assessment and design generation, it is important that the system can retrieve structured material data from the database. The system must manage both static and dynamic attributes.

System requirements:

- Cross-table queries using foreign key relationships.
- Filtering and sorting based on any attribute.
- Exclusion of incomplete or invalid entries.

- Data normalization and unit conversions (e.g. volume from dimensions).
- Retrieval of linked data and history records for traceability.

3. Environmental impact assessment and scoring

The core functionality is to support environmental informed design decisions. The assessments are conducted on both individual elements and full material configurations.

System requirements:

- Retrieve GWP and MKI values from linked data sources.
- Scale impact values based on user-defined units (e.g. m², pcs).
- Aggregate scores for reuse, hybrid, and new-material scenarios.
- Include transport and (de)construction emissions based on project context.
- Follow relevant standards: ISO 14040, ISO 14042, EN 15804+A2, and NMD calculation guidelines.

Required outputs:

- Total and per-unit GWP scores.
- Reuse percentage and environmental savings.
- Scenario comparisons to support early-stage decision-making.

4. Generation of material configuration and decision support

The system must generate viable reuse configurations that satisfy user-defined material demands and constraints. These configurations must support informed design decisions based on environmental performance.

System requirements:

- Match available elements to required quantity and characteristics.
- Apply filters for dimensions, location, condition, and reuse type.
- Propose alternative combinations when exact matches are not possible.
- Score and rank configurations by reuse percentage, fit, and GWP impact.
- Support iterative refinement of input parameters and recalculation.

Required outputs:

- Structured configuration lists of selected elements and their attributes.
- Performance summaries including total impact and reuse metrics.
- Exportable results for integration into external tools or project documentation.

5.3 Functional definition

This section composes the tool into its core functionalities and ensures clarity how the system works. The framework is divided into three primary sections:

1. Data structure – how material data is retrieved, formatted, and used as input.
2. Application processing – how algorithms process material constraints and environmental impact.
3. Data presentation – how the tool present data output for decision support for optimized material selection to users.

5.3.1 Structured data input

To enable the automated material selection and environmental impact calculation, the system requires a well-structured, queryable, and scalable database. A relational database management system (RDBMS) is used to meet all these criteria. The data in a RDBMS is

stored in interconnected tables that align with the material passport framework of Chapter 4 and the data requirements that are defined in Section 5.2.3.

To conceptualise the database, a UML Class Diagram (Figure 13) is used. This diagram outlines the core data entities and their relationships. Each class in the diagram represents a table in the database and each attribute define the columns of the tables. The modular structure supports future expansion because new classes or attributes could be added without disrupting the existing schema.

The UML Class Diagram represent an abstract conceptual model of the RDBMS. A class diagram can be implemented in an RDBMS through and Enhanced Entity Relationship (EER) diagram which will be explored in the next section. Class diagrams represent classes and not induvial objects (rows) that will populate the database. Converting a class diagram to an EER diagram will create functionalities so that it can be used to support an actual database structure in a management system. MySQL has been chosen for the RDBMS because it is open-source, scalable, and has a user-friendly interface.

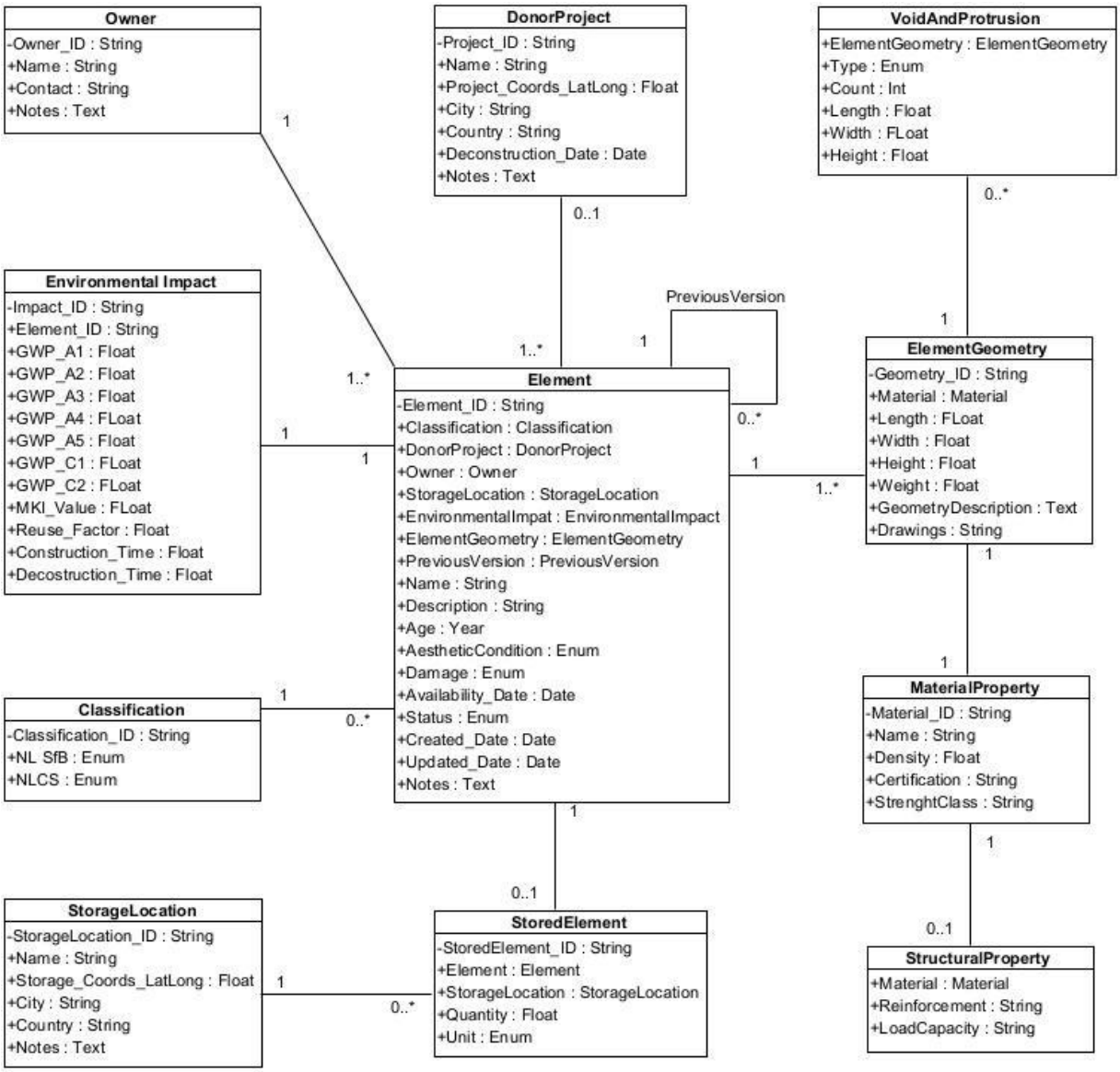


Figure 12: UML Class Diagram of database structure for data collection.

5.3.2 Data storage and retrieval

Figure 14 present the EER diagram which represent the database structure in MySQL. The overall database schema follows the same structure as explained in the UML Class Diagram. The database schema is specifically designed with relationships between tables to create the digital links, also known as primary and foreign keys. For every table in the EER diagram, a primary key (PK) is defined, which uniquely identifies every stored record. The PK enables to query the database on individual records that can scale into an extensive amount of data entries. It is common practice to have an incrementing integer as a PK. However, because many tables are linked, excellent traceability is needed. Therefore, the PK consist out of unique a string of characters for each entry: a Globally Unique Identifier (GUID). The foreign key (FK) is created to make relationships between tables and enables data-linking and cross-referencing between the tables.

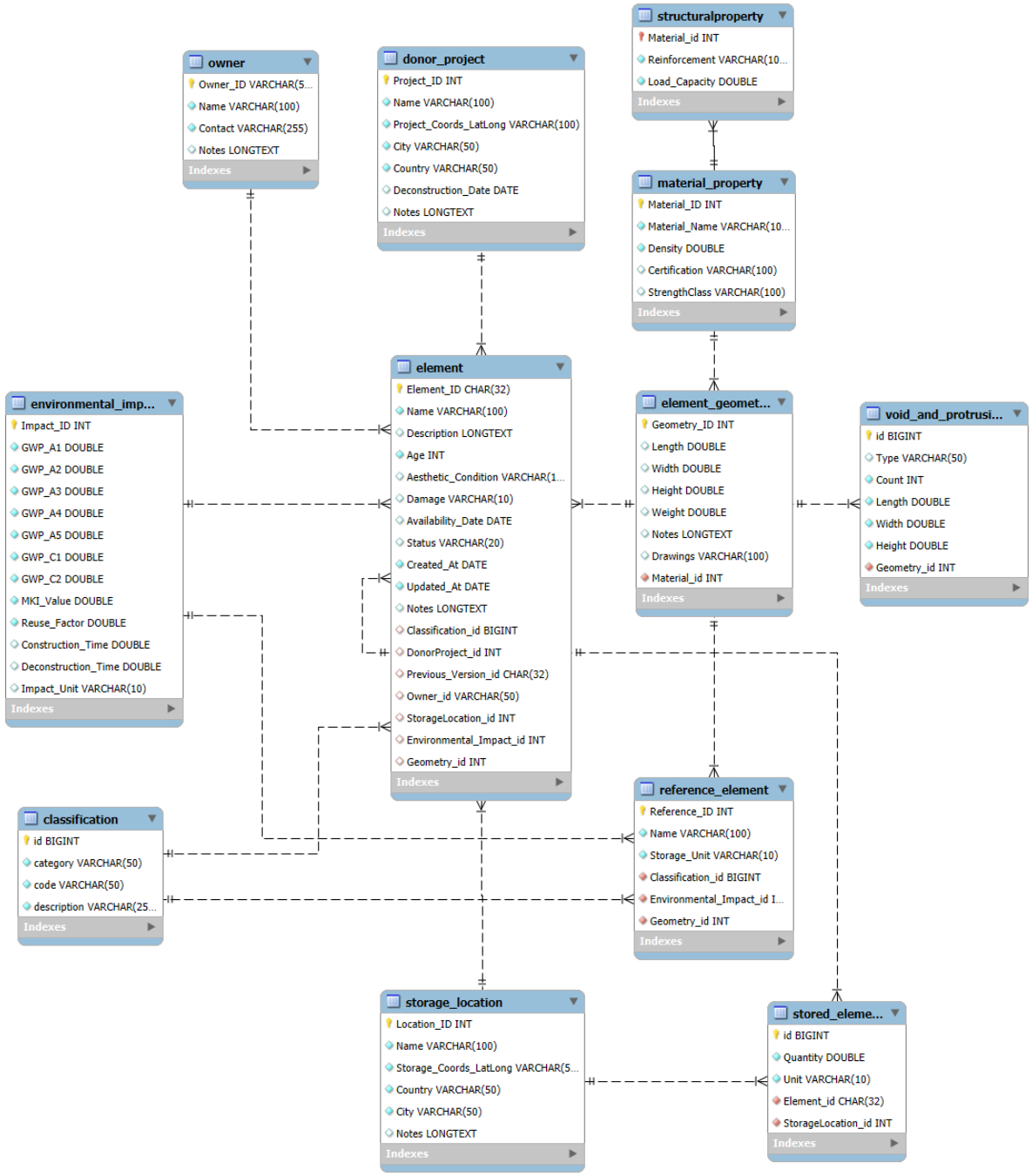


Figure 13: EER diagram of database structure stored in MySQL.

MySQL is a database system that is built on Structured Query Language (SQL). SQL is a standardized languages that is used to manage and manipulate relational databases. This language makes it possible to create, update, and delete records as well as querying data in a structured and efficient manner. These queries enable user to track changes to material instances, store new information about the elements, and update or retrieve data historical records of element when they move through different lifecycle stages.

For example, Table 9 shows the history record of a hollow core slab element that initially was registered as 'Kanaalplaatvloer_L001'. This element had its status and named modified, be saved with specific storage location, and then be updated again after it has been moved to a new location with an altered length. This process shows how SQL can trace elements with their changes to manage reusable element in the database over time. A full SQL code example showing this query is provided in Appendix C.

Element_ID	Element_Name	Status	Created_At	Updated_At	Previous_Version_id	DonorProject_Name
88e0027b7abf4f04a4c4a94ff0539be6	Kanaaplaat_300x6000	Available	2025-04-01	2025-04-01	2791f458c59840679c616d0ec7c0b6bc	Prinsenhof
2791f458c59840679c616d0ec7c0b6bc	Kanaaplaat_300x8000	Available	2025-04-01	2025-04-01	b04a76d58a884db69dd31ce0fa290dd1	Prinsenhof
b04a76d58a884db69dd31ce0fa290dd1	Kanaaplaatvloer_L001	Not available	2025-04-01	2025-04-01	NULL	Prinsenhof

Element_ID	StorageLocation_Name	StorageLocation_City	Length	Width	Height	Weight
88e0027b7abf4f04a4c4a94ff0539be6	Doetinchem Hub	Doetinchem	6000	1200	300	4751.99
2791f458c59840679c616d0ec7c0b6bc	TU/e	Eindhoven	8000	1200	300	6336
b04a76d58a884db69dd31ce0fa290dd1			8000	1200	300	6336

Table 9: database query of historical changes of construction element

The SQL queries, as shown in Table 9, demonstrate how the elements in the database can be filtered and how relevant information can be retrieved. This functionality is created through the EER model that defines how the elements and their attributes are stored, linked and how they can be queried. These capabilities correspond to the system's UML Use Case Diagram (Section 5.1.2) with the three primary system uses cases: (1) adding new elements to the database, (2) managing existing elements, and (3) generating reuse configurations based on environmental performance. To illustrate these core system functionalities and their interaction with the database, Figure 15 present a UML Activity Diagram. This diagram maps the user's interaction with the system and gives an overview of the process flow. The activity diagram covers both key workflows: (1) the structured input and validation of new material data into the system, and (2) the filtering, retrieval, and configuration of existing data to support material selection based on design constraints and environmental impact. The database management is not included in the diagram as this occurs directly within the MySQL Workbench, the interface of the RDBMS and through the interface of the tool. This will be further explained in system's architecture Section 5.4 Physical definition.

The top branch of the diagram illustrates how the system supports new data input, validates it, and stores it in the database. The bottom branch of the diagram illustrates how the tools logic queries the database using predefined constraints (filters), calculates the environmental impact and suggest configurations of reusable materials. These two processes together form the operational heart of the system where the logical database design (EER), the selection logic (SQL queries), and the user workflow (UML activity diagram) create a data-driven circular design approach.

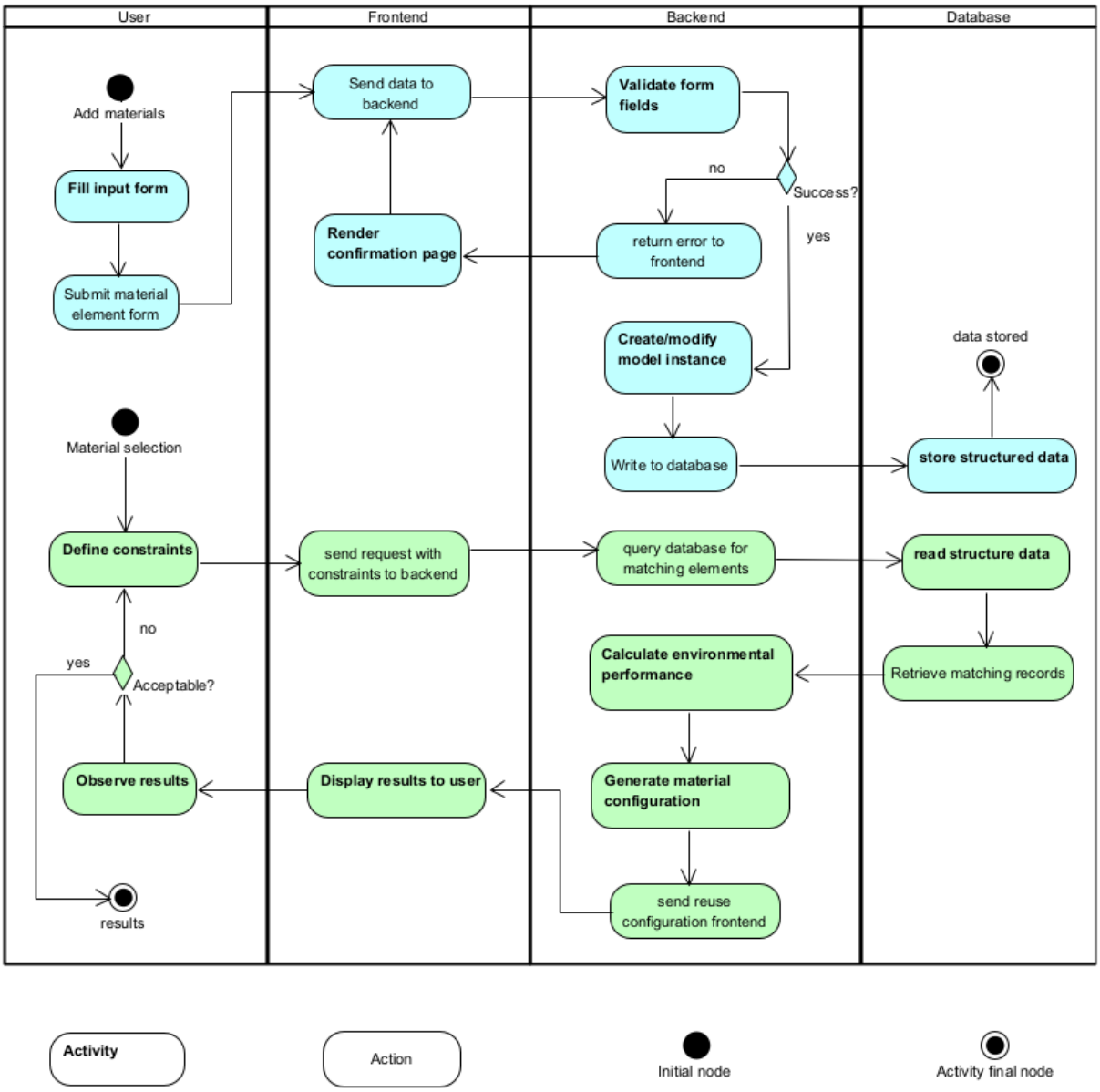


Figure 14: UML Activity Diagram with data input (green) and data retrieval (green) activities.

5.3.3 Application processing

Once the material data is successfully retrieved from the database the next step for the tool is to process this data. This happens through a series of backend operations which assesses the suitability for reuse and generates optimal material configurations. This is also called the application logic and is defined in terms of processing flow, decision logic, and generation of design suggestions. The interaction between components in this logic — from user input to algorithmic output — is captured in the sequence diagram in Figure 18. This diagram illustrates the time-ordered flow of operations.

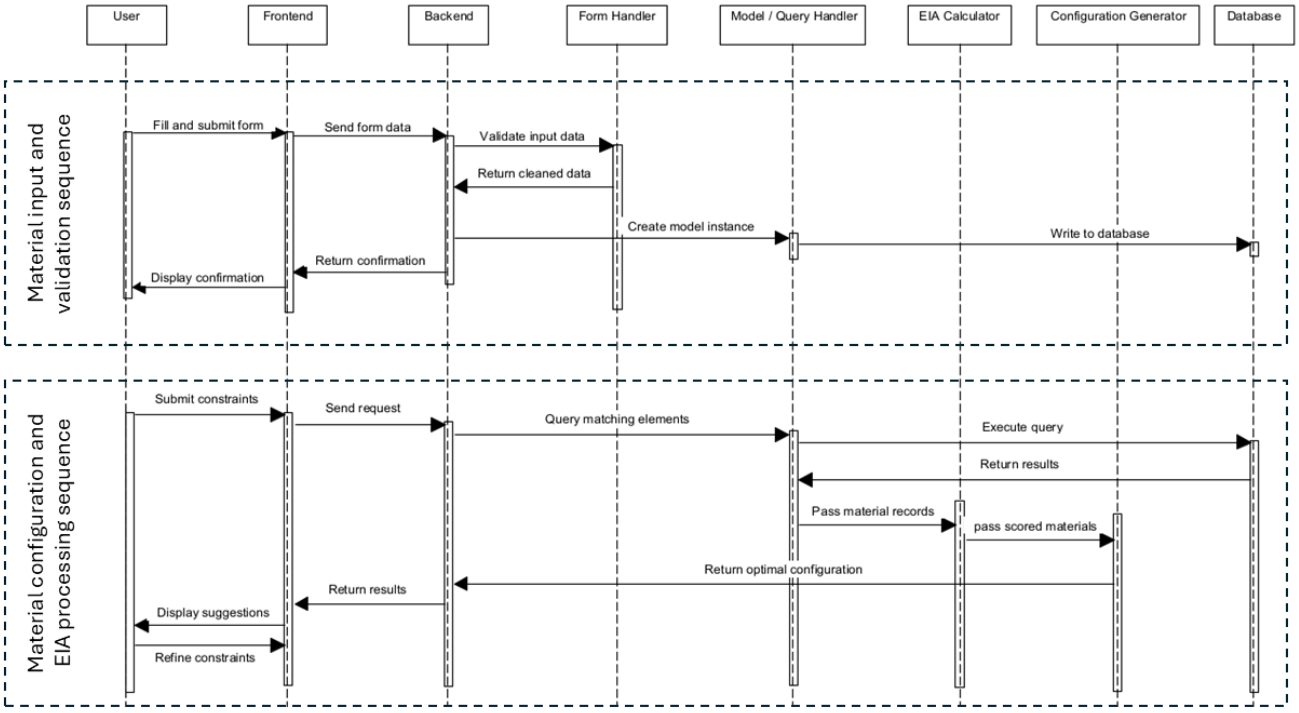


Figure 15: UML Sequence Diagram of material input and material configuration sequences.

The sequence diagram distinguishes the two main sequences also described in Figure 12 and 15. The top of Figure 16 illustrates the material input and validation sequence. This process starts with the user who fills in and submits a registration form for a reusable element in the front end of the system. The data is sent from the frontend to the backend which validates the input data. An instance is created, and the data is written to the database. The user will receive the confirmation that the element is successfully added to the database.

The material configuration sequence begins when the designer user submits a material query in the frontend of the system by defining the element constraints, such as the type of the element, dimensions, quality etc. These inputs are sent to the backend which performs a database query. Relevant material records are returned, and the environmental performance metrics are calculated based on predefined LCA formulas. Following, the system will create a viable configuration based on the requested amount (e.g., area, volume, number of pieces etc). This set is scored and compared based on cumulative environmental impact. If an exact match cannot be achieved, the system can propose design alternatives (e.g., using fewer or hybrid elements) with lower environmental footprint or higher reuse potential.

5.3.4 Output data presentation

In the final functional stage, the raw material data is transformed into usable output by applying constraints and environmental optimization to generate material selection or configuration. The system does not only function as a searchable database, but the system enables users to actively define a required quantity of material and to set attribute-based filters, such as type, condition, etc, to identify reuse options that meet these criteria while minimizing the environmental impact of the option.

Before users go into constraint-driven searching, the tool allows users to browse the material database more freely. This includes reviewing available stock and analysing the key attributes of the stored elements. In this way, designers can explore unique design strategies by adjusting the constraints and observe how this effects the resulting configuration.
The complete output generation and decision support consist out of the following:

1. A list of selected elements that fulfil the design requirements (e.g., m3, m2, m, kg, pcs), sorted by environmental performance.
2. A projected GWP for the full configuration and the relative impact of reused vs. newly produced elements.
3. A fill strategy which shows how different material batches contribute to the total required quantity.
4. Trade-off insides that for example show if you adjust the quantity slightly you avoid new production.

The actual structure and appearance of the interface together with the backend logic that supports this, is addressed in Section 5.4 Physical definition.

5.4 Physical definition

The physical definition defines the actual system structure of the tool. It describes how the backend, database, interface, and external systems interact. It describes the physical architecture and gives a breakdown of the components.

5.4.1 Web-based application

To operationalize the functional and non-functional goals defined in the previous sections the architecture of the tool must be modular and scalable and need to support robust data handling, user interaction, and algorithmic processing. The system must conform to a set of baseline physical and technical requirements to ensure performance, maintainability, and future extensibility. Therefore, it is chosen to create a web-based application. More specifically, the system is developed using the Django framework, which is a high-level Python web framework that promotes modular design, scalability, and is easy to maintain (Chen et al., 2020). Django follows the model-view-template (MVT) software architecture pattern. This architecture cleanly separates the data (model), application logic (view), and presentation (template), and is visualised in Figure 19. Django enables fast development while maintaining a clean codebase, which makes is suitable for this research-driven prototype and supports the system’s requirements defined in Section 5.2.

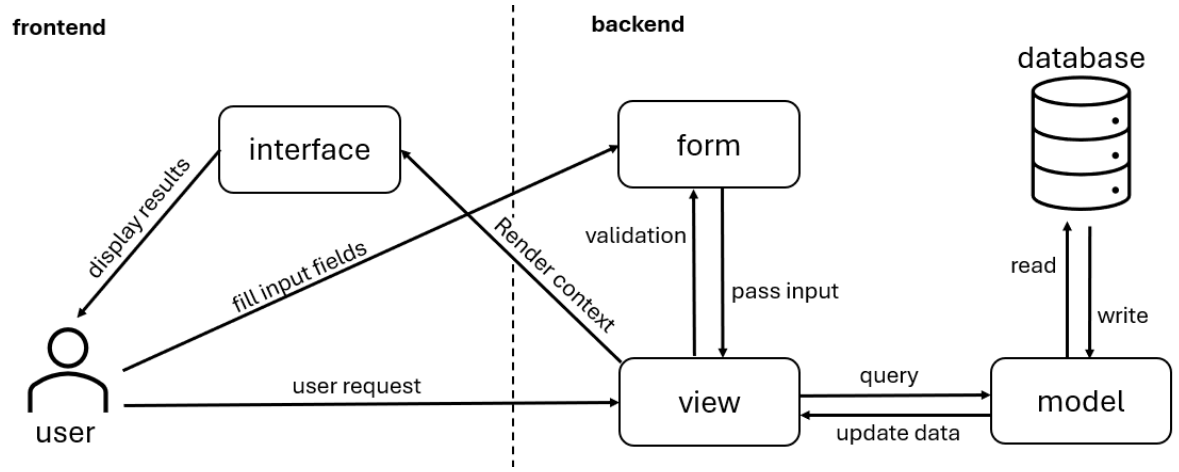


Figure 16: Components of web-based application.

The MVT architecture aligns well with the logical structure of the system that is defined in Section 5.3. Below is the logical structure of the system explained in terms of MVT structure.

- Model: the model represents the structure of the data. In this system the model corresponds to the relational database schema, which is defined in the EER diagram (Figure 14). The model contains the classes and attributes based on the UML Class Diagram (Figure 13).
- View: the view manages the core application logic. In the system the view contains the logic for data validation, environmental impact calculations, and selection configuration logic, which is all detailed in the UML Sequence Diagram (Figure 16).
- Template: the template defines the front-end interface where users interact with the system. This includes forms for data input, material filtering tools, result displays, and configuration summaries, which is all discussed in Section 5.3.4.
- Form: the form acts as in intermediary layer. This layer manages the input validation and data conversion. Django forms validate the incoming data against predefined rules and structure it so it can be processed by the view and model.

The MVT architecture thus ensures a robust, modular foundation that supports the defined functionalities and the system's specific needs:

- Modular design: each major function – data input, environmental assessment, configuration logic – is implemented as a standalone module within the Django application. This supports future adaptation and extensions.
- Scalability: as the database of reusable element expand, the Django application can scale with it through database abstraction. Predefined SQL queries can create intuitive filtering for good user experience.
- Rapid prototyping: Django enables the quick development of forms, validation logic, and user interfaces. This is ideal for iterative development and validation of the design prototype.
- MySQL integration: Django supports the direct connection with MySQL through the mysql.connector.django database engine module. This ensures compatibility, efficient query handling, and seamless data management between the Django application and the relational MySQL database structure designed for the tool.

