

From Data to Paris Proof:

A Decision Support Model for Applying Circular Strategies to Reduce Embodied Carbon in Early Design Phases

CME5200: Master Thesis

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From Data to Paris Proof: A Decision Support Model for Applying Circular Strategies to Reduce Embodied Carbon in Early Design Phases

by

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Preface

*Ezra de Jong
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This thesis marks the completion of the Master's programme in Construction Management and Engineering at Delft University of Technology. This research explores how circularity can serve as a strategic tool to reduce upfront embodied carbon, while safeguarding financial feasibility. Balancing carbon, cost, and circularity is essential to enable both feasible and sustainable construction projects. To support this goal, a quantifiable model was developed, something that, to my knowledge, had not yet been formally established in this integrated form.

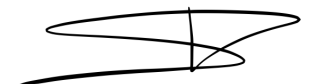
My interest in this subject did not arise by coincidence. My great-grandfather, Salomon (Sal) de Jong, after whom I am named, was a metal merchant in the period following the Second World War. He purchased scrap metal from demolished buildings, railways, and bridges, processed it, and sold it for reuse. Such reuse remains one of the most inherently sustainable strategies known today. Therefore, idea of circularity is therefore far from new. Yet, nearly 80 years later, in 2025, we still see that circularity is far from embedded in mainstream design processes. The construction sector remains largely tied to conventional habits. Against this backdrop, my curiosity was sparked: how can circularity be used not just as an ideal, but used as a design tool to reduce both carbon and costs? In that sense, this thesis is both a academic and personal journey. A journey that allowed me to walk in the footsteps of my great-grandfather.

Writing this thesis has been an honor and a rewarding experience. It came with its share of challenges and moments of doubt, yet each step ultimately led to progress and meaningful results. The research was carried out between March and September 2025 and included literature study, interviews, expert panel consultations and a case study. This wide range of methods proved necessary to capture the complexity of the topic and reflect the interdisciplinary reality of construction innovation.

This work may be of value to practitioners and researchers looking for actionable methods to align sustainability objectives with project constraints in the early design phase. I firmly believe that the most effective solutions emerge where academic insight and professional experience intersect, and that circular design offers one of the most promising arenas for that collaboration.

I have chosen to close this preface in the same way as in my bachelor thesis, to emphasize how strongly I believe in the relevance and urgency of circularity:

"It is my hope that this work contributes to the existing body of knowledge in its respective field and inspires