5.4.2 System architecture

Figure 20 illustrates the overall system architecture of the web-based application. The architecture follows a modular and layered approach and separate the core functionalities in three main layers: user interface (frontend), application core (backend), and the database.

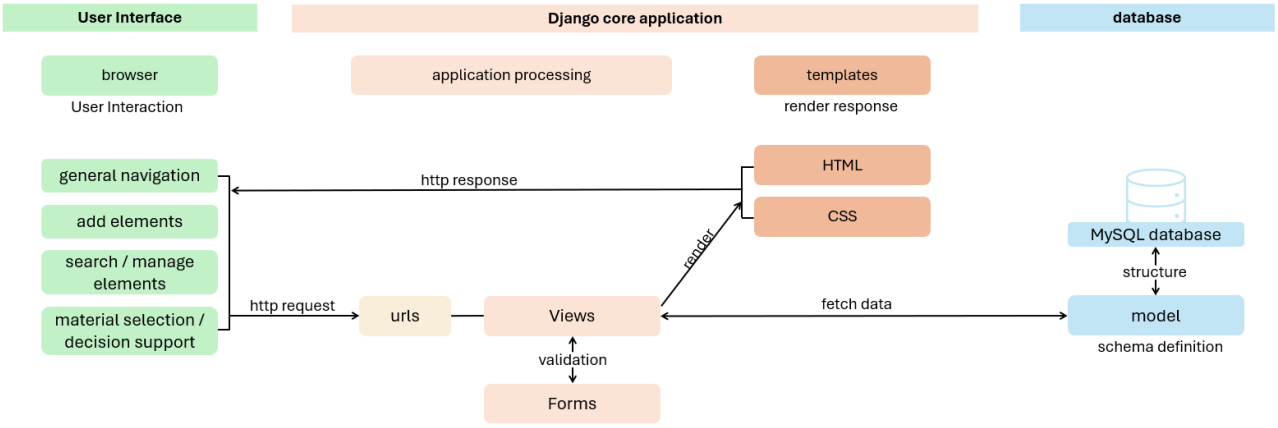


Figure 17: System Architecture

User interface (frontend layer)

The frontend is based on Django templates that render HTML/CSS pages where users can interact with the system. These templates include:

- *home.html*: main navigation page
- *add_element.html*: form-based page for structured input of new elements
- *select_element.html*: filtering and configuration interface for material selection.

The frontend does not directly manipulate the database. All database interaction is managed through the views in the backend.

Application core (backend layer)

The backend layer is responsible for the core logic of the system. The backend is composed out of the following Django modules:

- *views.py*: this module manages all user requests, processes form data, queries the database through models, calculate environmental impact, generates material configuration, and renders templates with results.
- *forms.py*: this module defines form classes that validate user input and map fields to model structures.
- *urls.py*: this module defines URL routing which maps user requests to the correct view functions.

Database layer

The database is a MySQL-based relational database which is structured according to the EER model (Figure 14). The Django module models.py define the table structures, relationships, and constraints in Python code. The *models.py* module makes use of Django's Object-Relational mapper (ORM) to manage database interactions without writing raw SQL queries. The Django ORM can automatically translate operations of the Python model into SQL commands. This allows developers to create, retrieve, update, and delete records using Python syntax instead of manual SQL statements. The MySQL database align directly with the object-oriented structure in the Django modules.

Interaction flow summary

At runtime, the system follows the following closed loop interaction:

1. User interacts with a template via the web browser (e.g., submits a material request).
2. Template triggers a view through a URL route.
3. View validates the input using a form, interacts with models, and processes queries.
4. Model reads from or writes to the MySQL database.
5. Results are passed back to the template and displayed to the user.

5.4.3 Backend Core Components

This section describes the implementation of the core backend modules. The following subsections focus on the most critical functions within each module. Full code listings are included in Appendix D.

models.py

The *models.py* module in Django defines the database schema and directly implements the structure that is designed in Section 5.3. The module translates the object-oriented conceptualization of elements into the tables of the relational database. The database is structured around the set of models defines in the EER diagram (Figure 14):

Element(models.Model), DonorProject(models.Model), Owner(models.Model), Classification(models,Model), ElementGeometry(models.Model) MaterialProperty(models.Model), StructuralProperty(models.Model), VoidAndProtrusion(models.Model), StorageLocation(models.Model), StoredElement(models.Model), EnvironmentalImpact(models.Model), ReferenceElement(models.Model).

Each model defines each owns attributes and contains PKs, FKs, and relationships as defined in EER diagram. The *Element(models.Model)* model shown in Listing 1 forms the core of this module. This model links together the classification, material, environmental performance, logistic data, etc. This model acts like the central node from where the other models are referenced.

```
# ---------------------------------
# Element Model
# ---------------------------------
class Element(models.Model):
    Element_ID = models.UUIDField(primary_key=True, default=uuid.uuid4,
editable=False)
    Classification = models.ForeignKey(Classification,
on_delete=models.SET_NULL, null=True, blank=True)
    Name = models.CharField(max_length=100)
    Description = models.TextField(blank=True, null=True)
    Age = models.IntegerField()
    Aesthetic_Condition = models.CharField(max_length=10, choices=[
        ('good', 'Good'),
        ('moderate', 'Moderate'),
        ('poor', 'Poor'),
    ], default='Available', null=True, blank=True)
```

```
    Damage = models.CharField(max_length=10, choices=[
        ('none', 'None'),
        ('minor', 'Minor'),
        ('major', 'Major'),
    ], null=True, blank=True)
    Availability_Date = models.DateField(blank=True, null=True)
    Status = models.CharField(max_length=20, choices=[
        ('Available', 'Available'),
        ('Pending', 'Pending'),
        ('Unavailable', 'Unavailable'),
        ('In Use', 'In Use')
    ], default='Available', blank=True, null=True)
    DonorProject = models.ForeignKey(DonorProject, on_delete=models.SET_NULL,
null=True, blank=True)
    Owner = models.ForeignKey(Owner, on_delete=models.SET_NULL, null=True,
blank=True)
    StorageLocation = models.ForeignKey(StorageLocation,
on_delete=models.SET_NULL, null=True, blank=True, related_name="elements")
    Previous_Version = models.ForeignKey('self', on_delete=models.SET_NULL,
null=True, blank=True)
    Created_At = models.DateField(auto_now_add=True)
    Updated_At = models.DateField(auto_now=True)
    Notes = models.TextField(blank=True, null=True)
    Geometry = models.ForeignKey('ElementGeometry', on_delete=models.PROTECT,
null=True, blank=True, related_name='elements')
    Environmental_Impact = models.ForeignKey('EnvironmentalImpact',
on_delete=models.PROTECT, null=True, blank=True, related_name='elements')

    class Meta:
        db_table = "element"
    def __str__(self):
        return f"Element {self.Element_ID} - {self.Name} (Prev:
{self.Previous_Version})"
```

Listing 1: Element model in models.py Django module

In Listing 1 can be seen that the attribute *Element_ID* is set as the PK with a default, automatically generated UUID, meaning that Django automatically assigns an ID primary key to an element. Enumerations are created for the attributes *Aesthetic_Condition, Damage,* and *Status*, where for the attributes *Status,* 'Available' is set as default. The *Previous_Version* attribute is self-referring, meaning that when changes are made in an element, a new primary key (ID) is assigned and the old primary key (ID) is assigned to the *Previous_Version* attribute, keeping track of the full history of an element, demonstrated in Table 9. The models *DonorProject(models.Model), Owner(models.Model), Classification(models,Model), ElementGeometry(models.Model) StorageLocation(models.Model), EnvironmentalImpact(models.Model),* are linked to the element model with FK's using *models.ForeignKey.*

The complete *models.py* code for the supporting models is included in Appendix D1 for reference. Each model follows the same modular and object-oriented structures as described above.

forms.py

The *forms.py* module in Django defines the form classes. The form classes function as intermediaries between the user interface and the database. The forms in Django are responsible for capturing the user input and validates the logic and convert the submitted data into the format that match the structure defined in the *models.py.* the forms play a central role in ensuring that the data that is submitted by the user is both complete and semantically valid before it is being stored in the database.

Every model has its own respective form. The form for the *Element(models.Model)* - *ElementForm(forms.ModelForm)* - is the most comprehensive and central to the functionality of the system. This form facilitates the structured data entry for reusable construction elements and combined fields from other models, like classification, donor project, and storage location, into a single form.

The *ElementForm(forms.ModelForm)* form supports the selection of an existing classification form the database or to add a new classification. Different user scenarios are created: reusing existing codes when available to limit manual input, or to create new ones if necessary. Listing two shows the logic for this process which is implemented in the *clean()* method.

```
    def clean(self):
        cleaned_data = super().clean()
        nl_sfb = cleaned_data.get("existing_nl_sfb")
        nlcs = cleaned_data.get("existing_nlcs")
        new_category = cleaned_data.get("new_classification_category")
        new_code = cleaned_data.get("new_classification_code")
        new_description = cleaned_data.get("new_classification_description")

        if not nl_sfb and not nlcs and not (new_category and new_code):
            raise forms.ValidationError("Please select an existing
classification or enter a new one.")

        if new_category and new_code:
            classification, created = Classification.objects.get_or_create(
                category=new_category, code=new_code,
                defaults={"description": new_description}
            )
            cleaned_data["classification"] = classification  # Assign
classification to cleaned data
        else:
            cleaned_data["classification"] = nl_sfb or nlcs

        return cleaned_data
```

Listing 2: Validation logic in ElementForm.clean() to manage classification input.

This validation ensures that the users cannot proceed without providing a classification. This can either by selecting an existing one or creating a new one. Preventing incomplete or unstructured entries.

In addition to data input validation, the form also overrides the *save()* method to correctly assign foreign key references. In the case of the *Element(models.Model)* this is done for *DonorProject* and *StorageLocation.* These operations take place after the form is submitted. This logic is implemented in the save() method as shown in Listing 3, ensuring that all relationships are stored correctly and that the element can be retrieved with complete references.

```
    def save(self, commit=True):
        element = super().save(commit=False)

        donor_project = self.cleaned_data.get("DonorProject")
        if donor_project:
            element.DonorProject = donor_project  # Assign DonorProject

        if commit:
            element.save()
            self.cleaned_data["storage_location"].elements.add(element)  #
Assign StorageLocation correctly

        return element
```

Listing 3: Save logic for assigning donor project and storage location to an element.

The *ElementForm(forms.ModelForm)* serves as the primary entry point for creating new elements. However, several other forms support the completeness, structure, and consistency of the dataset. These forms correspond directly to their respective models and enable the following key functionalities:

- Automatic weight calculation based on geometry and material density.
- Dual input for describing geometry (by volume or by description and drawing).
- Selection of existing material or creating a new material instance.
- Validation to ensure that the selected quantity unit aligns with the environmental impact unit for correct calculations.

The complete implementation of the *forms.py* module is provided in Appendix D2

views.py

The Django module *vies.py* contain the core application logic and links the user request to the data models and templates. This module defines how the system responds to user interactions, validate data using the *forms.py,* processes calculation, and returns structured outputs. The module serves as the controller layer of the web-application and manages all backend processes between input and output. Two key view functions are central in the system:

1. *add_element(request):* for structured element input, and
2. *select_elements(request):* for querying the database, calculating environmental performance, and returning configuration results.

Other auxiliary view functions, such as adding owners, donor projects, materials, classification, storage location, and fetching reference elements follow a similar structure and are included in Appendix D3.

The *add_element(request)* function enables users to add new reusable construction elements into the system through two different input strategies:

1. By referencing a predefined element, or
2. Through manual input

To simplify the user workflow and reduce input errors, the system supports reference-based entries. These reference elements are pre-populated in the database and are based on the findings from the Van Gelder material reuse study done in Chapter 4. This study identified high-frequency elements with strong reuse potential. When a user selects a reference element, the system automatically prefills core attributes such as geometry, material, and environmental impact data, but maintains flexible to enter project-specific details manually such as the condition, quantity, and storage location.

The selection of a reference element manages in the frontend of the system (*add_element.html)* via dropdown fields where users can narrow down their choice with classification and name. When a reference is selected, its associated data is loaded into the form automatically by the backend of the system. How this logic work in *views.py* is shown in Listing 4.

```
def add_element(request):
    if request.method == "POST":
        reference_element_id = request.POST.get("ReferenceElement")
        use_reference = bool(reference_element_id)

        # Always load these
        element_form = ElementForm(request.POST)
        stored_element_form = StoredElementForm(request.POST)

        # Conditionally load only if manual
        geometry_form = None
        impact_form = None
        if not use_reference:
            geometry_form = ElementGeometryForm(request.POST, request.FILES)
            impact_form = EnvironmentalImpactForm(request.POST)

        # Validation
        valid = element_form.is_valid() and stored_element_form.is_valid()
        if not use_reference:
            valid = valid and geometry_form.is_valid() and
impact_form.is_valid()

        if valid:
            element = element_form.save(commit=False)
            element.Classification =
element_form.cleaned_data.get("classification")

            if use_reference:
                # Assign existing foreign keys directly (NO saving!)
                reference =
ReferenceElement.objects.get(pk=reference_element_id)
                element.Geometry_id = reference.Geometry.Geometry_ID
                element.Environmental_Impact_id =
reference.Environmental_Impact.Impact_ID
            else:
```

```
                # Create new records only if manual
                geometry = geometry_form.save(commit=False)
                geometry.Element = element
                geometry.save()
                element.Geometry = geometry

                impact = impact_form.save(commit=False)
                impact.Element = element
                impact.save()
                element.Environmental_Impact = impact
```

Listing 4: Assigning geometry, material, and impact data via reference element or manual input.

When a reference element is being used, the remaining fields, such as *DonorProject, StorageLocation, Ownership* must still be provided. However, these fields are typically preloaded from the database and can be selected throughout dropdown menus to limit manual input and reduce the risk of user error and redundancy. Information like a description, condition, quantity can simply be added in the form. When an element is created from scratch, which is not the desired situation for a 'standard' user, but which can be done by a database manager or sustainability advisor, all fields must be filled in manually or selected from the database. This flexible structure ensures that most of the critical data is already structured and available in the system. However, it is still possible for user to input new data when needed and make the database grow overtime. It enhances the overall user experience, reduce input burden, and improves consistency in the database.

To create a new donor project and storage location in the input form, save I to the database and select in for the new reusable element, the system uses post-save logic. Meaning that the donor project and storage location are assigned after saving the main element instance:

```
            # Donor Project
            donor_project_id = request.POST.get("Donor_Project")
            if donor_project_id:
                try:
                    donor_project =
DonorProject.objects.get(pk=donor_project_id)
                    element.DonorProject = donor_project
                except DonorProject.DoesNotExist:
                    pass
            element.save()

    else:
    donor_projects = DonorProject.objects.all()
    storage_locations = StorageLocation.objects.all()
```

Listing 5: Assigning donor project and storage location post-save.

Additionally, when no reference element is selected it is possible to describe the geometry in two different ways: by giving its volume or describing the geometry and adding drawings. When the material and volume are defined, the system automatically calculates the weight of the stored element as shown in Listing 6. In the case of manual geometry description, it is necessary to manually give the weight of the element.

```
else:
                # Create new records only if manual
                geometry = geometry_form.save(commit=False)
                geometry.Element = element

                if geometry.Length and geometry.Width and geometry.Height:
                    material = geometry.Material
                    volume_m3 = (geometry.Length / 1000) * (geometry.Width /
1000) * (geometry.Height / 1000)
                    geometry.Weight = material.Density * volume_m3
                else:
                    geometry.Weight = request.POST.get("manual_weight", None)
                    geometry.Notes =
request.POST.get("describe_other_geometry", "").strip()

                geometry.save()
```

Listing 6: Automatic weight calculation based on geometry and material.

The *select_elements(request)* function manages the logic for querying the database based on search criteria, calculating the GWP for matching elements, and generating fill strategies to propose a material configuration that meets the required quantity with the lowest possible GWP.

The process begins when the user enters a required material type, quantity, and projected location via the selection form. All reusable elements in the database that matches these criteria are fetched together with their location and environmental impact data. The GWP per unit is calculated on the transport distance and stored LCA values. These distances are computed between the donor site, storage location, and projected site. The GWP per unit is calculated following the method described and Section 3.5 and the logic is shown in Listing 7. The formula uses the standard lifecycle stages A1-A5, C1, and C2 (as shown in Figure 9).

```
                storage = stored_element.StorageLocation
                donor_project = element.DonorProject
                if not storage or not donor_project:
                    continue

                try:
                    storage_lat, storage_lon = map(float,
storage.Storage_Coords_LatLong.split(","))
                    donor_lat, donor_lon = map(float,
donor_project.Project_Coords_LatLong.split(","))
                except ValueError:
                    continue

                d_A4 = geodesic((storage_lat, storage_lon), (project_lat,
project_lon)).km
                d_C2 = geodesic((donor_lat, donor_lon), (storage_lat,
storage_lon)).km

                GWP_m2 = (
```

```
                    ((impact.GWP_A1 + impact.GWP_A2 + impact.GWP_A3) *
impact.Reuse_Factor)
                    + (impact.GWP_C1 * impact.Deconstruction_Time)
                    + (impact.GWP_C2 * d_C2)
                    + (impact.GWP_A4 * d_A4)
                    + (impact.GWP_A5 * impact.Construction_Time)
                )
```

Listing 7: Calculating total GWP per unit based on lifecycle stages, reuse factor, and transport distances.

Once the GWP for each matching element has been calculated the system sorts all results by GWP per unit. Then the system can begin accumulating quantities with the lowest GWP to meet the user-defined requirements. The fill strategy is shown in Listing 8. Each reusable element contributes all or a part of its available stock. The algorithm continues to fill, until the required quantity is fulfilled or the available supply is exhausted.

```
# ------- Fulfill selection strategy -------
        accumulated = 0.0
        selected_elements = []
        total_gwp = 0.0

        for entry in sorted_elements:
            if accumulated >= required_quantity:
                break

            available = float(entry["Quantity"])
            unit_gwp = float(entry["GWP_m2"])
            to_use = min(required_quantity - accumulated, available)

            percent_used = to_use / available * 100
            gwp_contribution = to_use * unit_gwp

            selected_elements.append({
                "Element_ID": entry["Element_ID"],
                "Name": entry["Name"],
                "Used_Quantity": to_use,
                "Available_Quantity": available,
                "Used_Percent": round(percent_used, 1),
                "GWP_Per_Unit": unit_gwp,
                "GWP_Contribution": round(gwp_contribution, 2),
                "Unit": entry["Unit"],
            })

            accumulated += to_use
            total_gwp += gwp_contribution

        missing_quantity = required_quantity - accumulated if accumulated <
required_quantity else 0.0
```

Listing 8: Fill strategy based on lowest GWP to fulfill user-defined quantity.

When there is insufficient stock of reusable elements to meet the desired quantity of the user, the system can transition to a hybrid configuration mode. This means that reusable elements will get mixed with new produces elements. Therefore, the system retrieves a reference element (pre-defined in the database) and calculates the GWP required to fill the missing quantity using new production, shown in listing nine. This calculation follows the calculation methods of the NMD (Nationale Mileu Database, 2022). For this scenario only the lifecycle stages A1-A5 are considered and a fixed distance of 150km for A4, recommended by NMD.

```
# ------- GWP from new material if needed -------
        matching_refs =
ReferenceElement.objects.filter(Name__icontains=element_name)

        gwp_new_details = None

        if reference_id and matching_refs.exists() and missing_quantity > 0:
            ref = matching_refs.first()
            impact = ref.Environmental_Impact

            gwp_new_per_unit = (
                impact.GWP_A1 +
                impact.GWP_A2 +
                impact.GWP_A3 +
                (impact.GWP_A4 * 150) +
                impact.GWP_A5
            )

            gwp_new_element = round(gwp_new_per_unit * missing_quantity, 2)
            final_total_gwp = round(gwp_new_element + total_gwp, 2)

            gwp_new_details = {
                "Reference_Name": ref.Name,
                "GWP_per_Unit": round(gwp_new_per_unit, 2),
                "GWP_Total_New": gwp_new_element,
                "Final_GWP": final_total_gwp,
            }
```

Listing 9: Hybrid configuration logic using a reference element for the shortfall.

This strategy supports informed decision-making by giving the user a complete picture of the environmental trade-offs for reuse versus new production.
The final output includes:

- Reuse percentage
- Total GWP (reuse + new)
- Quantity contribution per element
- Visual comparison of reuse-only vs. hybrid configurations

The complete implementation of the *views.py* module is provided in Appendix D3

urls.py

The *urls.py* module defines the routing structure of the application. The module maps HTTP request to specific view functions. Meaning that when a user interacts with the frontend interface, their request is directed to the correct processing logic in the backend (*views.py).*

In the *urls.py* different URL patterns are defined that correspond to specific functionalities within the tool and consist of *add-element, add-owner, add-material, add-storage-location, add-donor-project, add-classification, select-elements, all-element, get-reference-data, get-reference-list.*

This routing logic allows the system to scale and support additional features. The full routing table that follows the Django's standard path-based syntax is implemented in the *urls.py* module and included in appendix D4.

5.4.4 Frontend Templates

Short intro: Django templates manage the presentation layer where the user interacts with the system.

home.html

The template *home.html* acts as the homepage of the application and is the primary entry point for all users as shown in Figure 19. The homepage guides the users to the three main functionalities of the tool: adding elements, selecting reusable elements, and managing the database.

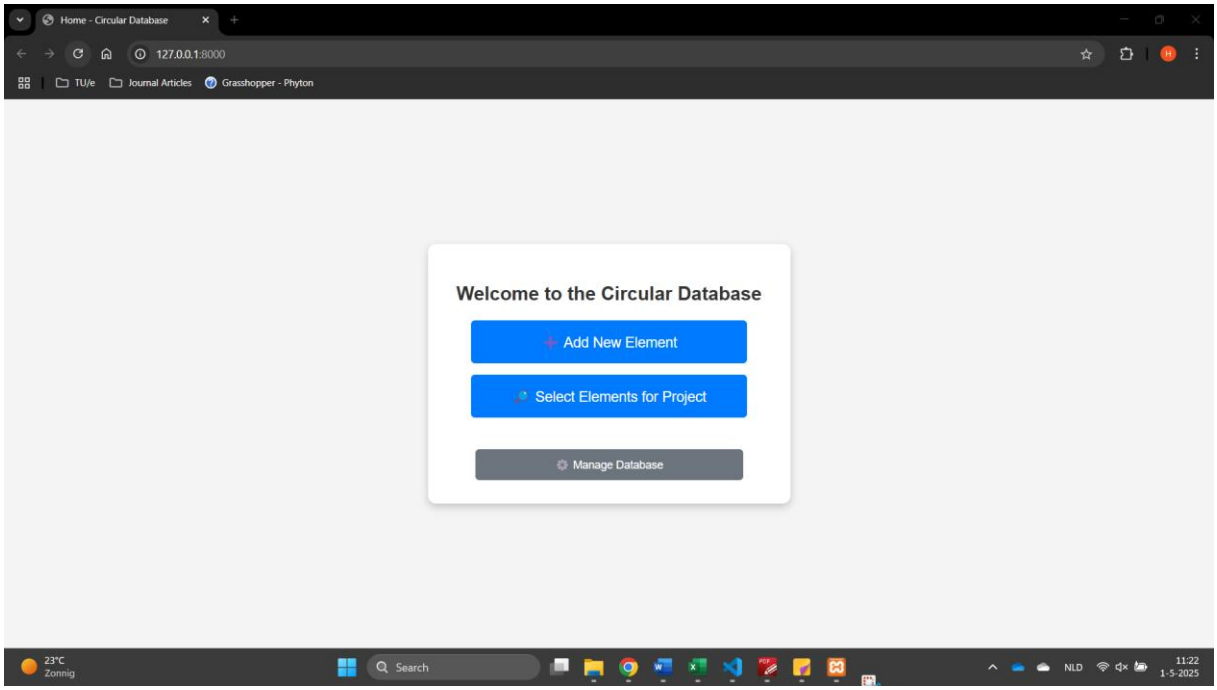


Figure 18: Homepage interface of the application rendered from home.html.

The homepage includes three clearly labelled action buttons which are each designed for a different user need:

- Add New Element: redirects users such as project managers or asset owners to the *add_element.html* template where via a form reusable construction element can be registered.
- Select Elements for Project: redirect users such as designers to the *select_elements.html* template where users can find all available reusable materials and search for specific project configuration with insights in the GWP.
- Manage Database: this button opens a link to phpMyAdmin interface from the database can be managed. This option will be hidden from typical users. However, it is useful for database managers or developers to monitor, inspect, or manually adjust database contents.

add_element.html

The *add_element.html* template provides a structured and interactive interface for registering reusable elements to the system, see Figure 20. As described, the form is designed for reference-based entry, by making use of dropdowns, predefined fields, and automated calculations, but does also support manual input when necessary.

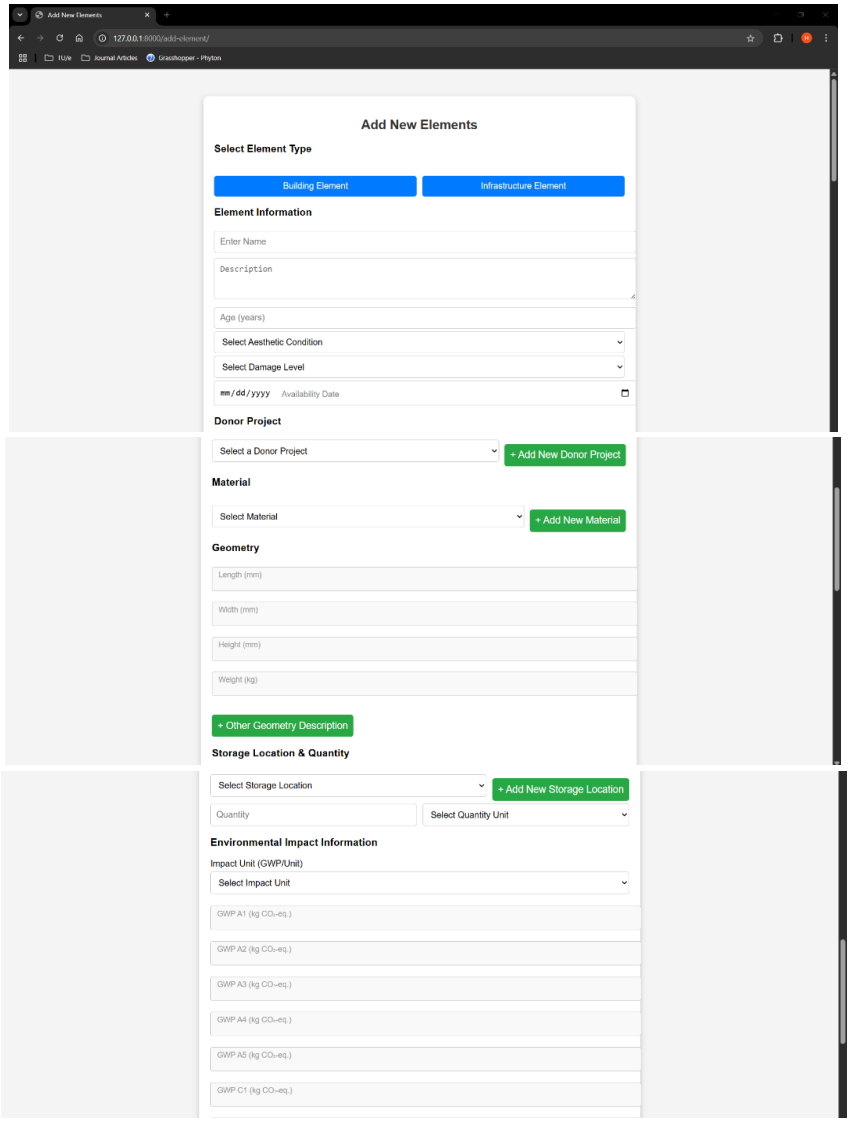


Figure 19: Form layout of the add_element.html template to register reusable elements to the system.

The user begins by selecting the type of element, building or infrastructure, and can select an existing classification. AI reference elements will be loaded, and the user can select one from the dropdown menu (Figure 21). When the element type is not populated yet, users may add new classifications and element types. After an element is selected (or created) users can continue with the general element information such as age, condition, and the date of when the

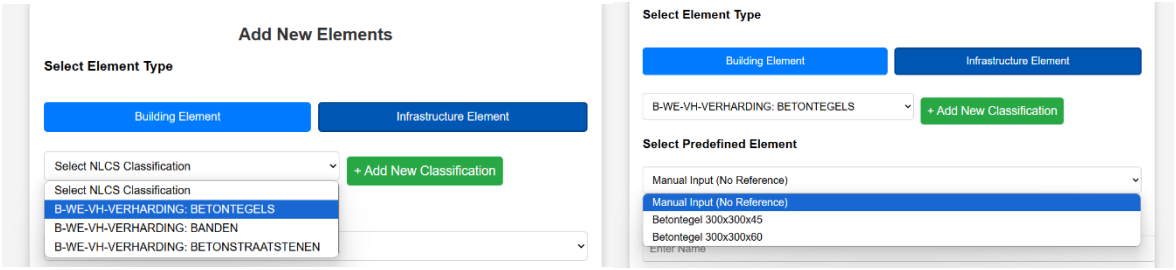


Figure 20: Selecting a pre-defined element type in the registration from

Following, the user can select the donor project and the storage location from preloaded lists. If a new location is required, it can be added through the '+ Add New' buttons (Figure 22). These new locations will be saved to the database, with the '+ Save' button, and can be selected in the dropdown menu in future registrations.

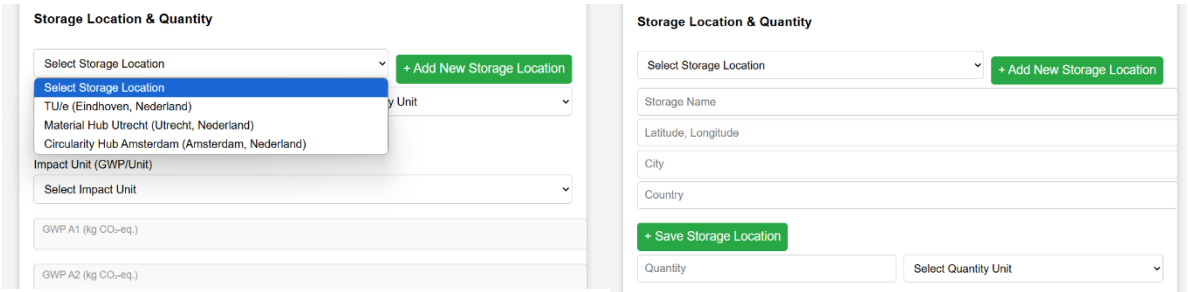


Figure 21: Selecting donor project and storage location in the registration form

When an element type is selected, the material, geometry and environmental impact information is automatically filled in (see Figure 23). However, when it is needed to create new element types, an existing material can be selected from the dropdown menu, or a completely new material can be created with the '+ Add New Material' button and saved to the database with the '+ Save' button (See Figure 24). New created materials can be selected from the dropdown menu in future registrations.

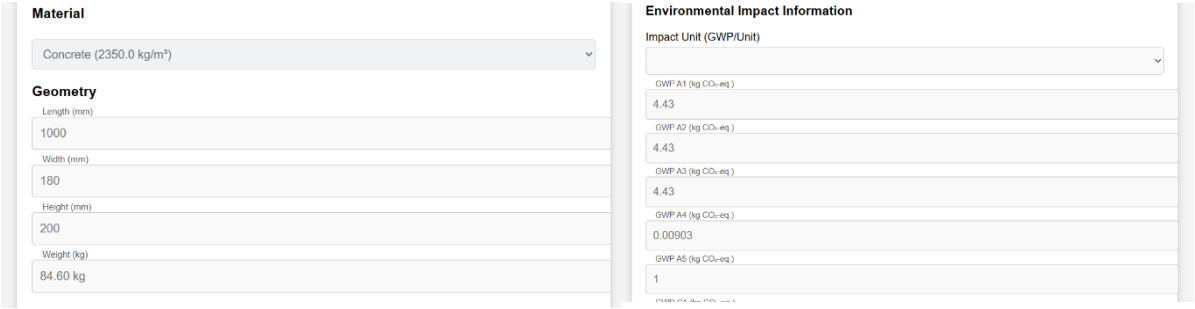


Figure 22: Auto fill-in material, geometry and environmental impact for a predefined element type

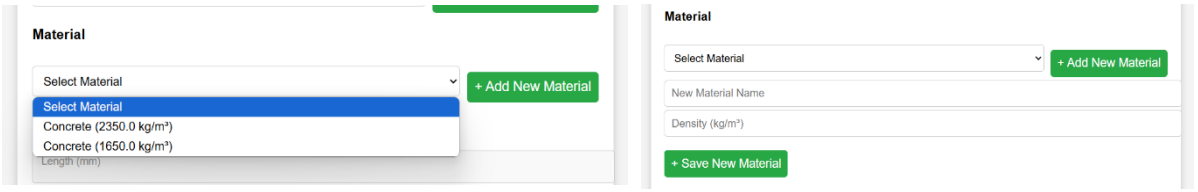


Figure 23: Manual material selection or addition of new material to the system

When the geometry is not automatically filled in when an existing element type is selected, the user has the possibility to either fill the geometry in a volumetric way for simple geometries. However, in the case of more complex geometry, the user can give a description and upload drawings (see Figure 25).

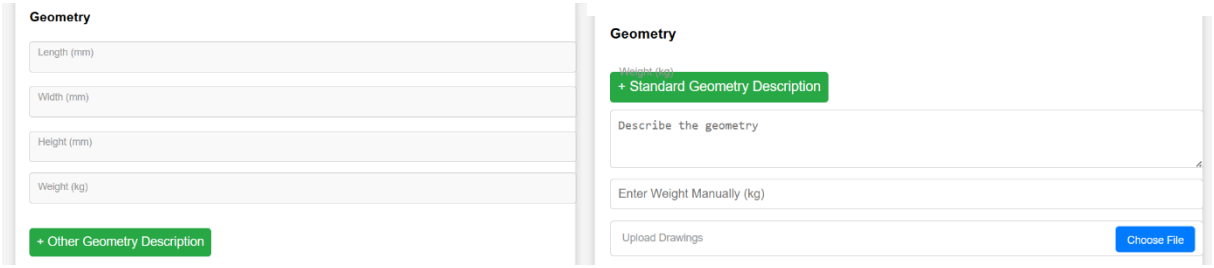


Figure 24: Volumetric geometry or complex geometry information in registration form

The form uses conditional logic in the template to hide or reveal sections depending on user actions. Fields are dynamically populated from the backend to avoid redundancy and prevent user errors. Furthermore, fields and units are validated for format and completeness. When the system notices any errors, an error message will be shown to the user on where and what to change.

select_elements.html

The *select_element.html* template provides two distinct but integrated functionalities that both support the designer in browsing through the database to see all available reusable elements and to generate an environmentally optimized material selection based on their design needs.

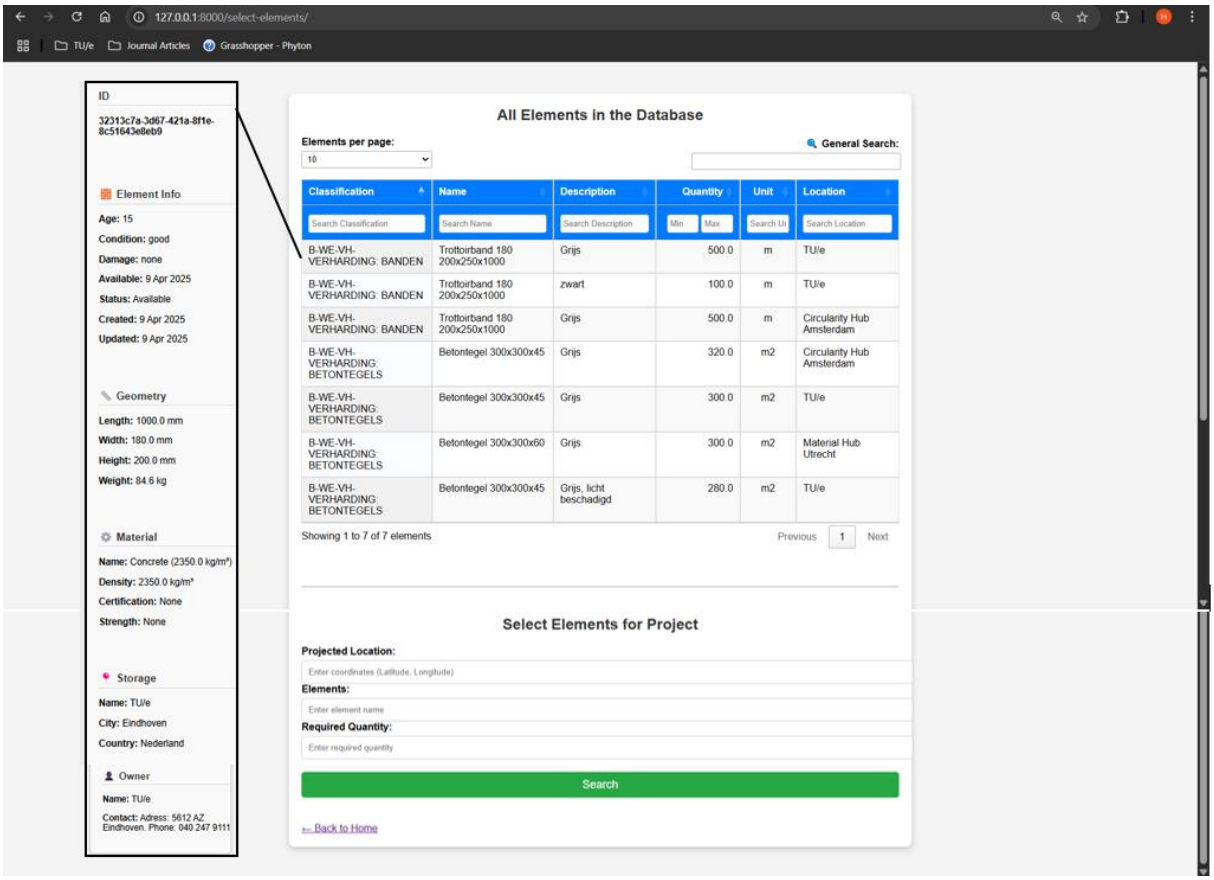


Figure 25: Application layout of the select_element.html template to search the database and generate a material selection.

Figure 26 shows the interactive material overview function and search function of the application. The first function allows user to explore the full list of reusable elements that are available in the system's database. This function is an interactive table rendered by using Django's DataTables module. The table includes a general search function as well as search function per column. Designers can filter materials by classification, name, description, quantity, and location to sort the table for quick access to relevant components (see Figure 27)

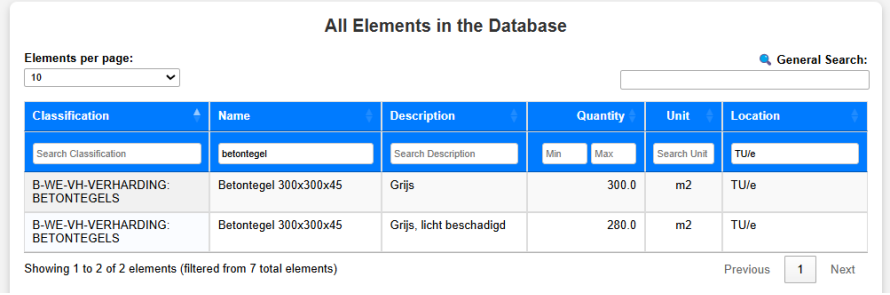


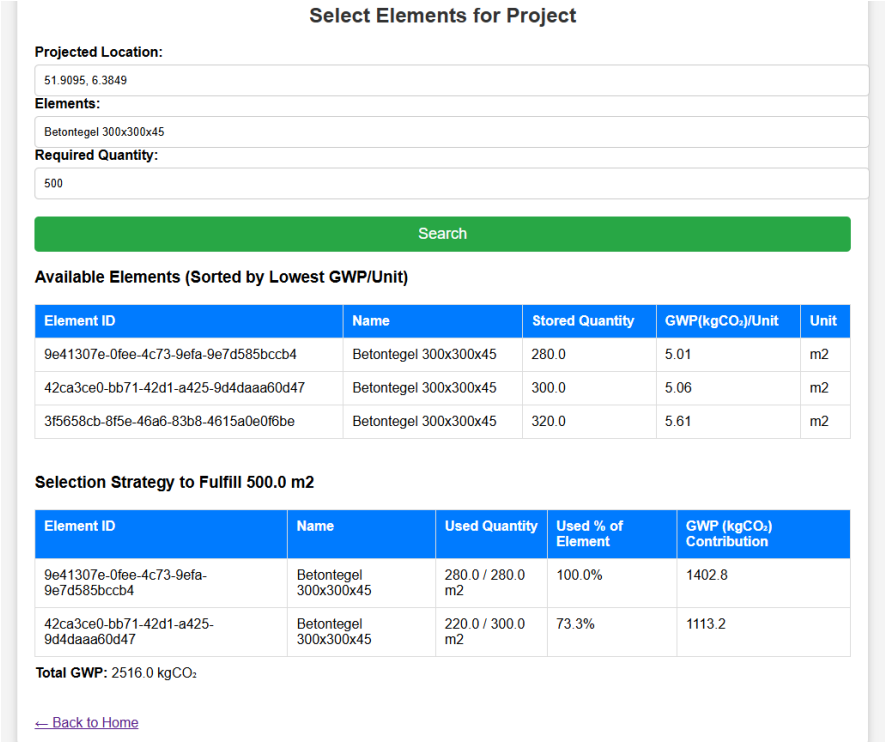
Figure 26: Example of elements that are filtered by name and location.

Clicking on a specific element row expands a collapsible panel (see black bordered box on the left side in Figure 26). This panel reveals detailed data about the selected element, such as age, condition, material information, and owner. Through this table, designers can gain insights into available resources and verify suitability before they proceed to automated selection.

The second function enables designers to generate a material configuration based on defined project criteria (Figure 28). The user provides:

- Project location,
- Element type or name,
- Required quantity.

Upon submission, the backend calculates a configuration strategy based on lifecycle impact and availability. First the database is queried, and all matching elements are found. For all these elements the transportation distance (A2 and C2 stages of Figure 9) is determined and the GWP per unit is calculated for the projected location using the environmental impact formula introduced in Section 4.5. Elements are ranked by their environmental impact contribution.



Select Elements for Project

Projected Location:

51.9095, 6.3849

Elements:

Betontegel 300x300x45

Required Quantity:

500

Search

Available Elements (Sorted by Lowest GWP/Unit)

Element ID	Name	Stored Quantity	GWP($kgCO_2$)/Unit	Unit
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0	5.01	m2
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0	5.06	m2
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0	5.61	m2

Selection Strategy to Fulfill 500.0 m2

Element ID	Name	Used Quantity	Used % of Element	GWP ($kgCO_2$) Contribution
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0 / 280.0 m2	100.0%	1402.8
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	220.0 / 300.0 m2	73.3%	1113.2

Total GWP: 2516.0 $kgCO_2$

← Back to Home

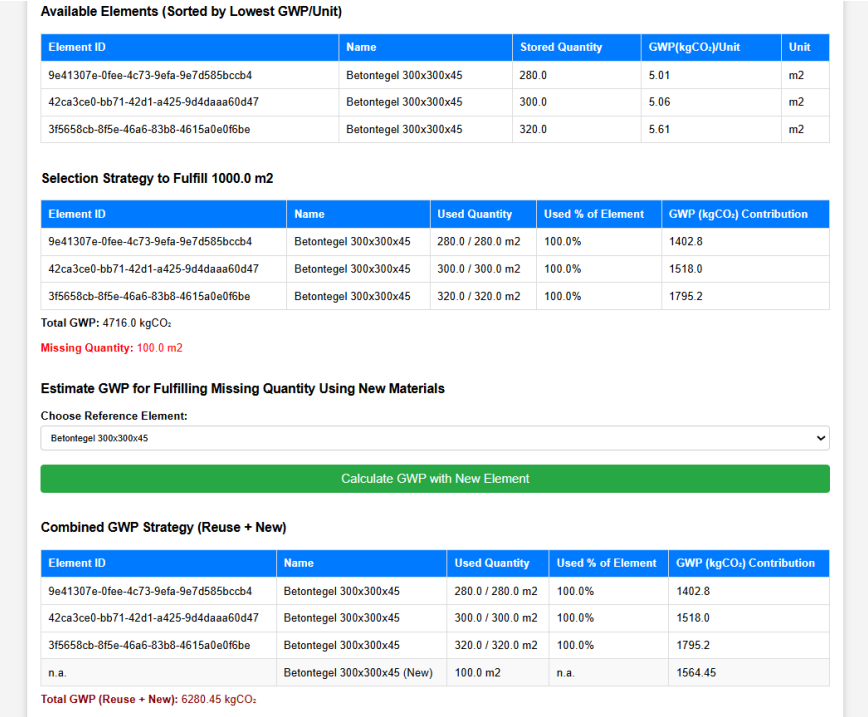
Figure 27: Selection strategy to fulfil a required quantity completely with reusable elements available in the database.

When all suitable elements are identified, GWP per unit being calculated, and ranked on their environmental impact contribution, the system applies a fill strategy. This fill strategy accumulates the available stock from the best performing elements until the requested quantity is fulfilled. The interface returns:

- A list of selected elements, their quantity contribution and their GWP contribution
- Total calculated GWP for the reuse scenario

When the available elements are insufficient to the required quantity, the tool enters a hybrid mode (Figure 31) where the selection is supplemented with new production for the shortfall. This new produced element is calculated based on the environmental impact formula in Section 4.5 and used lifecycle stages A1 to A5 (Figure 9) with an assumed transport distance of 150km, aligning with the calculation method of NMD. The GWP for both the reused and new material is calculated, and the combined result is shown the interface returns the following decision support data to the designer:

- Full reuse strategy vs hybrid option
- Comparison of environmental trade-offs
- Percentage of reused vs newly produced materials
- Total calculated GWP for hybrid-reuse scenario



Available Elements (Sorted by Lowest GWP/Unit)

Element ID	Name	Stored Quantity	GWP($kgCO_2$)/Unit	Unit
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0	5.01	m2
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0	5.06	m2
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0	5.61	m2

Selection Strategy to Fulfill 1000.0 m2

Element ID	Name	Used Quantity	Used % of Element	GWP ($kgCO_2$) Contribution
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0 / 280.0 m2	100.0%	1402.8
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0 / 300.0 m2	100.0%	1518.0
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0 / 320.0 m2	100.0%	1795.2

Total GWP: 4716.0 $kgCO_2$

Missing Quantity: 100.0 m2

Estimate GWP for Fulfilling Missing Quantity Using New Materials

Choose Reference Element:

Betontegel 300x300x45

Calculate GWP with New Element

Combined GWP Strategy (Reuse + New)

Element ID	Name	Used Quantity	Used % of Element	GWP ($kgCO_2$) Contribution
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0 / 280.0 m2	100.0%	1402.8
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0 / 300.0 m2	100.0%	1518.0
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0 / 320.0 m2	100.0%	1795.2
n.a.	Betontegel 300x300x45 (New)	100.0 m2	n.a.	1564.45

Total GWP (Reuse + New): 6280.45 $kgCO_2$

Figure 28: Hybrid selection strategy to fulfil required quantity with reusable and new produced elements.

The combination of complete overview of reusable resources and the material selection generation with feedback loop enhances the designer's ability to assess material availability and optimize the environmental performance for their project using this data-driven approach.

Admin interface

Next to the 'Add Element' and 'Select Element' buttons on the home screen, there is an option for database mangers called 'Manage Database.' When the database managers click on this button, a direct link phpMyAdmin interface will be opened via a local URL (http://127.0.0.1/phpmyadmin), which was integrated into the application using XAMPP and routed through Django. This interface provides full backend access to the MySQL database. Unlike MySQL Workbench - which requires separate installation and runs as a desktop application - phpMyAdmin runs entirely in the browser. This makes it directly accessible from the web interface. This web-based administration tool enables:

- Real-time inspection and editing of records.
- Manual data correction or bulk deletion.
- Monitoring of foreign key relationships and schema integrity.
- Quick import/export of tables for testing, debugging, or versioning.

This admin route is secured with a username and passport. By including this secure admin route within the sae interface, the system can be maintained and developed without needing to leave the web environment. This streamlines updates and reduces the need for switching tools during development or system management. While this feature is not meant for end-users, its integration enhances the tool's long-term scalability as discussed in Section 5.2.2.

5.5 Conclusion and outlook

This chapter translated the stakeholder needs identified in Chapter 4 into a functional system design. It defined the functional and non-functional requirements, conceptual logic, and system architecture for a system that supports circular material selection and environmental impact calculation. Key principles such as constraint-driven selection, reference elements, and environmental trade-off logic were formalized, and a complete database model was developed to support the implementation. Furthermore, this chapter demonstrated how the system architecture and logic is implemented into a functional web-based tool. The application enables structured data entry, GWP-based selection, reuse strategy generation, and transparent decision-making.

The outcomes of this chapter form the foundation for Chapter 6, where the developed system is validated. Chapter 6 also explores how the tool can potentially be implemented in real-world construction and design workflows and evaluates its impact on project performance.

Chapter 6: Design validation and implementation

6.1 Introduction

This chapter includes the third research phase, validation and implementation, and addresses Research Objective 3 and RQ3.1 to RQ3.3. It focuses on evaluating whether the developed system meets the defined requirements and explores how its functionalities could be integrated into design and construction workflows to support circular decision-making.
The chapter aims to:

1. Validate the system against stakeholder needs and the technical and functional requirements defined in earlier phases,
2. Theoretically demonstrate how the system's functionalities could be implemented in circular design and construction workflows,
3. Evaluate the system's potential impact on decision-making efficiency, environmental performance, and resource optimization.

6.2 System validation

To ensure that the developed system fulfils its intended purpose, this section validates its performance from both a stakeholder and technical perspective. It assesses how well the system meets the real-world needs, identified by experts, and it evaluates to what extend the system meets the functional and non-functional requirements.

6.2.1 Stakeholder validation: needs and alignment

Throughout this research, experts, and the literature, provided insights into practical challenges that professionals in the construction industry face when they want to reuse materials. These insights leaded into the system requirements, which leaded into the development of the web-based application. With these insights it is the goal to create a system that addressed real-world needs. This section reflects on the stakeholders concerns and validates whether the system addressed the most critical barriers to circular material reuse.

1. Lack of reliable and accessible material information
   Stakeholders emphasized that is difficult to identify, locate, and validate reusable materials. Designers often do not know what reusable materials are available. This means that reusable materials are overseen or not even considered.

   The web-based application addressed this need by offering a centralized and structured database. Designers can search on different parameters to look for materials that matches their design constraints, see Chapter 4 for UI. With this information, designers can make-informed decisions on the materials they want to use in their design.

2. Environmental impact must drive the choice for materials.
   Both the literature and experts stressed that the reuse of materials must contribute to lower environmental impacts in the construction industry. However, to measure and compare the environmental impact, there should be quantified environmental performance metrics that can justify the design choices to a client.

   The application includes a tool automated EIAs that compare reused and hybrid material configurations. This directly supports the sustainability-focused decision-making.

3. Stakeholder collaboration and data sharing
   To reach circular goals, it is important that stakeholders can collaborate across different roles: contractors, suppliers, clients, designers. Experts explained that they must share data to overcome that circularity remains fragmented and inefficient.

   The application creates a platform that fosters collaboration by enabling asset owners or project managers to offer reusable elements and for designers to query and reserve available elements. Because of the structured database, the right data types are given to each element to create a smooth flow from registration, searching to reusing.

4. Client and public acceptance
   A theme that was recurring in the interviews was the clients, and indirectly the public, can have resistance toward the reuse of elements, particularly because of the quality of the materials.

   The application provides traceable data and can track the history of each element. This can give the client insights into the kind of materials that will be used for their project. With the GWP calculations and comparison of reuse of hybrid strategies, clients and public can see the impact the materials make on their design. These insights can with the application be given in an early stage of the design, fostering participation and enhancing the acceptance.

6.2.2 Technical validation: requirement-based assessment

To evaluate whether the developed system meets the intended purpose, the web-based application is evaluated against the functional and non-functional requirements that are defined in Chapter 5. The technical validation tests if the application responds to the stakeholder needs but also if it is robust, usable, and scalable. The validation is grouped into three main categories, corresponding to the categories of Chapter 5: functional performance, non-functional qualities, and data completeness.

Functional requirements

The following core functional requirements were defined based on stakeholder needs and system goals:

Table 10: System validation against functional requirement

Requirement	Description	Validation result
FR-1	Store reusable elements in a structured database	Fully implemented with Django + MySQL
FR-2	Support two input modes: manual and reference-based entry	Fully implemented using dynamic form switching
FR-3	Minimize manual input and automatically populate fields from selected reference elements	Implemented with reference elements defined in reuse potential analysis and JavaScript + backend logic
FR-4	Calculate and store environmental impact per unit	Implemented for kgCO2/unit (m, m2, m3, pcs, kg)
FR-5	Support material selection based on material type, quantity, and GWP	Implemented with search page, filters, and ranking
FR-6	Allow users to define demand and retrieve optimal reuse strategy	Quantity-based logic with GWP fill strategy which can be fallback to hybrid strategies
FR-7	Display element details in expandable UI	Implemented using DataTables and dropdown panels
FR-8	Calculate total GWP of selected configuration	Summation logic working, hybrid GWP support included
FR-9	Support different reuse scenarios with distance calculations for transport	Calculated using donor and storage locations
FR-10	Batch upload of multiple elements	Supported with database structure but not yet implemented in logic
FR-11	Export of data	Supported with database structure but not yet implemented in logic
FR-12	Integration with external databases	Not yet supported; future API-based links possible
FR-13	User registration and access management	Not implemented: system currently operates without login features.

Non-functional requirements

The following non-functional requirements validate the technical properties of the system:

Table 11: System validation against non-functional requirements

Requirement	Description	Validation result
NFR-1	Web-based and platform independent	Locally run Django application that can be hosted on every surfer
NFR-2	User-friendly interface	Implemented with dropdown logic, prefilled input, and previews
NFR-3	Performance for database querying and filtering	Fast response time and easy searching and filtering with DataTables
NFR-4	Error prevention and input validation	Users get info on required fields, locked inputs for reference-based mode
NRF-5	Modular and scalable front- and backend	Django MVT structure allows easy extension of views and templates.
NRF-6	Secure data handling and role separation	Basic security included for database management. Advanced user roles possible in future versions.

Data requirements

The following requirements validate the data integrity completeness.

Table 12: System validation against data requirements

Requirement	Description	Validation result
DR-1	Store element under classification	Included in element form and dropdown
DR-2	Capture material and geometry	Reference materials included, geometry description and drawings included, linked via foreign keys, and stored per element
DR-3	Environmental impact data	Stored for reference elements using NMD, manual input possible and linked via foreign key
DR-4	Support multiple units	Enum logic applied consistently across storage and calculations

DR-5	Include quality and condition	Aesthetic condition and damage stored as enums
DR-6	Link elements t donor projects and storage location when transport is included	Pre-populated locations, manual input possible, and linked via foreign keys for each element.
DR-7	Track material history	New records created when changes are made with timestamps and linked with Element_ID.

This validation shows that the prototype of the web-based application affectively meets the core functional, non-functional and data requirements that are necessary to support data-driven circular design. However, there are also several features that are not yet fully implemented. These features consist out of batch upload, external database integration, data export, BIM integration, and user registration.

6.3 Implementation into design and construction workflows

To support the transition to circular construction, reusable elements must be matched more effectively with the needs of new designs. The materials must not only be catalogued in a structure way but also be integrated in both construction workflows and design workflows. This section explores how the developed system addresses current barriers and demonstrates theoretically how its functionalities could be embedded in construction workflows to support proactive reuse.

Current functionalities implemented in the selection system

The developed prototype includes and validates the following key functionalities:

- Structured registration of reusable elements in a centralized database, using standardized data aligned with the reuse-oriented material passport.
- Automated environmental impact calculation to evaluate reuse scenarios.
- Material matching logic which allows users to input material demands and receive reuse or hybrid reuse-new solutions, ranked by environmental performance and reuse percentage.

These functionalities have been validated in the previous Section. While these are not evaluated in a live project environment, they could be implemented in both construction and design workflows to enhance circularity.

Integration into construction workflows

Figures 29 and 30 show how the system can be embedded in circular construction workflows. The process starts during the deconstruction phase. In this phase materials are identified and registered in the system (Figure 29). When the materials are available in the system, contractors or planners can search the database to identify reuse opportunities for upcoming projects (Figure 30).

Currently enabled by the system:

- Contractors can register elements with consistent data attributes.
- Environmental performance can be calculated and compared.

- Reuse can be proactively planned by querying available materials in advance of new projects.

Fragmented tools like Excel or CAD can be replaced by a system with structured data and one that enables more transparent reuse planning across projects and locations.

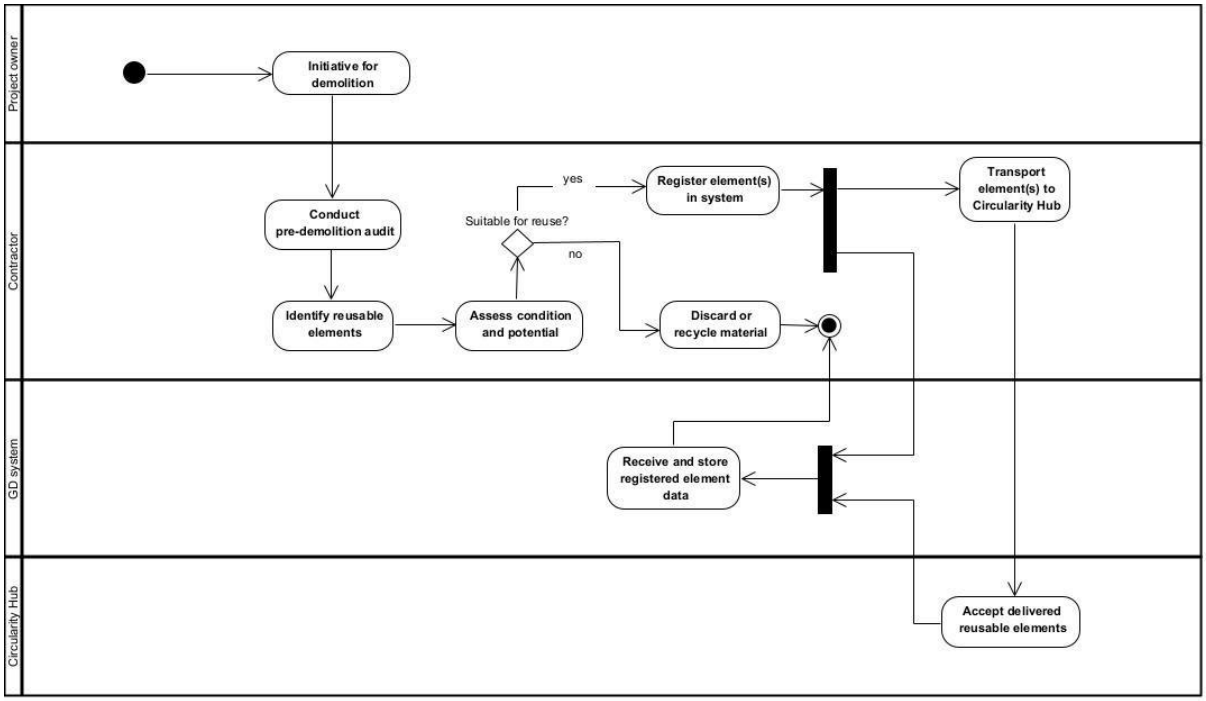


Figure 29: BPMN diagram (part 1) of deconstruction and registration of reusable elements in the database.

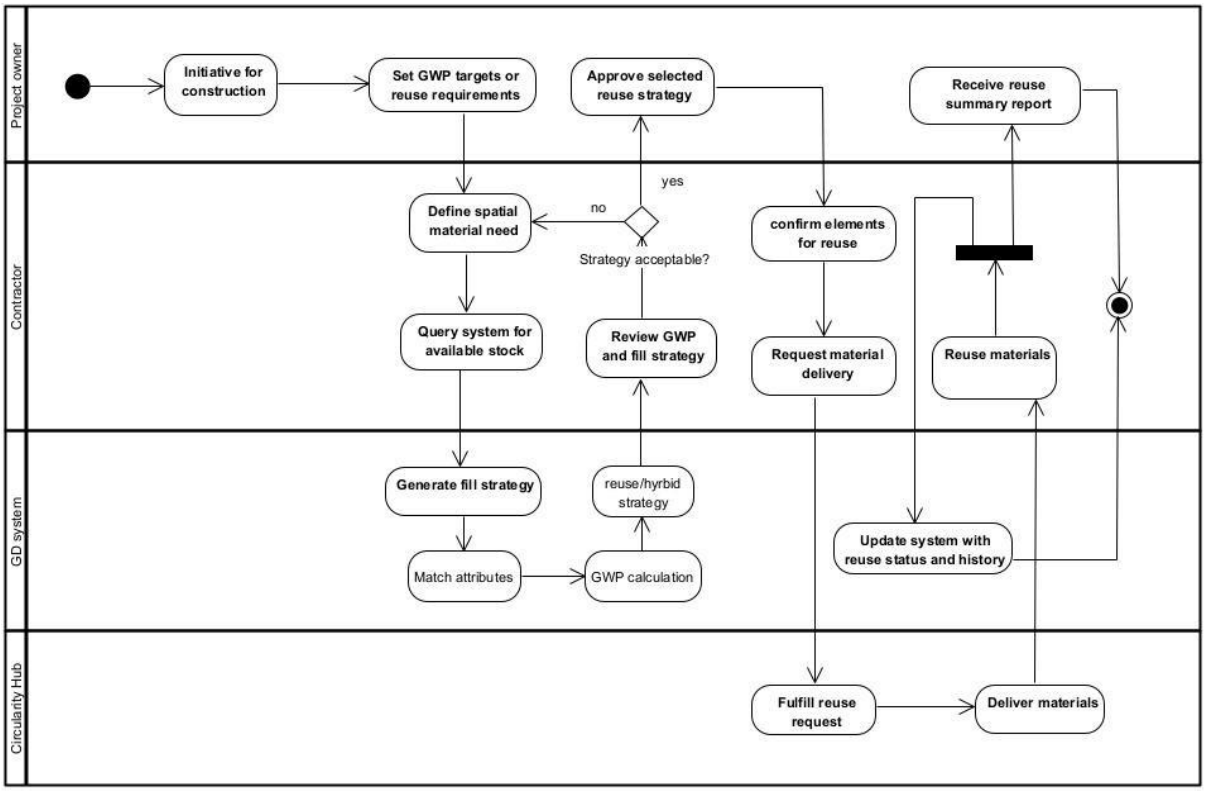


Figure 30: BPMN diagram (part 2) of material planning and selection using the circular resource selection system.

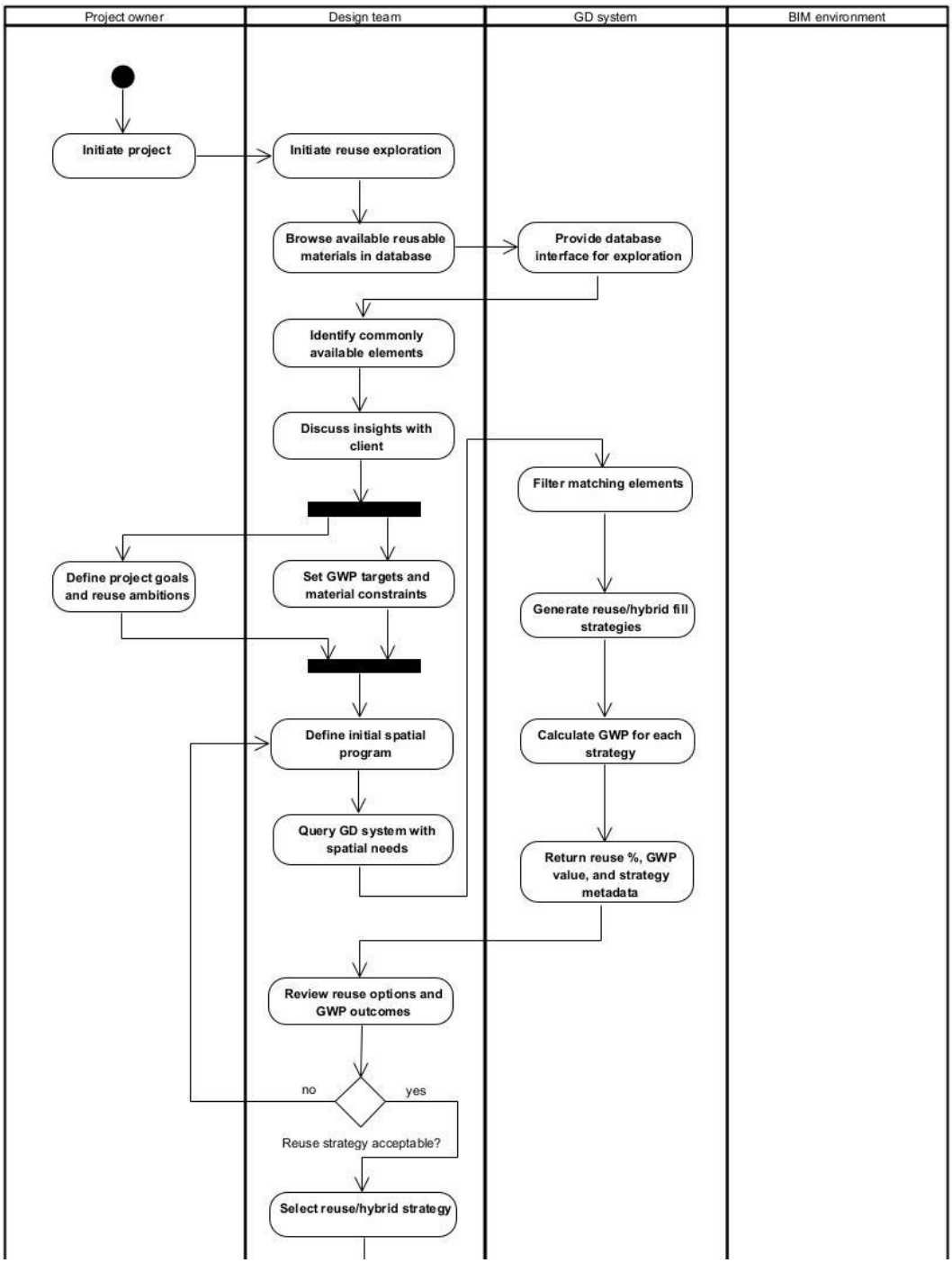
Integration into design workflows

Figure 31 shows how the system could be implemented into design workflows. Designers can input their material requirements that are based on performance or quantity. The system returns configurations of reused or hybrid materials, including environmental trade-offs.

Currently the system enables the following:

- Designers can input quantity demands and receive material configurations.
- Reuse strategies can be compared to new production using GWP calculations.
- Trade-offs between reuse percentage, quantity match, and environmental impact can be reviewed to support decision-making.

While the system does not yet support 3D modelling or spatial optimization, it provides designers with actionable data at early stages of the design.



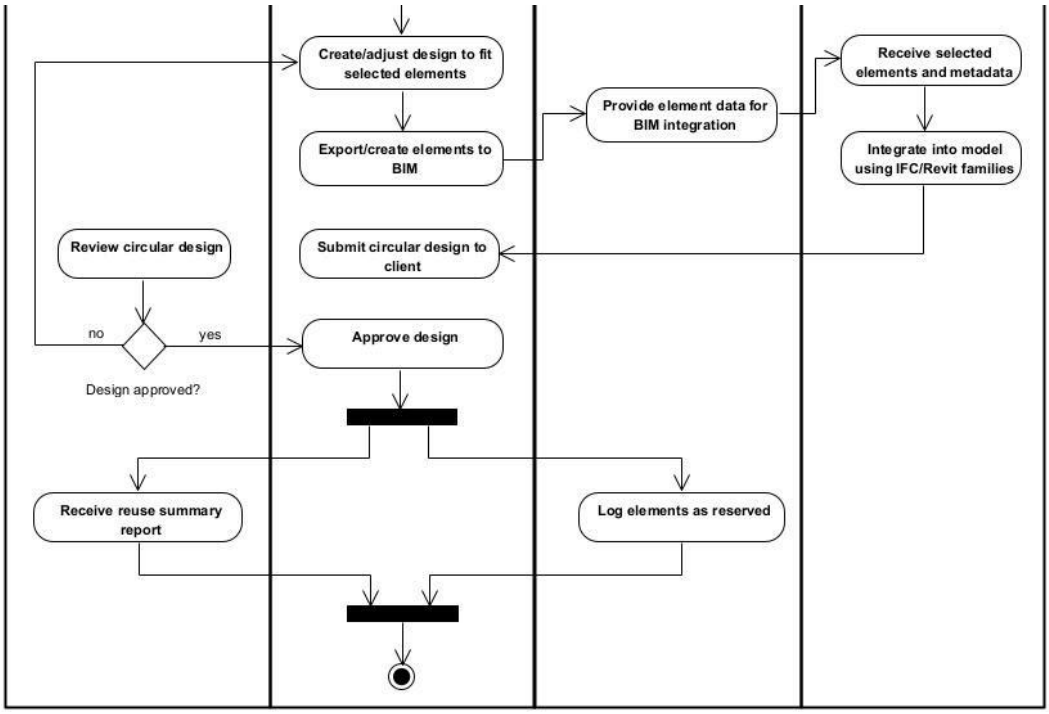


Figure 31: BPMN activity diagram of proposed circular design workflow.

Future opportunities

The system, as developed, provides a working prototype. The following extensions shows possible future opportunities but were not implemented or validated in this thesis:

- Real-time integration with contractor-specific emission profiles. As more contractors start with electrification of their construction processes this reflects the shift toward low-carbon logistics.
- Predictive reuse classification. Logged deconstruction data can be used to estimate reuse potential based on material attributes. When more reusable elements are identified, the database can grow and incorporate more and more reference elements.

These developments would further enhance system integration and scalability but require additional testing and development beyond the scope of this thesis.

6.3.1 Implementation in current tooling

In addition to developing a standalone prototype this research also explores how the core functionalities of the system could be integrated into existing tooling. This section shows how the developed logic and features of the system can be implemented in Van Gelder's CircuTool. A tool currently used to match supply and demand of materials based on construction and deconstruction drawings (see also Section 1.5 and 6.3.1). This theoretical integration was discussed in collaboration with system engineers at Van Gelder to assess the potential alignment between the developed tool and van Gelder's existing CircuTool. However, no technical integration or testing has been performed as that is beyond the scope of this thesis.

Figure 32 shows the original CircuTool workflow. In this system, a CAD-based drawing, also known as .dwg drawing, of both a construction and deconstruction plan are uploaded. These .dwg drawings contain layers where information is attached to. The CircuTool reads these layers and can understand the materials and quantities of the design in the drawing. Based on

overlapping material types, the CircuTool performs a matchmaking process between the demand and supply, and support project teams identify reusable materials from past projects.

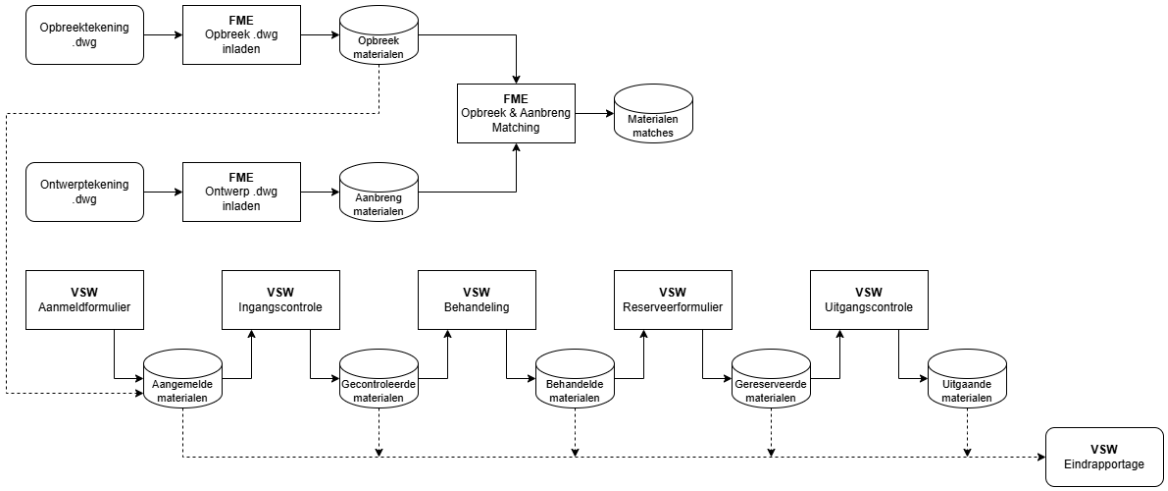


Figure 32: Process diagram of the CircuTool (Van Gelder, 2025)

The current CircuTool could be extended with the developed system by introducing structured data registration, reference elements, environmental impact calculations, and adaptive material matching strategies. Figure 33 shows how these functionalities could theoretically be implemented into the CircuTool:

- From Deconstruction Drawings:
  Material data extracted from CAD layers can be linked to reference elements in the database. Combined with inputs on condition and quality, a digital material passport is created. Data is stored directly in the system; this skips manual reporting and enables traceability.
- From Construction Drawings:
  Material demands can be extracted from the CAD design and are passed to the system, which queries the database for suitable matches. The system calculates environmental impacts and proposes reuse or hybrid reuse-new strategies. If supply is insufficient, the tool suggests alternatives with lower impact than new production. Resulting reuse plans and their environmental scores can be reported to project teams and stakeholders.

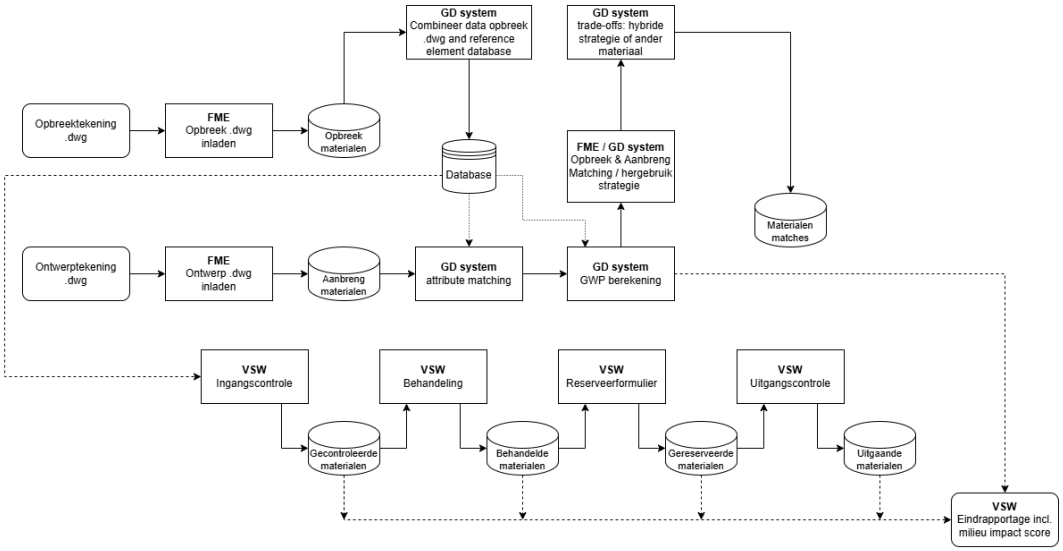


Figure 33: Process diagram of functionalities of selection system implemented in CircuTool.

When this integration is made, the capabilities of CircuTool could potentially be expanded with the following:

- Moving from static CAD-based matching to dynamic, data-driven reuse planning.
- Enabling automated environmental impact assessments based on standardized metrics.
- Offering adaptive reuse strategies and trade-off analysis rather than fixed material matches.
- Providing a centralized structure for material data across projects and locations.
- Laying the groundwork for future BIM integration by transitioning from 2D CAD to structured 3D data environments.

While this implementation remains conceptual, it demonstrates how the developed system could complement existing industry tools and workflows and supports the broader goal of embedding reuse intelligence into everyday infrastructure planning and design.

6.4 System impact

This section evaluates the potential impact that the developed system could have on three key objectives that were defined in this research. These include enhancing decision-making efficiency, improving environmental performance, and optimizing the use of available reusable resources. An evaluation is conducted using a scenario-based approach. This demonstrates how the system could influence key outcomes. This analysis is based on the functionalities for the users that are described in Chapter 5.

Table 13: Explanation of three key evaluation metrices

Metric	Measured As
decision-making efficiency	Ability to search, compare, and select materials in early design phases
Environmental performance	Calculated GWP per unit and configuration using system logic.
Resource optimization	Percentage of demand fulfilled by reusable elements

6.4.1 Scenario-based evaluation

To illustrate the potential impact of the system, the following scenario is used:

“An infrastructure engineer is tasked to deliver a 1000m^2 sidewalk with concrete paving tiles.”

Using the system search function, the engineer queries the available stock and finds:

Available Elements (Sorted by Lowest GWP/Unit)

Element ID	Name	Stored Quantity	GWP($kgCO_2$)/Unit	Unit
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0	5.01	m2
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0	5.06	m2
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0	5.61	m2

Selection Strategy to Fulfill 1000.0 m2

Element ID	Name	Used Quantity	Used % of Element	GWP ($kgCO_2$) Contribution
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0 / 280.0 m2	100.0%	1402.8
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0 / 300.0 m2	100.0%	1518.0
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0 / 320.0 m2	100.0%	1795.2

Total GWP: 4716.0 $kgCO_2$

Missing Quantity: 100.0 m2

Figure 34: Example of system query of 1000m2 of paving tiles.

The system identified 900m^2 of reusable concrete paving tiles and informs the engineer that there is still 100m^2 missing. The engineer continues and lets the system calculate the impact of adding the missing quantity with new materials. The system finds the following hybrid strategy:

Combined GWP Strategy (Reuse + New)

Element ID	Name	Used Quantity	Used % of Element	GWP ($kgCO_2$) Contribution
9e41307e-0fee-4c73-9efa-9e7d585bccb4	Betontegel 300x300x45	280.0 / 280.0 m2	100.0%	1402.8
42ca3ce0-bb71-42d1-a425-9d4daaa60d47	Betontegel 300x300x45	300.0 / 300.0 m2	100.0%	1518.0
3f5658cb-8f5e-46a6-83b8-4615a0e0f6be	Betontegel 300x300x45	320.0 / 320.0 m2	100.0%	1795.2
n.a.	Betontegel 300x300x45 (New)	100.0 m2	n.a.	1564.45

Total GWP (Reuse + New): 6280.45 $kgCO_2$

Figure 35: Example of system output for fill strategy for 1000m2 paving tiles.

6.4.2 Comparison of key impact areas

Based on the scenario of the previous section, the key impact areas are theoretical evaluated based on a conventional workflow and that of one with the developed system. The possible results are summarized in Table 14.

Table 14: Impact of the system on decision-making, environmental performance, and resource optimization

Evaluation criteria	Conventional workflow	With developed system
Decision-making efficiency	Reuse decision made late in the process	Early-stage querying or reusable stock
	No central inventory of available elements	Proactive planning based on availability
	Manual matching based	Structured filtering on multiple reuse-relevant attributes

Environmental performance	GWP rarely calculated in early design	Real-time GWP calculation for reuse, and hybrid calculation
	Environmental decisions mostly post-hoc	Transparent CO2 performance visible during design
Resource optimization	Lower reuse due to lack of visibility and match ability	Match percentage shown directly
	No prioritization of underused stock	Underutilized stock can be identified and prioritized
	Reuse limited to what happens to fit	Enables reuse-driven design adjustments

The theoretical evaluation shows that in potential the developed system could contributes to circular construction goals. It can enhance decision-making efficiency by enabling designers to work within the constraints from the beginning of their design. It could improve environmental performance by quantifying the GWP benefits of reuse and hybrid strategies and create trade-offs for design changes. Lastly, it can be able to support resource optimization by making underutilized elements visible or can give insights into design changes that require less new materials. As a result, the tool forms a practical foundation for more circular, data-driven design and construction.

6.5 Conclusion and outlook

This chapter validated the developed system and explored its potential implementation in real-world design and construction workflows. Through stakeholder input, technical testing, and integration scenarios, the chapter demonstrated how in potential the tool can enhance decision-making, environmental performance, and resource optimization.

The next and final chapter will reflect on the research. It will summarize key findings, discuss limitations and opportunities for future research and development, and provide concluding recommendations for how proactive circular design can accelerate the transition to a circular construction economy.

Chapter 7: Conclusion and discussion

7.1 Conclusion

This research explored how circular construction can be supported through a data-driven, rule-based workflow that enables designers and contractors to make informed reuse decisions early in the design process. The research was structured in three research phases: data foundation, system development, and validation and implementation. This section concludes for each phase the objective and associated research questions.

Phase 1: Data foundation
To support proactive reuse decision, the objective of the first phase was to identify the types of construction elements that are suitable for reuse. It explored the key data that is needed to support reuse decision-making and proposed a material passport tailored to circular reuse. Furthermore, the goal was to define a method for environmental impact assessment of circular materials.

Drawing from literature and expert input from Van Gelder, ReCreate, and TAUW, it became clear that to enable circular design and construction, structured data is needed. This means a standardized approach for collecting, storing, and utilizing data on circular construction elements. Clear data structures enable contractors and designers to make informed decisions on reuse during early stages of projects.

To identify construction elements with a high reuse potential, six key characteristics that describe elements that are most suitable for direct reuse according to R-3 of the 10-R ladder were defined: durability and longevity, ease of disassemble, standardization, high environmental impact during production, frequent use and availability, and transportation and storage. For each of these characteristics, relevant data attributes were defined to support reuse decision-making. This includes classifications, geometry and material, condition and quality, storage locations, and environmental performance. A reuse potential analysis has been conducted to identify the elements frequently used at Van Gelder with the highest reuse potential, these elements include paving elements, roadwork elements, traffic signs, and prefabricated structural construction elements.

To support environmental assessment, a GWP-bases methodology was developed to calculate the environmental performance of circular materials for three reuse scenarios': new production, reuse on same site, reuse on new site. This methodology follows the standard of EN 15804 and the guidelines of the Nationale Milieu Database to ensure alignment with current practices. Based on the identified data attributes and calculation method, a material passport was composed that captures the essential information for circular reuse and environmental impact assessment. This passport forms the foundation for the data model defined in the next research phase.

Phase 2: system design and engineering
In the second phase, the research objective was to define and developed a circular resource selection system. This research phase followed the system engineering methodology. This methodology consists out of three stages: requirements analysis, functional definition, and physical definition.

In the requirement analysis, the functional, non-functional, and data requirements were defined from the insights of the first research phase. The requirements were structured around three main clusters: (1) database setup and element registration, (2) inventory and data management, and (3) material selection and environmental evaluation. The key requirements that are defined in this step are:

- Structured and scalable data input that is aligned with defined material passport.
- Robust querying and filtering of all available materials in the database.
- Automated environmental impact calculation based on defined methodology.
- Generation of reuse and hybrid strategies to enable trade-off insights.
- Modular and extensible system architecture to allow future scalability and integration.

For the functional definition, these requirements were translated into a structured SQL data model that reflects the material passport framework, and a relational database schema was developed. Together with the conceptual logic, which was structured around rule-based selection, allowing the system to configure reuse strategies bases on availability, demand, and environmental performance, the backend of the system was defined.

The result of the physical definition was a rule-base selection tool implemented as a web-based application. A Model View Template architecture, using Phyton, Django and a MySQL backend, was used to develop the application. The application allows users to register elements, manually or via reference types (identified in the first research phase), to query materials by projected location and attributes, and to automatically generate a reuse or hybrid strategy based on environmental performance. A user-friendly frontend interface was created to ensure intuitive interaction with the system.

Phase 3: Validation and implementation

In the final research phase, the developed system was validated technically and through expert feedback. The critical functionalities that were defined in the second research phase, structured data input, environmental impact calculation, reuse strategies, were demonstrated in the validation. Although certain functions such as BIM exports or more advanced planning remained out of scope, the core tool was shown to be functional.

The potential implementation of the system was explored through BPMN diagrams and an integration proposal with Van Gelder's CircuTool. These scenarios show how the developed system can shift reuse planning from static document to dynamic, data-informed processes, and how the system can influence early-stage design decisions through environmentally performance information. However, it must be emphasized that the implementation was not evaluated on live projects and thus that the insight is theoretical and based on expert feedback.

The current prototype gives a solid foundation for structured material registration, environmental impact assessment, and reuse strategy generation. However, its broader integration is still a subject for future research and development. Nonetheless, the system shows potential to support proactive circular design by enabling earlier, data-driven, and environmentally informed material decisions.

7.2 Discussion

A very important outcome of this study is the realization the circularity does not begin with the deconstruction of buildings or procurement, but that circularity begins at the point of design conception. While the developed system was not evaluated in live design projects, it demonstrates how designers in theory could explore existing stock early in their projects, evaluate environmental trade-offs, and make informed decisions based on data such as geometry, location, material, quality, and GWP. For contractors, the tool offers a more structured approach to material documentation and lifecycle tracking, which may support more informed decisions around logistics, storage, and environmental reporting.

At the same time, the study also shows several important challenges that must be addressed for this approach to be successful in practice. One of the most important is the dependency of accurate and consistent data. Although the system supports a standardized registration process, the effectiveness of the system is limited when the data is incomplete, outdated, or not maintained. A related challenge is the variability and interpretation of environmental data. Many LCAs and EPDs include GWP values that are often calculated with the use of assumptions about transport distances, (de)construction activities, or energy sources. This does not reflect project-specific conditions. For example, the industry has an ongoing effort to electrify its machinery fleet. Electrification significantly reduces emissions during transport and (de)construction. These emission reductions are not yet captured in current GWP values. This applies also to innovations made in material production, which can lead to significant differences in environmental performance. This illustrates the importance of for context-specific GWP values and to develop a dynamic impact model that reflect these practices.

Another important observation is the types of elements that are currently supported by the system. The database and logic of the tool is currently optimized for element with high modularity and standardizations. These are the types of elements for which reuse is most feasible due to their predictability in size, function, and availability. However, to move to a complete circular economy, not only these ‘simple’ elements, but also the complex and less standardized elements should be included in the system. Moreover, the current system focuses only on direct reuse. However, the system could also be used for other circularity strategies, such as recycling.

Another important point to discuss is the complexity of reusing and combining elements with different quality levels. While hybrid strategies offer practical solutions for maximizing reuse, they may also result in the mixing of elements with varying durability or condition. In these cases, the overall quality of the assembled batch is only as strong as its weakest component. This could have long-term implications on the circularity. A short-term reduction in GWP can be achieved, however, the ability to reuse the same batch in future cycles could be compromised if the batch becomes heterogeneous or downgraded in quality. Not only choices need to be made on environmental performance today, but also about the long-term reuse potential of materials. This introduces the need for a more lifecycle-oriented strategy that includes not only the impact on current project but also the on the impact of multiple reuse loops over time.

Also, the balance between automation and control is important to discuss. The system’s strength is the ability to calculate and suggest the most environmentally favourable configuration. This provides a strong data foundation for circular decision-making. However,

designing is not always purely a rational or linear process. Things like aesthetics, client preference or functional constraints may require decisions that deviate from what is environmentally optimal. On one hand, the designer can be given more freedom to adjust system outputs. On the other hand, there is a risk that too much manual control can lead to a situation where the system's logic is diluted. A careful balance between the two is important where the designer guides and is not restricted and where the system informs but does not dictate.

Finally, one of the most valuable benefits of the system is the role it can have in creating more awareness about circularity. Circularity is not only the responsibility of a designer or contractor but is a joint effort form client, policymakers, and the broader public. The system developed in this thesis could help to make the concept of reuse more tangible and quantifiable. The data-driven insights could make it easier to justify reuse strategies to sceptical clients or to engage the public in circular choices. In this way the system does not only facilitate a better decision-making process but can creates a mindset where circularity is no longer just an afterthought, but a central part of modern construction practices.

7.3 Contributions

The research that is done in this thesis has academic relevance in circular construction by exploring how structured data, environmental impact assessment, and rule-based decision-making can be used to support reuse strategies in early design and construction planning. The research presents a conceptual and technical framework for a rule-based material selection system that is informed by the closed loop product lifecycle management, the 10-R framework, and the life-cycle stages of materials. Furthermore, the system engineering approach creates a replicable method for future academic research on circular design tooling and computational workflows.

From a practical point of view, the research delivered a functional prototype that shows how reusable materials can be registered, evaluated, and selected using environmental impact metrics and availability constraints. Despite the fact that the system was not evaluated in live projects, its functionalities were designed in collaboration with industry stakeholders and reflect real-world needs. The proposed integration with tools like Van Gelder's CircuTool shows how current workflows might be extended in the future. The tool shows potential, by structuring material data and enabling scenario-based reuse strategies, to support more transparent and data-driven reuse decisions in both construction and design processes.

7.4 Limitations and future research and development

While this study presents a functional system that demonstrates how a rule-based selection system can be applied to circular construction, this research also has its limitations. The system has not yet been validated through a full-scale implementation and is not evaluated in an ongoing project. While experts and practical examples have helped verify the concept of the developed system, its real-world usability, barriers to adoption, and long-term integration is still something that needs to be researched in practice.

Additionally, while the system is conceptually aligned with existing tools from ReCreate and Van Gelder, the full integration into platforms like Revit or the CircuTool has not yet been implemented. The implementation into design environments and digital workflows that are

commonly used is still at a conceptual stage. The functionalities of the system show potential but also need further testing to assess their impact on actual project outcomes.

Future research could focus on further developing the functionalities of the current system and to see if it can further integrate into existing workflows. Future development of such kind of systems could focus on the extension of the system for real-time use in BIM environments. This can integrate environmental impact assessment into 3D information models. In the long term, algorithmic or machine learning technologies could be further researched to see if it possible to improve the matchmaking between the available materials and project demands. These technologies could predict reuse suitability or generate design configurations directly from the available materials. This moves the system beyond rue-based selection and towards adaptive and generative reuse design.

8 References

Adan, I., Fecarotti, C., et al. (2023). Modular prefabricated construction: a circular asset management system for closed-loop supply and logistics chains. Technische Universiteit Eindhoven

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 170(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Alshehri, A. M., Hajj, F. A., Waqar, A., Bageis, A. S., Houda, M., & Benjeddou, O. (2024). Building information modeling (BIM) driven performance-based construction for the optimization of sustainable and smart structures development. Environmental Challenges, 16, 100980. https://doi.org/10.1016/j.envc.2024.100980

Andersen, S. C., Sohn, J., Oldfield, P., & Birkved, M. (2022). Evaluating the environmental impacts of conventional and modular buildings in absolute measures: A case study across different geographical contexts. Building and Environment, 223, 109509. https://doi.org/10.1016/j.buildenv.2022.109509

Antwi-Afari, P., Ng, S. T., & Chen, J. (2023b). Determining the optimal partition system of a modular building from a circular economy perspective: A multicriteria decision-making process. Renewable and Sustainable Energy Reviews, 185, 113601. https://doi.org/10.1016/j.rser.2023.113601

Antwi-Afari, P., Ng, S. T., Chen, J., Oluleye, B. I., Antwi-Afari, M. F., & Ababio, B. K. (2023a). Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. Building and Environment, 239, 110411. https://doi.org/10.1016/j.buildenv.2023.110411

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. Journal of Building Engineering, 43, 103233. https://doi.org/10.1016/j.jobe.2021.103233

Barbhuiya, S., & Das, B. B. (2023). Life Cycle Assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. Case Studies in Construction Materials, 19, e02326. https://doi.org/10.1016/j.cscm.2023.e02326

Boehm, B. (1986). A spiral model of software development and enhancement. ACM SIGSOFT Software Engineering Notes, 11(4), 14–24. https://doi.org/10.1145/12944.12948

Bellini, A., Andersen, B., Klungseth, N. J., & Tadayon, A. (2024). Achieving a circular economy through the effective reuse of construction products: A case study of a residential building. *Journal of Cleaner Production*, *450*, 141753. https://doi.org/10.1016/j.jclepro.2024.141753

Biskjaer, M. M., Dalsgaard, P., & Halskov, K. (2014). A constraint-based understanding of design spaces. *Association for Computing Machinery*. https://doi.org/10.1145/2598510.2598533

Caetano, I., Santos, L., & Leitão, A. (2020). Computational design in architecture: Defining parametric, generative, and algorithmic design. *Frontiers of Architectural Research*, *9*(2), 287–300. https://doi.org/10.1016/j.foar.2019.12.008

Charef, R., & Lu, W. (2021). Factor dynamics to facilitate circular economy adoption in construction. Journal of Cleaner Production, 319, 128639. https://doi.org/10.1016/j.jclepro.2021.128639

Charytonowicz, J., & Skowroński, M. (2015). Reuse of building materials. *Procedia Manufacturing*, *3*, 1633–1637. https://doi.org/10.1016/j.promfg.2015.07.456

Chen, S., Ahmmed, S., Lal, K., & Deming, C. (2020). Django Web Development Framework: Powering the Modern Web. American Journal of Trade and Policy, 7(3), 99–106. https://doi.org/10.18034/ajtp.v7i3.675

Dervishaj, A., & Gudmundsson, K. (2023). From LCA to circular design: A comparative study of digital tools for the built environment. *Resources Conservation and Recycling*, *200*, 107291. https://doi.org/10.1016/j.resconrec.2023.107291

Dixit, M., & Kumar, P. P. (2024). Embodied impacts of buildings from energy-carbon-water nexus perspective: A case study of university buildings. Cleaner Energy Systems, 7, 100108. https://doi.org/10.1016/j.cles.2024.100108

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/s0142-694x(01)00009-6

Elghaish, F., Matarneh, S. T., Edwards, D., Rahimian, F. P., El-Gohary, H., & Ejohwomu, O. (2022). Applications of Industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework. Construction Innovation: Information, Process, Management, 22(3), 647–670. https://doi.org/10.1108/ci-03-2022-0062

Ellen MacArthur Foundation. (2015). Circularity indicators: An approach to measuring circularity. In Ellen MacArthur Foundation. Retrieved November 13, 2023, from https://emf.thirdlight.com/link/ukiokhl9wek3-wfb5iv/@/preview/1?o

European Commission. (2020). Circular Economy Action Plan: The European Green Deal. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

European Comission. (n.d.). Life Cycle Assessment (LCA). European Platform on LCA | EPLCA. Retrieved January 25, 2025, from https://eplca.jrc.ec.europa.eu/lifecycleassessment.html#:~:text=LCA%20is%20defined%20by%20the,system%20throughout%20its%20life%20cycle.

Fivet, C., Brutting, J., 2020. Nothing is lost, nothing is created, everything is reused: structural design for a circular economy. Struct. Eng. 98, 74–81. https://doi.org/10.56330/LXAH1188

Gao, Y., Wang, J., & Yiu, T. W. (2023). Multi-information integration-based life cycle analysis of greenhouse gas emissions for prefabricated construction: A case study of Shenzhen. Environmental Impact Assessment Review, 104, 107330. https://doi.org/10.1016/j.eiar.2023.107330

Garusinghe, G. D. a. U., Perera, B. a. K. S., & Weerapperuma, U. S. (2023). Integrating circular economy principles in modular construction to enhance sustainability. *Sustainability*, *15*(15), 11730. https://doi.org/10.3390/su151511730

Ghisellini, P., Cialani, C., & Ulgiati, S. (2015). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Hong, W. (2020). Application to the modular construction. In Elsevier eBooks (pp. 331–346). https://doi.org/10.1016/b978-0-08-102721-9.00008-x

Hořínková, D. (2021). Advantages and Disadvantages of Modular Construction, including Environmental Impacts. *IOP Conference Series Materials Science and Engineering*, *1203*(3), 032002. https://doi.org/10.1088/1757-899x/1203/3/032002

Iacovidou, E., Purnell, P., Tsavdaridis, K. D., & Pologanathan, K. (2021). Digitally enabled modular construction for promoting modular components reuse: A UK view. Journal of Building Engineering, 42, 102820. https://doi.org/10.1016/j.jobe.2021.102820

Jansen, B. W., Van Stijn, A., Eberhardt, L. C. M., Van Bortel, G., & Gruis, V. (2022). The technical or biological loop? Economic and environmental performance of circular building components. Sustainable Production and Consumption, 34, 476–489. https://doi.org/10.1016/j.spc.2022.10.008

Jayawardana, J., Sandanayake, M., Jayasinghe, J., Kulatunga, A. K., & Zhang, G. (2023). A comparative life cycle assessment of prefabricated and traditional construction – A case of a developing country. Journal of Building Engineering, 72, 106550. https://doi.org/10.1016/j.jobe.2023.106550

Kanters, J. (2020). Circular Building Design: An analysis of barriers and drivers for a circular building sector. Buildings, 10(4), 77. https://doi.org/10.3390/buildings10040077

Kebede, R., Moscati, A., Tan, H., & Johansson, P. (2024). A modular ontology modeling approach to developing digital product passports to promote circular economy in the built environment. Sustainable Production and Consumption, 48, 248–268. https://doi.org/10.1016/j.spc.2024.05.007

Kilian, A. (2006). Design Innovation through Constraint Modeling. *International Journal of Architectural Computing*, *4*(1), 87–105. https://doi.org/10.1260/147807706777008993

Kirchherr, J., Reike, D., & Hekkert, M. P. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources Conservation and Recycling, 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kossiakoff, A., Sweet, W. N., Seymour, S. J., & Biemer, S. M. (2011). Systems engineering Principles and practice. https://doi.org/10.1002/9781118001028

Kręt-Grześkowiak, A., & Baborska-Narożny, M. (2023). Guidelines for disassembly and adaptation in architectural design compared to circular economy goals - A literature review. Sustainable Production and Consumption, 39, 1–12. https://doi.org/10.1016/j.spc.2023.04.020

Kumi, L., & Jeong, J. (2023). Optimization model for selecting optimal prefabricated column design considering environmental impacts and costs using genetic algorithm. Journal of Cleaner Production, 417, 137995. https://doi.org/10.1016/j.jclepro.2023.137995

Kunic, A., Angeletti, D., Marrone, G., & Naboni, R. (2024). Design and construction automation of reconfigurable timber slabs. Automation in Construction, 168, 105872. https://doi.org/10.1016/j.autcon.2024.105872

Lee, K. (2004). Life cycle assessment: Best Practices of ISO 14040 Series.

Leising, E., Quist, J., & Bocken, N. (2017). Circular Economy in the building sector: Three cases and a collaboration tool. Journal of Cleaner Production, 176, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

Li, Z., Tsavdaridis, K. D., & Katenbayeva, A. (2024b). Reusable Timber Modular Buildings, Material Circularity and Automation: The role of inter-locking connections. Journal of Building Engineering, 98, 110965. https://doi.org/10.1016/j.jobe.2024.110965

Ma, W., Wang, X., Wang, J., Xiang, X., & Sun, J. (2021). Generative Design in Building Information Modelling (BIM): Approaches and requirements. *Sensors*, *21*(16), 5439. https://doi.org/10.3390/s21165439

Ministerie van Infrastructuur en Waterstaat. (2024). *Nederland circulair in 2050*. Circulaire Economie | Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050

Munaro, M. R., & Tavares, S. F. (2021). Materials passport's review: challenges and opportunities toward a circular economy building sector. *Built Environment Project and Asset Management*, *11*(4), 767–782. https://doi.org/10.1108/bepam-02-2020-0027

Miu, I. (2020). *Fundamental characteristics and concept of material passports*. https://essay.utwente.nl/80682/

Mudge, F. (2024). ReCreate Studio: Design software for new building structures from a database of reused concrete components. Technische Universiteit Eindhoven.

Minunno, R., O'Grady, T., Morrison, G., Gruner, R., & Colling, M. (2018). Strategies for applying the circular economy to prefabricated buildings. *Buildings*, *8*(9), 125. https://doi.org/10.3390/buildings8090125

Nationale Milieu Database. (2022). LCA Rapportage categorie 3 Data Nationale Milieudatabase. In Milieudatabase. Retrieved January 14, 2025, from https://milieudatabase.nl/nl/rapporten-tool/report/33/

Nationale Milieu Database, Sant Verde, SGS Search, & Witteveen+Bos. (2021). LCA Rapportage categorie 3 Data Nationale Milieudatabase hoofdstuk 1000 t/m 8000 processen. In Nationale Milieu Database. Nationale Milieu Database. Retrieved May 1, 2025, from https://milieudatabase.nl/nl/rapporten-tool/report/131/

Olumo, A., & Haas, C. (2024). Building material reuse: An optimization framework for sourcing new and reclaimed building materials. Journal of Cleaner Production, 479, 143892. https://doi.org/10.1016/j.jclepro.2024.143892

Sanchez, B., Rausch, C., & Haas, C. (2022). Feature modeling for configurable and adaptable modular buildings. *Advanced Engineering Informatics*, *51*, 101514. https://doi.org/10.1016/j.aei.2021.101514

Shahi, S., Wozniczka, P., Rausch, C., Trudeau, I., & Haas, C. (2021). A computational methodology for generating modular design options for building extensions. Automation in Construction, 127, 103700. https://doi.org/10.1016/j.autcon.2021.103700

Sillanpää, M., & Ncibi, C. (2019a). Circular economy. In *Elsevier eBooks* (pp. 37–68). https://doi.org/10.1016/b978-0-12-815267-6.00002-5

Stichting Nationale Milieudatabase. (2020). Bepalingsmethode Milieuprestatie Bouwwerken. In Milieudatabase. Nationale Milieudatabase. Retrieved January 30, 2025, from https://milieudatabase.nl/media/filer_public/08/97/08978af7-15a0-4412-a782-28aee7a91b83/bepalingsmethode-milieuprestatie-bouwwerken-juli-2020.pdf

Stijn, Van, A., Eberhardt, L. M., Jansen, B. W., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. Resources Conservation and Recycling, 174, 105683. https://doi.org/10.1016/j.resconrec.2021.105683

Stijn, Van, A., Jansen, B. W., Gruis, V., & Van Bortel, G. (2023). Towards implementation of circular building components: A longitudinal study on the stakeholder choices in the development of 8 circular building components. *Journal of Cleaner Production*, *420*, 138287. https://doi.org/10.1016/j.jclepro.2023.138287

Suwa, M., Gero, J., & Purcell, T. (2000). Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies*, *21*(6), 539–567. https://doi.org/10.1016/s0142-694x(99)00034-4

Taghaddos, H., Hermann, U., & Abbasi, A. (2018). Automated Crane Planning and Optimization for modular construction. Automation in Construction, 95, 219–232. https://doi.org/10.1016/j.autcon.2018.07.009

Tong, X., Wang, T., Li, J., & Wang, X. (2024). Extended producer responsibility to reconstruct the circular value chain. Circular Economy, 3(1), 100076. https://doi.org/10.1016/j.cec.2024.100076

Reike, D., Vermeulen, W. J., & Witjes, S. (2017). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resources Conservation and Recycling, 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Rijksdienst voor Ondernemend Nederland. (2020, July). R-ladder - Strategieën van circulariteit. RVO.nl. Retrieved October 8, 2024, from https://www.rvo.nl/onderwerpen/r-ladder Sillanpää, M., & Ncibi, C. (2019). Getting holds of the circular economy concept. In *Elsevier eBooks* (pp. 1–35). https://doi.org/10.1016/b978-0-12-815267-6.00001-3

Vandervaeren, C., Galle, W., Stephan, A., & De Temmerman, N. (2021). More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. Resources Conservation and Recycling, 177, 106001. https://doi.org/10.1016/j.resconrec.2021.106001

Wei, Y., Choi, H., & Lei, Z. (2021). A generative design approach for modular construction in congested urban areas. Smart and Sustainable Built Environment, 11(4), 1163–1181. https://doi.org/10.1108/sasbe-04-2021-0068

Wijte, S., Vullings, M., & Lambrechts, T. (2023). Onderzoek Hergebruik prefab beton. Cement, 2023/7. https://www.cementonline.nl/artikelen/onderzoek-hergebruik-prefab-beton

Yang, Y., Zheng, B., Luk, C., Yuen, K., & Chan, A. (2024). Towards a sustainable circular economy: Understanding the environmental credits and loads of reusing modular building components from a multi-use cycle perspective. Sustainable Production and Consumption, 46, 543–558. https://doi.org/10.1016/j.spc.2024.02.027

Zairul, M. (2021b). The recent trends on prefabricated buildings with circular economy (CE) approach. *Cleaner Engineering and Technology*, *4*, 100239. https://doi.org/10.1016/j.clet.2021.100239

Zhang, B., & Li, B. (2024). From knowledge encoding to procedural generation for early-stage layout design: A case of linear shopping centres. *Frontiers of Architectural Research*. https://doi.org/10.1016/j.foar.2024.07.002

Zhuang, G., Shih, S., & Wagiri, F. (2023). Circular economy and sustainable development goals: Exploring the potentials of reusable modular components in circular economy business model. *Journal of Cleaner Production*, *414*, 137503. https://doi.org/10.1016/j.jclepro.2023.137503

Appendix A – Expert interviews

A1: Interview Van Gelder 1

Spaan, Hugo:
Could you briefly introduce yourself and your role within Van Gelder?
Interviewee:
I work as a project manager at Van Gelder. My focus is on infrastructure projects, where I participate in early-stage project development and client interaction, particularly in projects with a sustainability component.

Spaan, Hugo:
What kind of reusable materials are typically considered in your projects, and what data is currently used to evaluate them?
Interviewee:
We often work with prefab concrete elements such as retaining walls and beams. The biggest concern is quality assurance. Without clear specifications or proof of previous performance, it is difficult to justify reuse. Ideally, we would like to have data that shows the product still meets functional and structural requirements, including any damage or wear. However, this data is rarely available or standardized.

Spaan, Hugo:
How is reuse currently managed in workflows and what tools are used?
Interviewee:
We try to reuse materials opportunistically, but the process is ad hoc. There is no systematic approach or digital environment where you can check availability or suitability. If there were a database linked to BIM or design tools that allowed us to filter based on location, quantity, or condition, that would be a major improvement. Right now, reuse only happens when someone happens to know that something is available.

Spaan, Hugo:
How do you assess environmental impact, and does this influence design decisions?
Interviewee:
MKI scores are increasingly requested by clients, especially in tender documents. However, the way we calculate these scores is mostly generic. If we had reliable environmental impact data for reused products—including transport and preparation for reuse—it would help us make better trade-offs. Currently, there is no incentive to reuse unless it clearly results in cost or MKI savings, and without clear data this is hard to prove.

Spaan, Hugo:
What would an ideal reuse workflow or tool look like?
Interviewee:
A tool that allows us to browse reusable materials from other projects, check availability, and evaluate them based on environmental impact would be incredibly useful. If this is linked to BIM or our project planning tools, it becomes much easier to implement in daily practice. More important than fancy algorithms are that the data is complete, consistent, and accessible early in the process—ideally during tendering or initial design.

A2: Interview Van Gelder 2

Spaan, Hugo:
To start, could you introduce yourself briefly? What is your current role at Van Gelder, and what are your daily tasks?
Interviewee:
I am ****, and in short, I am responsible for asphalt development. My work involves reviewing the asphalt mixtures we currently have in our portfolio to see if they meet client demands. If not, we consider developing new mixtures. We commission research to achieve new asphalt mixtures, primarily focusing on temperature reduction. The industry aims to transition from hot-mix to warm-mix asphalt. Additionally, we focus on general sustainability, constantly striving for the lowest MKI value for asphalt while maintaining quality for the client.

Spaan, Hugo:
How does circularity feature in your daily work?
Interviewee:
Circularity is present throughout the process, from milling to when the asphalt leaves the plant. I have been working with the MKI value and am now the main contact person within the company for MKI regarding asphalt.

Spaan, Hugo:
Can you explain the concept of circularity and what it means to you?
Interviewee:
From an asphalt perspective, circularity means a design that requires minimal to no new raw materials, ideally enabling multiple cycles. For example, when milling asphalt, the goal is to reuse the entire mixture. Achieving 100% reuse is not possible yet, as some new materials still need to be added, but this chain is evolving.

Spaan, Hugo:
Does Van Gelder have specific guidelines or goals regarding circularity?
Interviewee:
Not directly within a design, it is closely tied to client requirements. As a company, we aim to make significant progress toward circularity by 2030.

Spaan, Hugo:
To what extent do you collaborate with stakeholders promoting circularity in projects?
Interviewee:
The last link to achieve full circularity is bitumen, where we depend heavily on market developments. We seek collaboration here. Additives should mostly come from available milled materials. Sourcing these from other chains raises questions about circularity—it might promote overall circularity but not within the asphalt chain itself. Shifting focus to secondary products could increase circularity, but it is challenging due to high transport costs and preparation for reuse.

Spaan, Hugo:
Beyond cost, what are other challenges in reusing materials from different chains?
Interviewee:

Technical quality. Each product must be individually assessed. It is more difficult with waste products than new ones since waste products come from various sources, requiring separate evaluation, which can lead to inconsistencies.

Spaan, Hugo:
Which materials and elements do you consider best suited for reuse and recycling?
Interviewee:
In infrastructure, many components, like roads, are flat surfaces and are not easily reusable but can be recycled effectively. Freestanding elements, like paving and street furniture, are more suitable for direct reuse.

Spaan, Hugo:
Is there a distinction made between loose materials and elements?
Interviewee:
Yes, this is becoming more apparent. Resource hubs are being established where materials like concrete curbs are stored for reuse in future projects. However, challenges arise with availability and timing. It is difficult to store materials for long periods when their reuse timeline is uncertain.

Spaan, Hugo:
When materials are sent to a hub, is it easy to reuse them directly in a new design?
Interviewee:
No. The specifications for materials in a new design are often very high, making it uncertain whether reused materials meet these requirements. Additionally, materials from different sources may not be compatible.

Spaan, Hugo:
What environmental requirements must a material meet to be suitable for direct reuse?
Interviewee:
The material must be free of harmful substances; otherwise, it must be cleaned first. For example, tar in asphalt needs to be evaluated in the field since such data is not readily available. Once at a hub or asphalt plant, the quality of materials can be assessed.

Spaan, Hugo:
When high-quality materials are recycled, do you aim to maintain their quality in the process?
Interviewee:
That is the goal, but it is often not achieved in practice. Due to speed, materials are not always properly separated, resulting in mixed materials that lower quality and hinder circularity.

Spaan, Hugo:
How is material information collected and managed?
Interviewee:
In the asphalt sector, we use PIM, a software package where raw material properties are recorded, along with supporting documents and evidence. Asphalt mixtures are designed in PIM, and research results are also documented there.

Spaan, Hugo:
To what extent is material information included in a project?
Interviewee:

Material passports are sometimes mentioned but are often just a few spreadsheets. Creating a good passport is challenging since there is no standard. A material passport is only useful if it is dynamic. Changes during a project should also be recorded. Platform CB23 has created an extensive document on this topic.

Spaan, Hugo:
Who do you see as responsible for collecting and managing material data?
Interviewee:
Van Gelder is responsible for providing the data, while the client is responsible for managing it. However, clients—often municipalities or Rijkswaterstaat—do not have information about the current state of materials. I would like to know the properties and quality of the used materials so I do not have to evaluate them myself and can determine how to reuse or recycle them. Management by clients is often inadequate. Management systems exist, but the data we need is not sufficiently included.

Spaan, Hugo:
What challenges do you face when sharing project and execution information with third parties?
Interviewee:
Currently, there is no standard. You do not know what information to share or in what format, so everyone does it differently. Efforts are being made to develop a standard format. Additionally, considerations are being made to share and manage this data in formats other than PDFs. There is some mistrust in the sector between contractors and clients regarding how the information is used and whether it might fuel competition. Within the PIM collective, we are working on standardizing data storage and offering it to clients. Rijkswaterstaat can currently retrieve information from PIM and import it into their management system. However, it does not work the other way around—we do not get information back, such as asphalt assessments managed by Rijkswaterstaat.

Spaan, Hugo:
Is there a classification system for the materials and elements you use?
Interviewee:
Yes, we have developed a code for all our materials, which is implemented in PIM. All partners collaborating at the asphalt plant and using the PIM software use the same code.

Spaan, Hugo:
How does Van Gelder calculate the environmental impact of a design?
Interviewee:
It depends on the client's request. We look at which products must be used and how much freedom we have in selecting these products. Based on the requirements, a suitable material is chosen, and its MKI value is retrieved. We then assess whether it is possible to lower this MKI value. Clients often impose extensive material requirements, quickly narrowing the choice to specific materials with corresponding MKI values. We weigh costs, quality, lifespan, and MKI. For example, a material with a low MKI but short lifespan would need frequent replacement, increasing the overall MKI.

Spaan, Hugo:
How can different options be compared?
Interviewee:

We have an LCA (Life Cycle Assessment) for all our materials. Using a tool, we can determine the MKI value for any design. Internally, we use an LCA, while externally, we communicate via an EPD (Environmental Product Declaration) to avoid sharing confidential business information. LCA data serves as input for project calculations. The set of calculation rules the LCA must adhere to is documented in the PCR-Asphalt, ensuring products are comparable.

Spaan, Hugo:
How is environmental impact communicated to stakeholders?
Interviewee:
Often, clients provide designs with specified requirements, including environmental loads (MKI). Sometimes, contractors can reduce the MKI value and receive a discount on their bid price. It then becomes a task to analyse which materials can achieve the lowest MKI at acceptable costs.

Spaan, Hugo:
How can you make the environmental impact visible to a client when no starting MKI value or reference exists?
Interviewee:
This is challenging. Usually, a ceiling is set. Often, material quantities are not specified, and everyone includes as little as possible in their calculations to achieve the lowest MKI value. Without a reference or framework, it is impossible to communicate environmental impact clearly to a client. Nowadays, industry reference values have been established. It is also essential to define calculation rules, so everyone calculates values the same way, making them directly comparable.

Spaan, Hugo:
How can you communicate the environmental impact of design choices to a less technically inclined client?
Interviewee:
This can indeed be difficult. Industry reference values are often used for benchmarking designs, showing that a product has a lower environmental impact than the average. You can then express this in percentages. Tools could play a role here, allowing clients to input their designs while we, as contractors, adapt the design and demonstrate how and to what extent the environmental impact can be reduced.

Spaan, Hugo:
What innovations will have the greatest impact on increasing circular construction in the future?
Interviewee:
Better separation of materials and sending them to resource depots instead of individual collection points. Collaboration and sharing materials, which can be bought from each other, will strengthen circularity. Contractors should establish resource hubs to assess and trade materials for reuse. Contractors are important stakeholders. To bridge the gap between availability and reuse, these depots are crucial. However, storing materials is only worthwhile if it is uncertain whether they will be fully recycled or treated as waste. In the case of asphalt, more goes out than comes in, so availability is not a concern.

Spaan, Hugo:
What tools are currently being used?
Interviewee:

AutoCAD, Civil 3D.

Spaan, Hugo:
What do you consider the most important functionalities for the tool being developed?
Interviewee:
The most important aspects are knowing how much material is available, its quality, costs (including retrieval and transport), and feasibility for reuse.

Spaan, Hugo:
At what stage in the design phase would the tool be most useful?
Interviewee:
During the tender phase, you need an idea of material availability, as this is when circularity commitments are made. It does not have to be fully detailed at that point, but it should become more concrete in the preparation phase. If I had to choose, the tool would be most useful when determining quantities. After quantities are established, a check can be performed to see how much reusable material can be applied.

Spaan, Hugo:
To what extent may the tool deviate from requirements to achieve results?
Interviewee:
It depends on the element and material. For example, paving stones need uniform dimensions for machine laying, but colours could vary. Different aspects may have varying tolerances. However, many material requirements are specified in a Program of Requirements (PoR). Clients with limited knowledge are difficult to convince to deviate from these requirements because they do not know what to expect. More knowledgeable clients may allow deviations because they understand the implications. With such clients, you can have a sustainability discussion, explaining how deviating by a certain amount can enable a percentage of materials to be reused. Maintenance costs are also an important factor for clients, alongside aesthetics—people expect new, clean tiles for a new sidewalk, not ones with visible wear.

Spaan, Hugo:
Can the described tool be applied directly to the current design process?
Interviewee:
I do not see why it could not. If tools like CircuTool can be used, your tool should also work. There might be feedback from procurement or preparation teams, but that is more relevant in later stages.

Spaan, Hugo:
What types of validation should the tool provide for designers to take responsibility for its use?
Interviewee:
The tool should clearly show the steps taken and the results based on input, offering a 1-2-3 scoring system for easy comparison. This way, designers can verify that the tool selected the best option. The tool could also be independently evaluated to ensure consistent results for given inputs, proving reliability.

A3: Interview Van Gelder 3

Spaan, Hugo:
What is your current role at Van Gelder, and what do your daily activities entail?
Interviewee:
I am ***, 47 years old, and have been working at Van Gelder for 10 years. Before that, I worked at BAM for 8 years. For the last few months, I have mostly worked as a design leader, primarily on integrated projects with UAV-GC contracts. Over the past two years, I have focused on Region East, managing smaller projects with shorter lead times. Recently, I have worked less as a design leader and more on tenders. Since last October, I have been working on process harmonization within Van Gelder. This involves aligning core, support, and strategic processes. As an interface manager, I manage dependencies within these different processes. Additionally, I evaluate current design processes, how they currently function, and how we can adapt our business management system and new system accordingly. As I mentioned, I work for Region East within the Infra division. My daily tasks involve directing road designers and specialists such as water management engineers, geotechnical consultants, and pavement specialists. Projects can include highway maintenance or constructing a cycling viaduct. Our clients include Rijkswaterstaat, the province, and municipalities.

Spaan, Hugo:
To what extent does circularity feature in your daily activities?
Interviewee:
Not daily, I would say. I deal with it more reactively. Often, sustainability is mentioned in a tender, requiring us to calculate CO2 emissions or provide a sustainability plan for the tender, such as emissions during construction or material choices. We comply with what is required rather than proactively exploring how to build sustainably or circularly beyond the stated requirements.

Spaan, Hugo:
Can you describe the concept of circularity?
Interviewee:
I would describe it as incorporating materials into a project and ensuring that these materials can continue to be used.

Spaan, Hugo:
Are there specific goals or guidelines to achieve a certain degree of circularity in projects?
Interviewee:
There are strategies, such as steps to be taken over a timeline, but I personally would not know where to find them exactly.

Spaan, Hugo:
What types of materials and elements are most suitable for direct reuse?
Interviewee:
The first thing that comes to mind is paving elements like concrete pavers. Another example is when I worked in a construction team on a town square project. We assessed the existing situation—benches, rubbish bins, etc.—to determine if they were good enough to reuse or, even better, retain in the project.

Spaan, Hugo:

When conducting an inventory of the existing situation, what information do you, as a designer, need to decide whether to retain or reuse elements?

Interviewee:

We conduct a survey or use existing drawings or measurement files from the client. Based on this, we check whether the AutoCAD file is well-structured and extract all necessary data. We then create a list of the elements present. To assess whether an element is reusable, we often need to inspect the site how is it installed, how will it look after deconstruction, and whether it remains reusable. Determining reusability is based on visual assessments and not measured scientifically.

Spaan, Hugo:

What digital information would you like to receive about an existing situation to make field research unnecessary?

Interviewee:

Interesting question. It varies by project. For asphalt, you need to know if it contains tar, so product composition is important. For materials like stones, the visual aspect plays a major role. Additionally, you want to know material properties to determine whether they can remain in place or be reused for another application. For example, the thickness of a rubble foundation determines if it is suitable for the new design.

Spaan, Hugo:

Is there a clear distinction between reuse and recycling?

Interviewee:

We often work according to the client's guidelines and requirements. A plan is usually already in place, so we focus on the technical aspects and requirements rather than emphasizing reuse and recycling unless specifically requested by the client. To enable more material reuse, you could set up "hubs" and collaborate with other contractors and the government, which often acts as both client and asset owner.

Spaan, Hugo:

How can a contractor gain more insight into where and when materials will be available to make strategic reuse decisions?

Interviewee:

I think of a system like what is used for traffic management. This system schedules upcoming projects and ensures no overlapping road closures. A comparable system could work for a material hub where projects are registered, and materials are listed with their availability date.

Spaan, Hugo:

How does Van Gelder collect and manage material data (e.g., physical properties, lifespan)?

Interviewee:

We do not collect this data internally. Sometimes we request it from suppliers. Certificates are often requested upon delivery, which include product details. I do not immediately see the added value of collecting all this data unless it is stored in a management system accessible to everyone. For Rijkswaterstaat, for instance, we must deliver drawings in a standardized format, which are then integrated into a GIS system where information can be retrieved. However, clients do not yet request something like a material passport.

Spaan, Hugo:

Are environmental impact calculations currently performed?

Interviewee:
Yes, we calculate the Environmental Cost Indicator (MKI) value when requested. This may also include NOX or CO2 emissions. We have a database with MKI values for commonly used materials, sourced from suppliers. Although cost is often the main driver for decisions, the MKI value could be integrated into decision-making, like a trade-off matrix for costs. Calculating MKI values repeatedly during the design process is time-intensive, so it would be better to automate this.

Spaan, Hugo:
Are there matrices besides the MKI to express and evaluate circularity and sustainability?
Interviewee:
I have the most experience with the MKI, but that depends on education and what I know or do not know. It also depends on what you want to assess. The MKI itself is a collection of metrics. If you know what you want to evaluate, you can determine how to express it. You could also think of a label to assign to a project. The difficulty with self-assigning such labels is that they lack a reference point and therefore no direct value. Even the MKI requires a reference point. Sometimes a reference value is provided, but if not, contractors must create a basic calculation to compare materials and equipment. Comparisons always require a baseline or standard. It is essential to express the outcomes of decisions. Especially when decisions come with higher costs, you need to prove to the client what benefits it offers so they can make informed choices about the investment.

Spaan, Hugo:
What innovations could significantly impact circularity throughout the design process?
Interviewee:
I like collaborating with experts who explain why certain decisions are optimal, as the rationale is crucial. Additionally, you want to make design process decisions more transparent and accessible. This allows designers to make choices more easily. For example, you could incorporate a live indicator in design software that reflects circularity or sustainability when specific decisions are made.

Spaan, Hugo:
Could materials be selected from a database alongside your design instead of adding material properties later based on supplier data?
Interviewee:
Yes, I can envision that. It is important that everyone works with the same data, from the same database. I see it as a sort of “comparison tool,” where materials can be compared on cost and environmental values. For example, when selecting curb stones, you could compare reused and new ones. This also raises awareness and gives people a better understanding.

Spaan, Hugo:
What challenges do you foresee when combining reusable and new materials in a project?
Interviewee:
The first thing that comes to mind is aesthetic quality, followed by other properties. For example, one stone may be new, while another has been in use for 15 years, but both must fulfill the same function and lifecycle. Key factors include visual aspects, structural properties, and manufacturability—whether the different types can be seamlessly integrated. Additionally, the client must prioritize sustainability. They could campaign for sustainable projects.

Spaan, Hugo:
What functionalities should the system/tool I presented to you have to optimize circularity in design?
Interviewee:
The tool should clearly identify what is needed in a design. It is important that the current design software workflow does not change much. The tool should function alongside the existing workflow without placing heavy demands on the designer. Additionally, the tool should offer some flexibility. For larger projects, you want to know what materials are available so you can explore how to use them.

Spaan, Hugo:
At what stage in the design phase would the tool be most applicable?
Interviewee:
The tool is used for making decisions. Decisions are made during the phases before the execution design. A circular design process may also require different considerations than traditional processes. For circular design, you might need material information much earlier. This means you would want this information during the preliminary design phase to make decisions for the definitive and execution designs.

Spaan, Hugo:
What forms of validation should the tool include to allow designers to take responsibility for their decisions?

Interviewee:
The first thing that comes to mind is certification or references. Additionally, you could include a manual explaining how to verify the tool's calculations. It is important to understand the assumptions behind the decisions. While I trust the tool can perform calculations, I would like to see the rationale behind those calculations.

A4: Interview Van Gelder 4

Spaan, Hugo:
What is your current role at Van Gelder, and what are your daily responsibilities?
Interviewee:
I am *** and have been working at Van Gelder for 10 years now. Before that, I worked at Heijmans for a year. I take part in asset management, maintenance contracts for Rijkswaterstaat, contract management, and project control. Currently, I am also working on information management and, in recent years, on setting up BIM processes.

Spaan, Hugo:
What are the current challenges in circularity within asset management?
Interviewee:
We primarily conduct repairs (extending lifespan) or replacements. This often results in materials being mixed, making them non-homogeneous. If you then want to recycle them, you must first separate all the materials, which is not always possible. For example, with asphalt, sometimes the material is rejected at the processing plant. Additionally, circularity is not yet a major part of our projects because it is often not specified in our contracts. This is also related to costs, as working more sustainably often involves higher expenses.

Spaan, Hugo:
I understand. But if you were to devise a strategy to execute circular projects, how would you approach it?
Interviewee:
You could propose circular, recycling, or biobased materials yourself and then clearly communicate the impact and costs to the client. The most important thing is to show the client what they will gain from it. As I mentioned, sustainable choices often cost more money, and since our clients are typically the national government or municipalities, the work is funded by taxpayers. The end users are the residents. If they find out that a project has cost significantly more, they will naturally want to know where the money went. Therefore, it is crucial to make this transparent, for example, by comparing CO2 emissions. The same applies to the reuse of materials. If residents expect a new sidewalk, but the tiles used are slightly discolored or damaged, you need to justify that decision well. Otherwise, people will complain, which could result in the sidewalk being replaced with new tiles anyway.

Spaan, Hugo:
How do you decide which materials can be used in a circular way?
Interviewee:
Primarily through our own knowledge and network. Additionally, we can explore the market to see if a product is available in a sustainable or circular variant. However, a recurring issue is that when you use "new" circular materials, clients often do not know their quality and therefore do not always accept them. We must be able to prove that they meet the required standards. Clients prefer to use new materials in a sort of pilot first. Certifications or independent inspections can help us prove the quality of specific materials.

Spaan, Hugo:
Earlier, you mentioned replacing or extending the lifespan of elements and objects. How do you assess whether a material has reached the end of its lifespan?

Interviewee:
It is important to discuss ontology here. If you look at the material level, we think of it as Lego bricks. What we manage is a model assembled from various Lego bricks. If, for example, a section of asphalt needs replacing, we remove it, but in doing so, we remove multiple types of "Lego bricks." So, we assess the entire construction part or asset, such as a bridge or a road segment. You can categorize this into three types: point objects, line objects, and surface objects. A point object can still be assessed one-to-one, a line object can sometimes be partially replaced, but with a surface object, you would not assess each Lego brick individually—you evaluate the entire surface and base your decision on that. This is always done through a physical on-site inspection.

Spaan, Hugo:
Is it possible to plan maintenance using data in management systems?
Interviewee:
This is quite difficult because there are many factors that cannot be captured in data. For example, if there were extreme weather conditions or if a loader has driven over the pavement, it may have subsided. According to the data, the pavement is far from reaching the end of its lifespan, but repairs are still needed. During an inspection, we always assess whether we can simply re-lay the same materials instead of replacing them. Furthermore, digital aspects are still lagging. Keeping digital records of what we have constructed is still done in separate documents and drawings. The design phase often has a lot of information, but after project completion, the actual as-built data is often lacking. This data is linked to the lifespan of the materials. Additionally, maintenance and repair work conducted during the asset's lifecycle is not well documented. This means that the quality of a material cannot be accurately traced due to a lack of proper data. Therefore, a physical assessment remains crucial.

Spaan, Hugo:
About your tasks in asset management, what type of data would you like to see about the objects you manage?
Interviewee:
That is a good question. I would like to know the location, material description, a map/overview of where everything is found, the year of installation, and a kind of logbook of all the work done during its lifecycle. Supplier information could also be useful, but it becomes less relevant as the years go by. Additionally, information such as dimensions and thicknesses would be important. Another key aspect is the technical lifespan, which helps estimate future maintenance needs and set aside budgets accordingly. This data should be structured at the same level as the design process—point, line, and surface objects. I am currently working on structuring all this information within BIM. We often have good designs, but they end up in storage, and inspections are recorded in separate documents. Ideally, everything should be linked, so that as-built data and maintenance history are integrated into the same BIM model. This would create a more structured workflow. I call this the "object tree." If BIM projects are professionally managed, this data can also be passed on to clients or asset owners, allowing them to manage their assets themselves. When we need to conduct work, we could then access this information and its history, making our work more efficient.

Spaan, Hugo:
What characteristics do objects need to be suitable for direct reuse?
Interviewee:

I think primarily about technical or expected lifespan, how long can an object last? Also, dimensional stability; if you are reinstalling something, it must keep its original shape. Aesthetic quality is also important. The final product should meet aesthetic expectations—not only for the client, who pays for a good-looking product, but also for employees, who take pride in their work.

Spaan, Hugo:
How can you convince a client to opt for reusable (less aesthetically perfect) materials?
Interviewee:
It is essential to make the results measurable. The client must be able to justify their choices internally, either through dashboards or public reporting. This could be expressed in numbers, such as sustainability metrics like CO2 footprints. Financial aspects also play a role, so costs should be clearly communicated. However, the coordination of reusable materials is often complex, making them more expensive than new materials. That is why it is crucial to clearly prove the environmental benefits when aesthetics is compromised, and costs are higher. CO2 and MKI (environmental cost indicator) are strong metrics that can be used to justify decisions. You need to show that it was a worthwhile investment.

Spaan, Hugo:
What are the main challenges in deconstruction, transportation, and storage of reusable materials?
Interviewee:
One major challenge is that materials are often glued together. Adhesives are used for a reason, but they make deconstruction difficult. Residual glue is impossible to remove. In such cases, you must rethink the assembly process, ensuring that materials stay securely fixed but can still be detached.

Spaan, Hugo:
Would you like all this information integrated into your management systems (BIM)?
Interviewee:
That would be extensive, but material passports are especially useful. A database with general object information and links to detailed libraries could be a good solution.

Spaan, Hugo:
Is a classification system currently used to categorize objects?
Interviewee:
We use the condition assessment standard NEN 2760. For asphalt, NEN 2660 is also commonly used.

Spaan, Hugo:
I would now like to ask a question about environmental impact calculations. What are the benefits of making these calculations, even when a client does not specifically request them?
Interviewee:
Now, clients focus on costs. However, if we can prove that our work results in a lower environmental impact, it can open doors and free up more funding from the client, which helps us as well. This means we could take on more projects. It would also be useful for us to gain more insight into the environmental impact of the choices we make, for example, from the supplier level. This would allow us to make better-informed decisions and make this

transparent for our clients, such as through CO_2 reporting. Additionally, a database that has CO_2 data for materials we want to use would be extremely helpful.

Spaan, Hugo:
What innovations will contribute to the transition to a circular economy in both the short and long term?
Interviewee:
In the long term, I think it will be crucial to properly document the supply chain and information about objects, ensuring that data is not stored in separate documents but is systematically managed. However, this will take time. In the short term, I see the potential for tools that help calculate environmental impact. For example, a tool that quickly compares impact differences and allows us to prove them to clients, which could help secure project budgets.

Spaan, Hugo:
Now that I have explained the working method of my database and tool, do you see any challenges I should be aware of?
Interviewee:
I do have a question or remark. Suppose you need 1,000 m² of paving stones, and you collect 300 m² from one hub, 200 m² from another, and 500 m² from a third hub. Initially, you have all the information about these stones, but once they are mixed, you are also mixing the information. This means that different qualities, residual lifespans, etc., are combined. If you want to reuse them again in the future, it becomes difficult to decide their exact quality based on data because they are no longer distinct materials. Keeping these material streams separate will be a challenge. While this might not be an issue for point objects, it can be particularly problematic for linear objects.
Another important consideration is the standard unit of measurement for a material. Paving stones, for example, are typically measured in square meters, but some materials are measured in kilograms or cubic meters. If you are processing different materials within the same database, you may need to document values differently or decide how best to standardize calculations.

A5: Interview TAUW

Spaan, Hugo:
What are your current roles at Tauw and what are your daily activities?

Interviewees:
I have a background in biobased science, where I did a major track with a focus on circular economy. I started at Tauw with an internship where I focused on applying circular design principles in the GWW sector. I now work as a sustainability and circularity advisor. My role is process-oriented: I put sustainability on the agenda within projects, set ambitions, and apply tools such as the Omgevingswijzer.

I have been working at Tauw for a longer time and within the design office I focus on stimulating sustainability in a broader sense. This includes not only circularity but also ecology and climate adaptation. We participate in a sustainability ambassadors' group where we aim to increase awareness among colleagues and make sustainability tangible within the design processes.

Spaan, Hugo:
What role does circularity currently play within Tauw and how is it applied?

Interviewees:
Circularity is still strongly determined by the people involved in the project. If, for example, a project leader or client is consciously working on circularity, then it can also play a major role in the design. But we also often see that if that awareness is not there, circularity tends to fade into the background. That is why we try to put a lot of effort into increasing awareness within Tauw, which is also the purpose of the ambassadors' network. The ambition is to structurally integrate circular design into the process.

Spaan, Hugo:
Have you agreed on any specific goals together?

Interviewees:
Yes, we have agreed within Tauw that by the end of 2025, at least 50% of all projects should be set up as sustainable projects. We also try to encourage circular design principles by already including them as provisional items in the offer phase. That way they can be discussed right from the start.

Spaan, Hugo:
In your view, what is needed to properly integrate reuse into the design process? What would such a process ideally look like?

Interviewees:
To reuse properly, you must first make clear what is available. This can be done by performing an early survey on site. If you know what is available, the design can then be adjusted accordingly. A good example is the ***, in that project we were able to reuse 80–90% of the released materials on site. A footpath, for example, was designed based on available materials. Light design adjustments were also made to ensure there were enough materials for the profiles. These choices do require flexibility in the design and good coordination with the client. Ideally, you want to do all this already in the sketch design phase. At that point there is still more freedom, and the materialization and design can be adjusted to what might be available.

Spaan, Hugo:
Which elements do you think are the most promising for direct reuse?

Interviewees:
I think elements such as paving stones, concrete tiles, or other standard street furniture. The advantage of these elements is that they are often easy to dismantle and are not glued. They are also not technically complex. I think other elements such as concrete kerbs can also be reused well. They just need to be removable in a neat way. The advantage in the GWW sector is that there are fewer composite materials than in the building sector.

Spaan, Hugo:
Besides disassembly, what else determines whether an element is suitable for reuse?

Interviewees:
The visual quality plays a role, for example how good a material still looks. Timelessness also plays a part. A dated piece of street furniture is not something you would quickly use again in a modern design. The more beautiful and neutral the element is, the better its chances of being reused.

Spaan, Hugo:
Do you experience any specific barriers in practice when applying reuse?

Interviewees:
The biggest barrier is the internal awareness among project leaders and clients. If there is no specific steering on circularity or no motivation for it, it often will not be included. Now it is still too optional: if it is not explicitly requested, it usually will not be applied. It often happens that clients themselves are not aware of their own municipal sustainability goals, such as the ambition to be 50% circular by 2030.

Spaan, Hugo:
So, what do you do to ensure this happens more?

Interviewees:
We usually start a conversation to plant a ‘seed.’ If clients, then become enthusiastic and see the benefits—both financially and from a policy perspective—then much more becomes possible.

Spaan, Hugo:
How is circularity discussed with clients?

Interviewees:
We actively try to bring circularity to the table already during the offer phase. By including it as a provisional item, it is explicitly named, and space is created to discuss the topic, even if it was not mentioned in the tender. In a conversation with the client, we then explain that circular design does not necessarily have to be more expensive. In fact, we have saved costs in some projects through reuse. We also point out the societal value and policy goals that municipalities need to meet.

Spaan, Hugo:
What kind of information or data can you present to a client to convince them to make more sustainable choices and show that this can be beneficial for them?

Interviewees:
You can provide information about the savings it delivers. This is often done via the MKI (Environmental Cost Indicator). We then show how much an ‘environmentally friendly design’ can reduce the MKI. In addition, there are also subsidies available such as the SPUK scheme from the RVO, which we can point out.

Spaan, Hugo:
One of the criticisms of circular design is that it is more expensive. How do you deal with that?

Interviewees:
Costs are often a point of discussion. Yet there are several examples where circular design turned out to be cheaper. In a project in Friesland, exclusively reused materials were used, without incurring extra costs. Of course, design costs can be slightly higher, or there might be more coordination time, but these are often offset by major savings in materials and transport. We also prefer to look at the total cost of ownership or life cycle costs. From an environmental performance point of view, the MKI is becoming increasingly important, and reuse often scores well there too. The key is that clients look at the full picture, not just the initial investment costs.

Spaan, Hugo:
What do you think is needed to apply circularity more broadly and structurally?

Interviewees:
It all starts with awareness and repetition. Not every planted seed leads to action immediately, but with enough repetition, movement starts to happen within an organization. Tools and practical guides are valuable, especially for designers who want to quickly know what they can apply. Standardization is also important—for example, of material passports and process steps. Including circularity as a standard item in every offer can already be a big step. That way, it is at least addressed in every project, regardless of the client.

Spaan, Hugo:
Municipalities are often the client, but citizens are the end users of public space. How do you deal with their expectations?

Interviewees:
Thats an interesting challenge. Citizens are still rarely involved in circular design decisions. Resistance often arises when reused materials differ from aesthetic expectations. That is why it is essential to communicate clearly about the choice for reuse—such as explaining why a concrete paving stone is being reused and how these fits into broader sustainability goals. In participatory processes, you could present information about material origin, environmental benefit, and lifespan. In city centres or districts with higher aesthetic demands, the trade-off will be different than in outer neighbourhoods. Sometimes vandalism sensitivity also plays a role, such as with benches or bus shelters. So, there is no one-size-fits-all approach; participation and communication must be tailored to the project and location.

Spaan, Hugo:
In my research I focus on material data and databases. How important do you consider data management and digital support for reuse?

Interviewees:
Data management is essential. Without insight into what is available, reuse becomes impossible. There are now initiatives such as municipal depots or the circular depot in Utrecht, where materials are stored before new projects begin. One challenge is selecting what to store and what not. Space and time are limited. You can compare it a bit to a supermarket: you need to know what is in stock, what sells, and what is just gathering dust. Planning is crucial. It is important to be able to match supply and demand. A database must also be universally accessible to work effectively. We believe this should be organized regionally or per sector. That way, multiple projects can use it. Technical and aesthetic use characteristics of an element should also be recorded—this could be done well via a material passport.

Spaan, Hugo:
What makes an element suitable for inclusion in a depot or reuse database?

Interviewees:
The most important characteristics are timeless design, visual quality, disassembly (so not glued), ease of disassembly, and a high likelihood of reuse within a short timeframe. Sometimes materials even improve over time—paving stones are a good example. But for items like street furniture, aesthetics plays an important role. It may be technically fine to reuse, but still not meet the desired look for the neighbourhood. So, both technical and spatial quality control are needed.

Spaan, Hugo:
If you were to design based on existing elements, what are the biggest challenges?

Interviewees:
One of the biggest challenges is that many designs are already largely fixed before there is insight into what materials are available. Ideally, the design process should start with an inventory of available materials, and then the design would be based on that. In practice, this is difficult because many clients already come with a predefined plan. In addition, many projects lack an overview of what materials are becoming available elsewhere. There is a need for better asset management and collaboration between projects.

Spaan, Hugo:
What is needed to assess the quality of reused elements?

Interviewees:
That depends a lot on the type of element. For some objects, a visual inspection is enough—for example, paving stones or concrete tiles. For other objects, like lamp posts or bridge parts, you need technical data such as structural properties, remaining lifespan, and degree of corrosion. This information should be recorded in material passports as much as possible, preferably during the element's first use. But what is even more important is that this data remains accessible—20 or 30 years from now—when the element is reused. Storing that information is a major challenge. Even more difficult is ensuring that the data is still available in the long term.

Spaan, Hugo:
What is your vision for the future of circular design?

Interviewees:
We believe circularity is still too voluntary at this stage. In the future, it should become much more the standard. We expect that in 10 to 20 years, designing with existing elements will be just as normal as designing with new materials. To get there, we need to keep investing effort, have conversations, provide inspiration, and show that it can be done. It comes down to three things: awareness, availability of data, and collaboration in the chain.

Appendix B – Material Passport and reuse potential

B1: Example MP Van Gelder

van gelder **Voorbeeld materiaalpaspoort**

	Asfalt (Civiel)
Naam	26770250 AC 16 Bin 30/45 ECO 70% PR DAT-7
Type materiaal	Asfalt
Kleur (onnodig?)	Zwart
Gewicht	2375 kg/m3
Afmetingen (laagdikte)	60 mm
Eigenschappen	Sterkte (verkeersklasse): AC 16 bin TL-A, TL-B, TL-C, TL-IB
Samenstelling	Rivierzand 0/2, ECO-granulaat 0/4, Bestone 4/8, Wigras 40K, …, etc.
Percentage secundair materiaal	98%
Milieutechnisch	(minder relevant voor asfalt, wel voor andere materialen)
MKI waarde (A1 – A3)	€2,108
Ontwerplevensduur (jaar van aanleg beter)	20 jaar - 2024
Toepassing eindelevensduur (hergebruik/recycling)	100% recycling
Fabrikant & Fabricagedatum	APMN -
Product Informatie Blad	Mengseldocument (CE-blad, DoP en Verkort Verslag)
Verwerkingsinstructie hergebruik/recycling	Geschikt voor warm hergebruik

B2: Reuse potential multicriteria analysis

1. Doel en werkwijze

Doel:

Dit Excel document helpt bij het beoordelen van materialen en elementen op herbruikbaarheid binnen infraprojecten van Van Gelder. Door verschillende kenmerken van materialen te scoren en te wegen, kan worden bepaald of een materiaal geschikt is voor hergebruik.

Werkwijze:

1. Vul de materiaalgegevens in op het tabblad 'beoordelingsformulier'
2. Beoordeel het materiaal op 7 criteria met een score van 1 tot 5, zie uileg hieronder, en vu
3. Kies per criterium een weging om aan te geven hoe belangrijk dit criterium is voor het hergebruik van de specifieke toepassing van het materiaal.
4. Excel berekent automatisch een gewogen hergebruikscore
5. Analyseer het resultaat: materialen met een hoge score zijn geschikt voor hergebruik, materialen met een lage score niet.

2. Uitleg van de 7 beoordelingscriteria

#	Criterium	Uitleg
1	Duurzaamheid & levensduur	Hoe lang gaat het materiaal mee en blijft het bruikbaar na meerdere hergebruikcycli?
2	Demontagegemak	Kan het material zonder schade worden verwijderd en opnieuw worden gebruikt?
3	Standaardisatie	Heeft het materiaal een gangbare maatvoering en aansluiting, waardoor hergebruik eenvoudiger is?
4	Milieu-impact	Hoeveel CO_2 en andere emissies worden bespaard door dit materiaal te hergebruiken in plaats van nieuw
5	Beschikbaarheid & hoeveelheid	Hoe vaak komt dit materiaal beschikbaar en is er voldoende voorraad?
6	Opslag & trasport	Hoe makkelijk is het materiaal op te slaan en te transporteren?

3. Uitleg scoringschalen per criterium

Elk criterium in het beoordelingsformulier wordt gescoord van 1 tot 5, waarbij 1 de laagste geschiktheid voor hergerbuik betekent en 5 de hoogste. De onderstaande tabellen geven een duidelijke uitleg wat elke score betekend per criterium.

3.1 Duurzaamheid & levensduur

Score	Uitleg
1	Materiaal is breekbaar, verslechtert snel of is niet ontworpen voor hergebruik. Kan falen onder normale omstandigheden.
2	Redelijk duurzaam, maar zal naar verwachting na één hergebruikscyclus degraderen.
3	Matig duurzaam; kan 2-3 keer hergebruikt worden met minimaal prestatieverlies.
4	Hoge duurzaamheid; kan meerdere keren (3+ cycli) hergebruikt worden zonder grote problemen.
5	Zeer duurzaam; verwacht wordt dat het materiaal vele levenscycli meegaat zonder degradatie.

3.2 Demontagegemak

Score	Uitleg
1	Volledig geïntegreerd in de constructie; verwijdering veroorzaakt aanzienlijke schade.
2	Moeilijk te verwijderen; vereist zagen, breken of arbeidsintensieve demontage.
3	Redelijk eenvoudig te verwijderen, maar er wordt enige schade verwacht.
4	Ontworpen voor demontage; kan worden verwijderd met standaard gereedschap en minimale inspanning.
5	Volledig modulair of geprefabriceerd; kan snel worden verwijderd zonder schade.

3.3 Standaardisatie

Score	Uitleg
1	Uniek of op maat gemaakt element; moeilijk te matchen met andere projecten.
2	Gedeeltelijk gestandaardiseerd, maar vereist aanpassingen voor hergebruik.
3	Voldoet aan industriestandaarden, maar kan enkele aanpassingen nodig hebben.
4	Veelgebruikte standaardmaat, eenvoudig te integreren in nieuwe projecten.
5	Volledig gestandaardiseerd; past naadloos in meerdere projecten zonder aanpassing.

3.4 Milieu-impact

Score	Uitleg
1	Geen significante milieuvoordelen ten opzichte van nieuw materiaal.
2	Enige milieuwinst, maar hoog energieverbruik of emissies tijdens hergebruik.
3	Matige impactreductie; hergebruik heeft een duidelijk voordeel ten opzichte van nieuwproductie.
4	Aanzienlijke milieuwinst, inclusief vermindering van ingebedde koolstofuitstoot.
5	Grote milieubesparing; materialen met een hoge impact (bijv. beton, staal) die grote CO_2-emissies voorkomen door hergebruik.

3.5 Beschikbaarheid & hoeveelheid

Score	Uitleg
1	Zeer zeldzaam; moeilijk om voldoende hergebruikte materialen te verkrijgen.
2	Soms beschikbaar, maar de aanvoer is inconsistent.
3	Matige beschikbaarheid, soms op voorraad, maar niet altijd.
4	Regelmatig beschikbaar in opslagplaatsen en sloopprojecten.
5	Altijd in grote hoeveelheden beschikbaar; eenvoudig te verkrijgen voor meerdere projecten.

3.6 Transport & opslag

Score	Uitleg
1	Zeer moeilijk op te slaan of te vervoeren (bijv. zwaar, breekbaar, speciale behandeling vereist).
2	Logistieke uitdagingen, maar mogelijk met extra inspanning.
3	Kan worden opgeslagen en vervoerd, maar vereist enige aanpassingen.
4	Relatief eenvoudig op te slaan en te vervoeren met standaard logistiek.
5	Zeer eenvoudig op te slaan en te vervoeren; modulaire of stapelbare elementen.

4. Uitleg wegingsschaal

Naast de score moet je aangeven hoe belangrijk elk criterium is voor het hergebruik van dit specifieke materiaal met onderstaande wegingen:

Weging	Betekenis
0.5	Niet belangrijk voor deze toepassing.
0.75	Minder belangrijk, maar speelt een rol.
1	Neutraal: niet belangrijk, maar ook niet onbelangrijk.
1.25	Belangrijk voor de toepassing van dit materiaal.
1.5	Zeer belangrijk, bepalend voor de keuze om dit materiaal te hergebruiken.

B3: Results of reuse potential multicriteria analysis

Invultabel voor toetsing
Materiaal:
beton
Element:
graskei
Toepassing:
Bermverharding, open verharding t.b.v. infiltratie en/of vergroening

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	2	1	2
Standaardisatie	2	1	2
Milieu-impact	5	1	5
Beschikbaarheid	1	1	1
Transport & opslag	3	1	3
TOTAAL	15		15

Gewogen score			
Score	15	**Resultaat**	Niet geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
beton
Element:
trottoirtegel 30x30x(4,5/6)
Toepassing:
Elementenverharding, toegepast in trottoirs

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	3	1	3
Demontagegemak	4	1	4
Standaardisatie	4	1	4
Milieu-impact	5	1	5
Beschikbaarheid	4	1	4
Transport & opslag	3	1	3
TOTAAL	23		23

Gewogen score			
Score	23	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Beton
Element:
Betonstraatsteen (BSS) Betonklinkerkei (BKK) (keiformaat / dikformaat / waalformaat / enz.)
Toepassing:
Elementenverharding, toegepast in rijbaan en parkeerterrein

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	4	1	4
Milieu-impact	5	1	5
Beschikbaarheid	3	1	3
Transport & opslag	3	1	3
TOTAAL	20		20

Gewogen score			
Score	20	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Beton
Element:
Opsluitband recht
Toepassing:
Toegepast als opsluiting van straatwerk

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	3	1	3
Milieu-impact	5	1	5
Beschikbaarheid	4	1	4
Transport & opslag	4	1	4
TOTAAL	21		21

Gewogen score			
Score	21	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Beton
Element:
Opsluitband bochtstraat
Toepassing:
Toegepast als opsluiting van straatwerk

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	2	1	2
Milieu-impact	5	1	5
Beschikbaarheid	3	1	3
Transport & opslag	3	1	3
TOTAAL	18		18

Gewogen score			
Score	18	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Beton
Element:
trottoirband
Toepassing:
Toegepast als opsluiting van straatwerk

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	4	1	4
Milieu-impact	5	1	5
Beschikbaarheid	4	1	4
Transport & opslag	4	1	4
TOTAAL	22		22

Gewogen score			
Score	22	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Beton
Element:
trottoirband bochstraal
Toepassing:
Toegepast als opsluiting van straatwerk

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	2	1	2
Milieu-impact	5	1	5
Beschikbaarheid	3	1	3
Transport & opslag	3	1	3
TOTAAL	18		18

Gewogen score			
Score	18	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Gebakken klei
Element:
Klinkerkei (KK) (keiformaat / dikformaat / waalformaat / enz.)
Toepassing:

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1	4
Demontagegemak	2	1	2
Standaardisatie	4	1	4
Milieu-impact	4	1	4
Beschikbaarheid	2	1	2
Transport & opslag	4	1	4
TOTAAL	20		20

Gewogen score			
Score	20	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Metaal, hout,
Element:
Installatie slagboom
Toepassing:
Regelt verkeersdoorstroming bij overwegen t.b.v. het treinverkeer

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	3	1.25	3.75
Demontagegemak	4	1	4
Standaardisatie	2	1	2
Milieu-impact	3	1	3
Beschikbaarheid	2	1.25	2.5
Transport & opslag	3	1	3
TOTAAL	17		18.25

Gewogen score			
Score	18.25	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Steenslag
Element:
Steenslag/ballast
Toepassing:
Zorgt voor stabiliteit van het spoor

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1.25	2.5
Demontagegemak	5	1	5
Standaardisatie	4	1	4
Milieu-impact	4	1.25	5
Beschikbaarheid	3	1	3
Transport & opslag	3	1	3
TOTAAL	21		22.5

Gewogen score			
Score	22.5	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Metaal met beton/hout
Element:
Wissel
Toepassing:
Zorgt voor geleiden van de trein van bijv. het linker naar het rechterspoor

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	3	1	3
Demontagegemak	2	1	2
Standaardisatie	2	1.25	2.5
Milieu-impact	3	1.25	3.75
Beschikbaarheid	2	1	2
Transport & opslag	3	1	3
TOTAAL	15		16.25

Gewogen score			
Score	16.25	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Kunststof en metaal (koper, aluminium)
Element:
Grondkabel
Toepassing:
Zorgt voor o.a. het geleiden van signalen en stroom

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	1	2
Demontagegemak	3	1	3
Standaardisatie	4	0.75	3
Milieu-impact	4	1.25	5
Beschikbaarheid	2	0.5	1
Transport & opslag	4	0.75	3
TOTAAL	19		17

Gewogen score			
Score	17	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Staal
Element:
Fietsnietjes, afzetbalken, kiwisluis, slagbomen
Toepassing:
Het stallen en geleiden van weggebruikers

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	3	1	3
Demontagegemak	3	0.75	2.25
Standaardisatie	4	1	4
Milieu-impact	4	1	4
Beschikbaarheid	1	1.5	1.5
Transport & opslag	3	1	3
TOTAAL	18		17.75

Gewogen score			
Score	17.75	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Afzet/verkeerspalen
Element:
Kunststof
Toepassing:
Illegaal inrijden/ gebruik voorkomen

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1	4
Demontagegemak	3	1	3
Standaardisatie	4	1	4
Milieu-impact	2	1	2
Beschikbaarheid	1	1.5	1.5
Transport & opslag	5	1	5
TOTAAL	19		19.5

Gewogen score			
Score	19.5	**Resultaat**	Herbruikbaar, maar met beperkingen

Invultabel voor toetsing
Materiaal:
Aluminium bord met sticker
Element:
Verkeersbord
Toepassing:
Het informeren en geleiden van de weggebruiker

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1	4
Demontagegemak	4	1	4
Standaardisatie	5	1.5	7.5
Milieu-impact	5	1	5
Beschikbaarheid	2	1.5	3
Transport & opslag	5	0.5	2.5
TOTAAL	25		26

Gewogen score			
Score	26	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Grond
Element:
Zand voor ophoging en zand voor zandbed
Toepassing:
Inzet in ophogingen bij infrawerken (zand voor ophoging) en zandbed in infrawerken. Alterna

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1.5	5.5
Demontagegemak	3	0.5	3.5
Standaardisatie	4	1	5
Milieu-impact	5	1	6
Beschikbaarheid	5	0.75	5.75
Transport & opslag	2	1	3
TOTAAL	23		28.75

Gewogen score			
Score	28.75	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Grond
Element:
Klei met een erosieklassen
Toepassing:
Hoogwaardige kleigrond geschikt voor afwerking waterkerende dijken (dijkenklei). Kan met

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	5	1.5	6.5
Demontagegemak	4	0.75	4.75
Standaardisatie	4	1.25	5.25
Milieu-impact	5	1	6
Beschikbaarheid	2	0.75	2.75
Transport & opslag	4	0.75	4.75
TOTAAL	24		30

Gewogen score			
Score	30	**Resultaat**	Zeer geschikt voor hergebruik

Invultabel voor toetsing
Materiaal:
Grond
Element:
Grond
Toepassing:
Hergebruik laagwaardige grond zonder civieltechnisch gunstige eigenschappen in bijvoorbe

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1.25	5.25
Demontagegemak	2	0.5	2.5
Standaardisatie	4	0.5	4.5
Milieu-impact	4	1.25	5.25
Beschikbaarheid	5	0.5	5.5
Transport & opslag	4	0.5	4.5
TOTAAL	23		27.5

Gewogen score			
Score	27.5	**Resultaat**	Zeer geschikt voor hergebruik

*The following criteria assessment are not assessed for direct reuse but for recycling

Invultabel voor toetsing
Materiaal:
Asfalt
Element:
Asfaltverharding
Toepassing:
Asfalt dat wordt bereden door verkeer

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	4	1.5	6
Demontagegemak	2	0.5	1
Standaardisatie	4	1	4
Milieu-impact	4	1.25	5
Beschikbaarheid	5	1.5	7.5
Transport & opslag	4	1	4
TOTAAL	23		27.5

Gewogen score			
Score	27.5	**Resultaat**	Zeer geschikt voor recycling

Invultabel voor toetsing
Materiaal:
Menggranulaat
Element:
Funderingsmateriaal
Toepassing:
Asfalt dat wordt bereden door verkeer

Toetsing per criterium			
Criterium	**Score (1-5)**	**Weging (0.5-1.5)**	**Gewogen score**
Duurzaamheid	2	0.75	1.5
Demontagegemak	4	0.5	2
Standaardisatie	4	1	4
Milieu-impact	4	1.5	6
Beschikbaarheid	4	1.5	6
Transport & opslag	4	1.25	5
TOTAAL	22		24.5

Gewogen score			
Score	24.5	**Resultaat**	Zeer geschikt voor recycling

B4: GWP and MKI values for reference elements

Projectnaam	Mkl- en CO2 data uit MKI
Versienummer	4.1
KennCalc versie	KennCalc 4.1.0
MKI Bibliotheek	nl19-jan-24
Export datum gebouw	nl19-jan-24
Export datum project	nl19-jan-24
Gebruikte set	Basis ontwikkeling basis bibliotheek

| Project overzicht | | | | | | | | Product overzicht | | | | | | | |

Appendix C – SQL query

```
WITH RECURSIVE version_history AS (
  SELECT
    e.Element_ID,
    e.Name AS Element_Name,
    e.Status,
    e.Created_At,
    e.Updated_At,
    e.Previous_Version_id,
    dp.Name AS DonorProject_Name,
    dp.City AS DonorProject_City,
    sl.Name AS StorageLocation_Name,
    sl.City AS StorageLocation_City,
    eg.Length,
    eg.Width,
    eg.Height,
    eg.Weight
  FROM
    element e
  LEFT JOIN
    donor_project dp ON e.DonorProject_id = dp.Project_ID
  LEFT JOIN
    storage_location sl ON e.StorageLocation_id = sl.Location_ID
  LEFT JOIN
    element_geometry eg ON e.Element_ID = eg.Element_id
  WHERE
    e.Element_ID = '88e0027b7abf4f04a4c4a94ff0539be6'

  UNION ALL

  SELECT
    e.Element_ID,
    e.Name AS Element_Name,
    e.Status,
    e.Created_At,
    e.Updated_At,
    e.Previous_Version_id,
    dp.Name AS DonorProject_Name,
    dp.City AS DonorProject_City,
    sl.Name AS StorageLocation_Name,
    sl.City AS StorageLocation_City,
    eg.Length,
    eg.Width,
    eg.Height,
    eg.Weight
  FROM
```

```
    element e
  LEFT JOIN
    donor_project dp ON e.DonorProject_id = dp.Project_ID
  LEFT JOIN
    storage_location sl ON e.StorageLocation_id = sl.Location_ID
  LEFT JOIN
    element_geometry eg ON e.Element_ID = eg.Element_id
  INNER JOIN
    version_history vh ON e.Element_ID = vh.Previous_Version_id
)

SELECT * FROM version_history
ORDER BY Created_At DESC;
```

Appendix D – Django code

D1: models.py Django module

```
from django.db import models
import uuid

# ---------------------------------
# Donor Project Model
# ---------------------------------
class DonorProject(models.Model):
    Project_ID = models.AutoField(primary_key=True)
    Name = models.CharField(max_length=100, unique=True)
    Project_Coords_LatLong = models.CharField(max_length=100)
    City = models.CharField(max_length=50)
    Country = models.CharField(max_length=50)
    Deconstruction_Date = models.DateField(blank=True, null=True)
    Notes = models.TextField(blank=True, null=True)

    class Meta:
        db_table = "donor_project"

    def __str__(self):
        return self.Name


# ---------------------------------
# Owner Model
# ---------------------------------
class Owner(models.Model):
    Owner_ID = models.CharField(max_length=50, primary_key=True)
    Name = models.CharField(max_length=100)
    Contact = models.CharField(max_length=255)
    Notes = models.TextField(blank=True, null=True)

    class Meta:
        db_table = "owner"

    def __str__(self):
        return self.Name

# ---------------------------------
# Storage Location Model
# ---------------------------------
class StorageLocation(models.Model):
    Location_ID = models.AutoField(primary_key=True)
    Name = models.CharField(max_length=100)
    Storage_Coords_LatLong = models.CharField(max_length=50)
    Country = models.CharField(max_length=50)
    City = models.CharField(max_length=50)
```

```
    Notes = models.TextField(blank=True, null=True)

    class Meta:
        db_table = "storage_location"

    def __str__(self):
        return f"{self.Name} ({self.City}, {self.Country})"


# ---------------------------------
# Classification Model
# ---------------------------------
class Classification(models.Model):
    CATEGORY_CHOICES = [
        ('NL-SfB', 'NL-SfB (Building Elements)'),
        ('NLCS', 'NLCS (Infrastructure Elements)'),
    ]
    category = models.CharField(max_length=50, choices=CATEGORY_CHOICES)
    code = models.CharField(max_length=50)  # Classification code
    description = models.CharField(max_length=255)  # Classification
description

    class Meta:
        db_table = "classification"

    def __str__(self):
        return f"{self.category} - {self.code}: {self.description}"

# ---------------------------------
# Element Model
# ---------------------------------
class Element(models.Model):
    Element_ID = models.UUIDField(primary_key=True, default=uuid.uuid4,
editable=False)
    Classification = models.ForeignKey(Classification,
on_delete=models.SET_NULL, null=True, blank=True)
    Name = models.CharField(max_length=100)
    Description = models.TextField(blank=True, null=True)
    Age = models.IntegerField()
    Aesthetic_Condition = models.CharField(max_length=10, choices=[
        ('good', 'Good'),
        ('moderate', 'Moderate'),
        ('poor', 'Poor'),
    ], default='Available', null=True, blank=True)

    Damage = models.CharField(max_length=10, choices=[
        ('none', 'None'),
        ('minor', 'Minor'),
        ('major', 'Major'),
    ], null=True, blank=True)
```

```
    Availability_Date = models.DateField(blank=True, null=True)

    Status = models.CharField(max_length=20, choices=[
        ('Available', 'Available'),
        ('Pending', 'Pending'),
        ('Unavailable', 'Unavailable'),
        ('In Use', 'In Use')
    ], default='Available', blank=True, null=True)

    DonorProject = models.ForeignKey(DonorProject, on_delete=models.SET_NULL,
null=True, blank=True)
    Owner = models.ForeignKey(Owner, on_delete=models.SET_NULL, null=True,
blank=True)
    StorageLocation = models.ForeignKey(StorageLocation,
on_delete=models.SET_NULL, null=True, blank=True, related_name="elements")
    Previous_Version = models.ForeignKey('self', on_delete=models.SET_NULL,
null=True, blank=True)
    Created_At = models.DateField(auto_now_add=True)
    Updated_At = models.DateField(auto_now=True)
    Notes = models.TextField(blank=True, null=True)

    # Foreign keys for table references for pre-population #
    Geometry = models.ForeignKey('ElementGeometry', on_delete=models.PROTECT,
null=True, blank=True, related_name='elements')
    Environmental_Impact = models.ForeignKey('EnvironmentalImpact',
on_delete=models.PROTECT, null=True, blank=True, related_name='elements')


    class Meta:
        db_table = "element"

    def __str__(self):
        return f"Element {self.Element_ID} - {self.Name} (Prev:
{self.Previous_Version})"

# ---------------------------------
# StoredElement
# ---------------------------------
class StoredElement(models.Model):
    Element = models.ForeignKey(Element, on_delete=models.CASCADE,
related_name='stored_elements')
    StorageLocation = models.ForeignKey(StorageLocation,
on_delete=models.CASCADE)
    Quantity = models.FloatField()
    Unit = models.CharField(max_length=10, choices=[
        ('pieces', 'Pieces'),
        ('m', 'Meters'),
        ('m2', 'Square Meters'),
        ('m3', 'Cubic Meters'),
```

```
        ('kg', 'Kilograms'),
    ])

    class Meta:
        db_table = "stored_element"

    def __str__(self):
        return f"{self.Quantity} {self.Unit} of {self.Element.Name} at
{self.StorageLocation.Name}"

# ---------------------------------
# Material Property Model
# ---------------------------------
class MaterialProperty(models.Model):
    Material_ID = models.AutoField(primary_key=True)
    Material_Name = models.CharField(max_length=100, unique=True)
    Density = models.FloatField(help_text="Density in kg/m³", default=0.0)
    Certification = models.CharField(max_length=100, blank=True, null=True)
    StrengthClass = models.CharField(max_length=100, blank=True, null=True)

    class Meta:
        db_table = "material_property"

    def save(self, *args, **kwargs):
        """Ensure materials are always stored as 'Name (density kg/m³)' only
once"""
        if f"({self.Density} kg/m³)" not in self.Material_Name:
            self.Material_Name = f"{self.Material_Name} ({self.Density}
kg/m³)"
        super().save(*args, **kwargs)

    def __str__(self):
        return self.Material_Name

# --------------------------
# StructuralProperty Model
# --------------------------
class StructuralProperty(models.Model):
    Material = models.OneToOneField(MaterialProperty,
on_delete=models.CASCADE, primary_key=True)
    Reinforcement = models.CharField(max_length=100)
    Load_Capacity = models.FloatField()

    class Meta:
        db_table = "structuralproperty"

    def __str__(self):
        return f"Structural Properties of {self.Material.Name}"

# ---------------------------------
```

```python
# Element Geometry Model
# --------------------------------
class ElementGeometry(models.Model):
    Geometry_ID = models.AutoField(primary_key=True)
    Material = models.ForeignKey(MaterialProperty, on_delete=models.CASCADE)

    # Cubic dimensions
    Length = models.FloatField(null=True, blank=True)
    Width = models.FloatField(null=True, blank=True)
    Height = models.FloatField(null=True, blank=True)

    # Non-editable weight
    Weight = models.FloatField(null=True, blank=True)

    # Alternative geometry description
    Notes = models.TextField(blank=True, null=True)
    Drawings = models.FileField(upload_to="drawings/", blank=True, null=True)

    class Meta:
        db_table = "element_geometry"

    def save(self, *args, **kwargs):
        """Automatically calculates Weight if cubic dimensions exist,
otherwise allows manual input"""
        if self.Length and self.Width and self.Height:
            volume_m3 = (self.Length / 1000) * (self.Width / 1000) *
(self.Height / 1000)  # Convert to m³
            self.Weight = self.Material.Density * volume_m3
        super().save(*args, **kwargs)

    def __str__(self):
        return f"Geometry ID {self.Geometry_ID} - Weight: {self.Weight if
self.Weight else 'Manual Entry'} kg"

# -------------------------
# VoidAndProtrusion Model
# -------------------------
class VoidAndProtrusion(models.Model):

    Geometry = models.ForeignKey(ElementGeometry, on_delete=models.CASCADE)
    Type = models.CharField(max_length=50, choices=[
        ('void', 'Void'),
        ('protrusion', 'Protrusion'),
    ], blank=True, null=True)
    Count = models.IntegerField()
    Length = models.FloatField()
    Width = models.FloatField()
    Height = models.FloatField()

    class Meta:
```

```
        db_table = "void_and_protrusion"

    def __str__(self):
        return f"{self.Type} in {self.Geometry.Element.Name}"

# ---------------------------------
# Environmental Impact Model
# ---------------------------------
class EnvironmentalImpact(models.Model):
    Impact_ID = models.AutoField(primary_key=True)
    GWP_A1 = models.FloatField()
    GWP_A2 = models.FloatField()
    GWP_A3 = models.FloatField()
    GWP_A4 = models.FloatField()
    GWP_A5 = models.FloatField()
    GWP_C1 = models.FloatField()
    GWP_C2 = models.FloatField()
    MKI_Value = models.FloatField()
    Reuse_Factor = models.FloatField()
    Construction_Time = models.FloatField(help_text="Construction time in
hours", null=True, blank=True)
    Deconstruction_Time = models.FloatField(help_text="Deconstruction time in
hours", null=True, blank=True)
    Impact_Unit = models.CharField(max_length=10,choices=[
        ('pieces', 'Pieces'),
        ('m', 'Meters'),
        ('m2', 'Square Meters'),
        ('m3', 'Cubic Meters'),
        ('kg', 'Kilograms'),
    ],null=True,blank=True)

    class Meta:
        db_table = "environmental_impact"

    def __str__(self):
        return f"Environmental Impact ID {self.Impact_ID}"


# ---------------------------------
# Reference / Pre-population Model
# ---------------------------------
class ReferenceElement(models.Model):
    Reference_ID = models.AutoField(primary_key=True)
    Classification = models.ForeignKey(Classification,
on_delete=models.CASCADE)
    Name = models.CharField(max_length=100)

    Geometry = models.ForeignKey(ElementGeometry, on_delete=models.PROTECT)
    Environmental_Impact = models.ForeignKey(EnvironmentalImpact,
on_delete=models.PROTECT)
```

```
    Storage_Unit = models.CharField(max_length=10, choices=[
        ('pieces', 'Pieces'),
        ('m', 'Meters'),
        ('m2', 'Square Meters'),
        ('m3', 'Cubic Meters'),
        ('kg', 'Kilograms'),
    ])

    class Meta:
        db_table = "reference_element"

    def __str__(self):
        return f"{self.Name} ({self.Classification.code})"
```

D2: forms.py Django module

```
from django import forms
from datetime import datetime
from .models import Owner, Element, ElementGeometry, Classification,
DonorProject, EnvironmentalImpact, MaterialProperty, StorageLocation,
StoredElement


class ElementForm(forms.ModelForm):
    # Dropdowns for existing classifications
    existing_nl_sfb = forms.ModelChoiceField(
        queryset=Classification.objects.filter(category='NL-SfB'),
        required=False,
        empty_label="Select NL-SfB Classification",
        widget=forms.Select(attrs={'class': 'form-control'})
    )

    existing_nlcs = forms.ModelChoiceField(
        queryset=Classification.objects.filter(category='NLCS'),
        required=False,
        empty_label="Select NLCS Classification",
        widget=forms.Select(attrs={'class': 'form-control'})
    )

    # Allow users to enter a new classification
    new_classification_category = forms.ChoiceField(
        choices=Classification.CATEGORY_CHOICES,
        required=False,
        widget=forms.Select(attrs={'class': 'form-control'})
    )
    new_classification_code = forms.CharField(
        required=False,
        widget=forms.TextInput(attrs={'class': 'form-control', 'placeholder':
'Enter New Classification Code'})
    )
    new_classification_description = forms.CharField(
        required=False,
        widget=forms.TextInput(attrs={'class': 'form-control', 'placeholder':
'Enter Description'})
    )

    storage_location = forms.ModelChoiceField(
        queryset=StorageLocation.objects.all(),
        required=False,
        empty_label="Select Storage Location",
        widget=forms.Select(attrs={'class': 'form-control'})
    )

    DonorProject = forms.ModelChoiceField(
```

```
        queryset=DonorProject.objects.all(),
        required=False,
        empty_label="Select Existing Donor Project",
        widget=forms.Select(attrs={"class": "form-control"})
    )

    class Meta:
        model = Element
        fields = "__all__"
        widgets = {
            "Availability_Date": forms.DateInput(attrs={"class": "form-
control", "type": "date"}),
        }

    def clean(self):
        cleaned_data = super().clean()
        nl_sfb = cleaned_data.get("existing_nl_sfb")
        nlcs = cleaned_data.get("existing_nlcs")
        new_category = cleaned_data.get("new_classification_category")
        new_code = cleaned_data.get("new_classification_code")
        new_description = cleaned_data.get("new_classification_description")

        if not nl_sfb and not nlcs and not (new_category and new_code):
            raise forms.ValidationError("Please select an existing
classification or enter a new one.")

        if new_category and new_code:
            classification, created = Classification.objects.get_or_create(
                category=new_category, code=new_code,
                defaults={"description": new_description}
            )
            cleaned_data["classification"] = classification  # Assign
classification to cleaned data
        else:
            cleaned_data["classification"] = nl_sfb or nlcs

        return cleaned_data

    def save(self, commit=True):
        element = super().save(commit=False)

        donor_project = self.cleaned_data.get("DonorProject")
        if donor_project:
            element.DonorProject = donor_project  # Assign DonorProject

        if commit:
            element.save()
            self.cleaned_data["storage_location"].elements.add(element)  #
Assign StorageLocation correctly
```

```
        return element


class OwnerForm(forms.ModelForm):
    class Meta:
        model = Owner
        fields = ['Name', 'Contact', 'Notes']
        widgets = {
            'Name': forms.TextInput(attrs={'class': 'form-control'}),
            'Contact': forms.TextInput(attrs={'class': 'form-control'}),
            'Notes': forms.Textarea(attrs={'class': 'form-control', 'rows':
3}),
        }


class ElementGeometryForm(forms.ModelForm):
    new_material_name = forms.CharField(
        required=False,
        max_length=100,
        widget=forms.TextInput(attrs={"placeholder": "New Material Name"})
    )
    new_material_density = forms.FloatField(
        required=False,
        widget=forms.NumberInput(attrs={"placeholder": "Density (kg/m³)"})
    )

    # Manual inputs for alternative geometry
    describe_other_geometry = forms.CharField(
        required=False,
        widget=forms.Textarea(attrs={
            "placeholder": "Describe the geometry",
            "class": "form-control",
            "rows": 4,  # Make the text box larger
            "style": "font-family: Arial; width: 100%;"  # Apply Arial font
and align
        })
    )
    manual_weight = forms.FloatField(
        required=False,
        widget=forms.NumberInput(attrs={
            "placeholder": "Enter Weight Manually (kg)",
            "class": "form-control"
        })
    )

    class Meta:
        model = ElementGeometry
        fields = [
            "Length", "Width", "Height", "Weight", "Notes", "Drawings",
"Material"
```

```
        ]
        widgets = {
            "Length": forms.NumberInput(attrs={"placeholder": "Length (mm)",
"required": False}),
            "Width": forms.NumberInput(attrs={"placeholder": "Width (mm)",
"required": False}),
            "Height": forms.NumberInput(attrs={"placeholder": "Height (mm)",
"required": False}),
            "Weight": forms.NumberInput(attrs={"readonly": "readonly",
"placeholder": "Weight (kg)", "required": False}),
            "Notes": forms.Textarea(attrs={"placeholder": "Geometry Notes",
"rows": 3, "required": False}),
            "Drawings": forms.ClearableFileInput(attrs={"required": False}),
            "Material": forms.Select(attrs={"class": "form-control",
"required": False})
        }

    def clean(self):
        cleaned_data = super().clean()
        length = cleaned_data.get("Length")
        width = cleaned_data.get("Width")
        height = cleaned_data.get("Height")
        manual_weight = cleaned_data.get("manual_weight")
        describe_other_geometry = cleaned_data.get("describe_other_geometry")

        # Ensure either cubic dimensions OR manual weight and description is
provided
        if (length and width and height) and (manual_weight or
describe_other_geometry):
            raise forms.ValidationError("Either specify cubic dimensions OR
describe other geometry, not both.")

        if not ((length and width and height) or (manual_weight and
describe_other_geometry)):
            raise forms.ValidationError("Please provide either cubic
dimensions or describe the geometry with weight.")

        return cleaned_data

    def save(self, commit=True):
        geometry = super().save(commit=False)

        # Handle new material creation if provided
        new_material_name = self.cleaned_data.get("new_material_name")
        new_material_density = self.cleaned_data.get("new_material_density")

        if new_material_name and new_material_density:
            formatted_material_name = f"{new_material_name}
({new_material_density} kg/m³)"
            material, created = MaterialProperty.objects.get_or_create(
```

```
                Material_Name=formatted_material_name,
                defaults={"Density": new_material_density}
            )
            geometry.Material = material  # Assign new material

        # Handle cubic dimensions vs. manual weight
        if geometry.Length and geometry.Width and geometry.Height:
            material = geometry.Material
            volume_m3 = (geometry.Length / 1000) * (geometry.Width / 1000) *
(geometry.Height / 1000)
            geometry.Weight = material.Density * volume_m3
        else:
            geometry.Weight = self.cleaned_data.get("manual_weight")
            geometry.Notes = self.cleaned_data.get("describe_other_geometry")

        if commit:
            geometry.save()

        return geometry


class EnvironmentalImpactForm(forms.ModelForm):
    UNIT_CHOICES = [
        ('pieces', 'Pieces'),
        ('m3', 'Cubic Meters (m³)'),
        ('m2', 'Square Meters (m²)'),
        ('m', 'Meters (m)'),
        ('kg', 'Kilograms (kg)'),
    ]

    # Explicitly override the field to set required=False
    Impact_Unit = forms.ChoiceField(
        required=False,
        choices=UNIT_CHOICES,
        widget=forms.Select(attrs={"class": "form-control"})
    )

    # Override each field in __init__ to make them optional
    def __init__(self, *args, **kwargs):
        super().__init__(*args, **kwargs)
        for field_name in self.fields:
            self.fields[field_name].required = False  # Make all fields
optional

    class Meta:
        model = EnvironmentalImpact
        fields = [
            "GWP_A1", "GWP_A2", "GWP_A3", "GWP_A4", "GWP_A5",
            "GWP_C1", "GWP_C2", "MKI_Value", "Reuse_Factor",
            "Construction_Time", "Deconstruction_Time", "Impact_Unit"
```

```
        ]
        widgets = {
            "GWP_A1": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_A2": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_A3": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_A4": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_A5": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_C1": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "GWP_C2": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "MKI_Value": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "Reuse_Factor": forms.NumberInput(attrs={"class": "form-control",
"step": "any"}),
            "Construction_Time": forms.NumberInput(attrs={"class": "form-
control", "step": "any"}),
            "Deconstruction_Time": forms.NumberInput(attrs={"class": "form-
control", "step": "any"}),
        }


class MaterialPropertyForm(forms.ModelForm):
    class Meta:
        model = MaterialProperty
        fields = ["Material_Name", "Density"]
        widgets = {
            "Material_Name": forms.TextInput(attrs={"class": "form-control"}),
            "Density": forms.NumberInput(attrs={"class": "form-control",
"placeholder": "Density (kg/m³)"}),
        }

    def clean_Density(self):
        """Ensure Density is greater than 0"""
        density = self.cleaned_data.get("Density")
        if density <= 0:
            raise forms.ValidationError("Density must be greater than 0
kg/m³.")
        return density

class StorageLocationForm(forms.ModelForm):
    class Meta:
        model = StorageLocation
        fields = ['Name', 'Storage_Coords_LatLong', 'City', 'Country']
        widgets = {
```

```
            'Name': forms.TextInput(attrs={'class': 'form-control',
'placeholder': 'Storage Name'}),
            'Storage_Coords_LatLong': forms.TextInput(attrs={'class': 'form-
control', 'placeholder': 'Latitude, Longitude'}),
            'City': forms.TextInput(attrs={'class': 'form-control',
'placeholder': 'City'}),
            'Country': forms.TextInput(attrs={'class': 'form-control',
'placeholder': 'Country'}),
        }


class StoredElementForm(forms.ModelForm):
    class Meta:
        model = StoredElement
        fields = ["StorageLocation", "Quantity", "Unit"]
        widgets = {
            "StorageLocation": forms.Select(attrs={'class': 'form-control'}),
            "Quantity": forms.NumberInput(attrs={'class': 'form-control',
'placeholder': 'Quantity'}),
            "Unit": forms.Select(attrs={'class': 'form-control'}),
        }


class DonorProjectForm(forms.ModelForm):
    class Meta:
        model = DonorProject
        fields = ["Name", "Project_Coords_LatLong", "City", "Country"]
        widgets = {
            "Name": forms.TextInput(attrs={"class": "form-control"}),
            "Project_Coords_LatLong": forms.TextInput(attrs={"class": "form-
control"}),
            "City": forms.TextInput(attrs={"class": "form-control"}),
            "Country": forms.TextInput(attrs={"class": "form-control"}),
        }
```

D3: views.py Django module

```
from django.shortcuts import render, redirect, get_object_or_404
from django.contrib import messages
from django.db.models import Q
from .forms import ElementForm, OwnerForm, ElementGeometryForm,
EnvironmentalImpactForm, StoredElementForm, DonorProjectForm
from .models import Element, ElementGeometry, EnvironmentalImpact,
StorageLocation, Classification, MaterialProperty, DonorProject,
StoredElement, ReferenceElement
from django.http import JsonResponse
from geopy.distance import geodesic
import json
from django.views.decorators.csrf import csrf_exempt
geometry_form = None
impact_form = None
geometry = None
impact = None


def home(request):
    return render(request, "elements/home.html")


def add_owner(request):
    """Handles adding a new owner"""
    if request.method == "POST":
        form = OwnerForm(request.POST)
        if form.is_valid():
            form.save()
            return redirect("add_element")
    else:
        form = OwnerForm()
    return render(request, "elements/add_owner.html", {"form": form})


def add_element(request):
    if request.method == "POST":
        reference_element_id = request.POST.get("ReferenceElement")
        use_reference = bool(reference_element_id)

        # Always load these
        element_form = ElementForm(request.POST)
        stored_element_form = StoredElementForm(request.POST)

        # Conditionally load only if manual
        geometry_form = None
        impact_form = None
        if not use_reference:
            geometry_form = ElementGeometryForm(request.POST, request.FILES)
            impact_form = EnvironmentalImpactForm(request.POST)
```

```
        # Validation
        valid = element_form.is_valid() and stored_element_form.is_valid()
        if not use_reference:
            valid = valid and geometry_form.is_valid() and
impact_form.is_valid()

        if valid:
            element = element_form.save(commit=False)
            element.Classification =
element_form.cleaned_data.get("classification")

            if use_reference:
                # Assign existing foreign keys directly (NO saving!)
                reference =
ReferenceElement.objects.get(pk=reference_element_id)
                element.Geometry_id = reference.Geometry.Geometry_ID
                element.Environmental_Impact_id =
reference.Environmental_Impact.Impact_ID
            else:
                #  Create new records only if manual
                geometry = geometry_form.save(commit=False)
                geometry.Element = element

                if geometry.Length and geometry.Width and geometry.Height:
                    material = geometry.Material
                    volume_m3 = (geometry.Length / 1000) * (geometry.Width /
1000) * (geometry.Height / 1000)
                    geometry.Weight = material.Density * volume_m3
                else:
                    geometry.Weight = request.POST.get("manual_weight", None)
                    geometry.Notes =
request.POST.get("describe_other_geometry", "").strip()

                geometry.save()
                element.Geometry = geometry

                impact = impact_form.save(commit=False)
                impact.Element = element
                impact.save()
                element.Environmental_Impact = impact

            # Donor Project
            donor_project_id = request.POST.get("Donor_Project")
            if donor_project_id:
                try:
                    donor_project =
DonorProject.objects.get(pk=donor_project_id)
                    element.DonorProject = donor_project
                except DonorProject.DoesNotExist:
```

```
                    pass

            element.save()

            # StoredElement (quantity/unit/storage)
            stored_element = stored_element_form.save(commit=False)
            stored_element.Element = element
            stored_element.save()

            return redirect("home")

    else:
        # GET request
        element_form = ElementForm()
        stored_element_form = StoredElementForm()
        geometry_form = ElementGeometryForm()
        impact_form = EnvironmentalImpactForm()

    reference_elements =
ReferenceElement.objects.select_related('Classification').all()
    donor_projects = DonorProject.objects.all()
    storage_locations = StorageLocation.objects.all()

    return render(
        request,
        "elements/add_element.html",
        {
            "element_form": element_form,
            "stored_element_form": stored_element_form,
            "geometry_form": geometry_form,
            "impact_form": impact_form,
            "storage_locations": storage_locations,
            "donor_projects": donor_projects,
            "reference_elements": reference_elements,
        },
    )




def add_material(request):
    if request.method == "POST":
        try:
            data = json.loads(request.body)
            material_name = data.get("Material_Name", "").strip()
            material_density = data.get("Density", 0)

            print("Received data:", data)  # DEBUG: Check received request
```

```
            if not material_name:
                return JsonResponse({"success": False, "error": "Material name
cannot be empty."})

            try:
                material_density = float(material_density)  # Convert to float
safely
                if material_density <= 0:
                    return JsonResponse({"success": False, "error": "Density
must be greater than 0 kg/m³."})
            except ValueError:
                return JsonResponse({"success": False, "error": "Invalid
density value."})



            # Ensure material is saved in "Name (Density kg/m³)" format
            formatted_material_name = f"{material_name} ({material_density}
kg/m³)"

            material, created = MaterialProperty.objects.get_or_create(
                Material_Name=formatted_material_name,
                defaults={"Density": material_density}
            )

            return JsonResponse({"success": True, "id": material.pk, "name":
material.Material_Name})

        except Exception as e:
            print("Error in add_material:", str(e))  # DEBUG
            return JsonResponse({"success": False, "error": str(e)})

    return JsonResponse({"success": False, "error": "Invalid request."})


def add_storage_location(request):
    if request.method == "POST":
        try:
            data = json.loads(request.body)
            name = data.get("Name", "").strip()
            coords = data.get("Storage_Coords_LatLong", "").strip()
            city = data.get("City", "").strip()
            country = data.get("Country", "").strip()

            print("Received storage location data:", data)  #DEBUG

            if not name or not coords or not city or not country:
                return JsonResponse({"success": False, "error": "All fields
are required."})
```

```
            # Ensure the storage location is created
            storage, created = StorageLocation.objects.get_or_create(
                Name=name,
                defaults={"Storage_Coords_LatLong": coords, "City": city,
"Country": country}
            )

            return JsonResponse({"success": True, "id": storage.pk, "name":
storage.Name})

        except Exception as e:
            print("Error in add_storage_location:", str(e))  # DEBUG
            return JsonResponse({"success": False, "error": str(e)})

    return JsonResponse({"success": False, "error": "Invalid request."})

@csrf_exempt
def add_classification(request):
    """Handles adding a new classification via AJAX."""
    if request.method == "POST":
        try:
            data = json.loads(request.body)
            category = data.get("category", "").strip()
            code = data.get("code", "").strip()
            description = data.get("description", "").strip()

            if not category or not code or not description:
                return JsonResponse({"success": False, "error": "All fields
are required."})

            classification, created = Classification.objects.get_or_create(
                code=code,
                category=category,
                defaults={"description": description}
            )

            return JsonResponse({
                "success": True,
                "id": classification.pk,
                "code": classification.code,
                "description": classification.description
            })

        except Exception as e:
            print("Error in add_classification:", str(e))
            return JsonResponse({"success": False, "error": str(e)})

    return JsonResponse({"success": False, "error": "Invalid request
method."})
```

```python
@csrf_exempt  # Allow AJAX request without CSRF token issues
def add_donor_project(request):
    """Handles adding a new Donor Project from the frontend."""
    if request.method == "POST":
        form = DonorProjectForm(request.POST)
        if form.is_valid():
            donor_project = form.save()
            return JsonResponse({
                "success": True,
                "id": donor_project.Project_ID,
                "name": donor_project.Name
            })
        else:
            return JsonResponse({
                "success": False,
                "errors": form.errors
            })

    return JsonResponse({
        "success": False,
        "errors": "Invalid request method"
    })




#### database pre-population ###

from django.http import JsonResponse
from .models import ReferenceElement

def get_reference_element_data(request, ref_id):
    try:
        reference = ReferenceElement.objects.select_related(
            'Geometry', 'Geometry__Material', 'Environmental_Impact'
        ).get(pk=ref_id)

        data = {
            "name": reference.Name,
            'material_name': reference.Geometry.Material.Material_Name,
            'material_density': reference.Geometry.Material.Density,
            'length': reference.Geometry.Length,
            'width': reference.Geometry.Width,
            'height': reference.Geometry.Height,
            'weight': reference.Geometry.Weight,
            'unit': reference.Storage_Unit,
            'impact': {
                'GWP_A1': reference.Environmental_Impact.GWP_A1,
                'GWP_A2': reference.Environmental_Impact.GWP_A2,
```

```
                'GWP_A3': reference.Environmental_Impact.GWP_A3,
                'GWP_A4': reference.Environmental_Impact.GWP_A4,
                'GWP_A5': reference.Environmental_Impact.GWP_A5,
                'GWP_C1': reference.Environmental_Impact.GWP_C1,
                'GWP_C2': reference.Environmental_Impact.GWP_C2,
                'MKI_Value': reference.Environmental_Impact.MKI_Value,
                'Reuse_Factor': reference.Environmental_Impact.Reuse_Factor,
                'Construction_Time':
reference.Environmental_Impact.Construction_Time,
                'Deconstruction_Time':
reference.Environmental_Impact.Deconstruction_Time,
                'Impact_Unit': reference.Environmental_Impact.Impact_Unit,
            }
        }

        return JsonResponse({'success': True, 'data': data})

    except ReferenceElement.DoesNotExist:
        return JsonResponse({'success': False, 'error': 'ReferenceElement not
found.'})

def get_reference_elements_by_classification(request, classification_id):
    references =
ReferenceElement.objects.filter(Classification_id=classification_id)
    data = [{'id': ref.Reference_ID, 'name': ref.Name} for ref in references]
    return JsonResponse(data, safe=False)




def select_elements(request):
    all_elements = (
                Element.objects
                .select_related("Classification", "Geometry__Material",
"StorageLocation", "Owner")
                .all()
            )

    if request.method == "POST":
        location = request.POST.get("location", "").strip()
        element_name = request.POST.get("element_name", "").strip()
        reference_id = request.POST.get("reference_choice")


        if request.method == "POST":
            location = request.POST.get("location", "").strip()
            element_name = request.POST.get("element_name", "").strip()
            reference_id = request.POST.get("reference_choice")
```

```
            if not location or not element_name:
                return render(request, "elements/select_elements.html", {
                    "error": "Please fill in all fields",
                    "all_elements": all_elements
                })

            try:
                project_lat, project_lon = map(float, location.split(","))
            except ValueError:
                return render(request, "elements/select_elements.html", {
                    "error": "Invalid format for coordinates",
                    "all_elements": all_elements
                })

            try:
                required_quantity =
float(request.POST.get("required_quantity", "0"))
            except ValueError:
                return render(request, "elements/select_elements.html", {
                    "error": "Invalid quantity",
                    "all_elements": all_elements
                })

            matching_elements =
Element.objects.filter(Name__icontains=element_name)
            element_data = []

        if not location or not element_name:
            return render(request, "elements/select_elements.html", {"error":
"Please fill in all fields"})

        try:
            project_lat, project_lon = map(float, location.split(","))
        except ValueError:
            return render(request, "elements/select_elements.html", {"error":
"Invalid format for coordinates"})

        try:
            required_quantity = float(request.POST.get("required_quantity",
"0"))
        except ValueError:
            return render(request, "elements/select_elements.html", {"error":
"Invalid quantity"})

        matching_elements =
Element.objects.filter(Name__icontains=element_name)
        element_data = []

        for element in matching_elements:
            stored_elements = StoredElement.objects.filter(Element=element)
```

```
            if not stored_elements.exists():
                continue

            for stored_element in stored_elements:
                impact = element.Environmental_Impact
                if not impact:
                    continue

                storage = stored_element.StorageLocation
                donor_project = element.DonorProject
                if not storage or not donor_project:
                    continue

                try:
                    storage_lat, storage_lon = map(float,
storage.Storage_Coords_LatLong.split(","))
                    donor_lat, donor_lon = map(float,
donor_project.Project_Coords_LatLong.split(","))
                except ValueError:
                    continue

                d_A4 = geodesic((storage_lat, storage_lon), (project_lat,
project_lon)).km
                d_C2 = geodesic((donor_lat, donor_lon), (storage_lat,
storage_lon)).km

                GWP_m2 = (
                    ((impact.GWP_A1 + impact.GWP_A2 + impact.GWP_A3) *
impact.Reuse_Factor)
                    + (impact.GWP_C1 * impact.Deconstruction_Time)
                    + (impact.GWP_C2 * d_C2)
                    + (impact.GWP_A4 * d_A4)
                    + (impact.GWP_A5 * impact.Construction_Time)
                )

                element_data.append({
                    "Element_ID": element.Element_ID,
                    "Name": element.Name,
                    "Quantity": stored_element.Quantity,
                    "Unit": stored_element.Unit,
                    "GWP_m2": round(GWP_m2, 2),
                })

        sorted_elements = sorted(element_data, key=lambda x: x["GWP_m2"])

        # ------- Fulfill selection strategy -------
        accumulated = 0.0
        selected_elements = []
        total_gwp = 0.0
```

```
        for entry in sorted_elements:
            if accumulated >= required_quantity:
                break

            available = float(entry["Quantity"])
            unit_gwp = float(entry["GWP_m2"])
            to_use = min(required_quantity - accumulated, available)

            percent_used = to_use / available * 100
            gwp_contribution = to_use * unit_gwp

            selected_elements.append({
                "Element_ID": entry["Element_ID"],
                "Name": entry["Name"],
                "Used_Quantity": to_use,
                "Available_Quantity": available,
                "Used_Percent": round(percent_used, 1),
                "GWP_Per_Unit": unit_gwp,
                "GWP_Contribution": round(gwp_contribution, 2),
                "Unit": entry["Unit"],
            })

            accumulated += to_use
            total_gwp += gwp_contribution

        missing_quantity = required_quantity - accumulated if accumulated <
required_quantity else 0.0

        # ------- GWP from new material if needed -------
        matching_refs =
ReferenceElement.objects.filter(Name__icontains=element_name)

        gwp_new_details = None

        if reference_id and matching_refs.exists() and missing_quantity > 0:
            ref = matching_refs.first()
            impact = ref.Environmental_Impact

            gwp_new_per_unit = (
                impact.GWP_A1 +
                impact.GWP_A2 +
                impact.GWP_A3 +
                (impact.GWP_A4 * 150) +
                impact.GWP_A5
            )

            gwp_new_element = round(gwp_new_per_unit * missing_quantity, 2)
            final_total_gwp = round(gwp_new_element + total_gwp, 2)

            gwp_new_details = {
```

```
                "Reference_Name": ref.Name,
                "GWP_per_Unit": round(gwp_new_per_unit, 2),
                "GWP_Total_New": gwp_new_element,
                "Final_GWP": final_total_gwp,
            }



        return render(request, "elements/select_elements.html", {
            "elements": sorted_elements[:10],
            "selected_elements": selected_elements,
            "total_gwp": round(total_gwp, 2),
            "missing_quantity": round(missing_quantity, 2),
            "required_quantity": required_quantity,
            "gwp_new_details": gwp_new_details,
            "matching_reference_elements": matching_refs if missing_quantity >
0 else None,
            "all_elements": all_elements,
        })

    return render(request, "elements/select_elements.html", {
        "all_elements": all_elements
    })



def all_elements_view(request):
    all_elements = (
        Element.objects
        .select_related(
            "Geometry__Material",
            "StorageLocation",
            "Owner"
        )
        .all()
    )
```

D4: urls.py Django module

```
from django.urls import path
from .views import home, add_element, add_owner, add_storage_location,
add_material, add_donor_project, select_elements, add_classification,
get_reference_element_data, get_reference_elements_by_classification,
all_elements_view

urlpatterns = [
    path('', home, name='home'),
    path('add-element/', add_element, name='add_element'),
    path('add-owner/', add_owner, name='add_owner'),
    path('add-material/', add_material, name='add_material'),
    path('add-storage-location/', add_storage_location,
name='add_storage_location'),
    path('add-donor-project/', add_donor_project, name='add_donor_project'),
    path('select-elements/', select_elements, name='select_elements'),
    path('add-classification/', add_classification,
name='add_classification'),
    path('get-reference-data/<int:ref_id>/', get_reference_element_data,
name='get_reference_element_data'),
    path('get-reference-list/<int:classification_id>/',
get_reference_elements_by_classification,
name='get_reference_elements_by_classification'),
    path("all-elements/", all_elements_view, name="all_elements"),

]
```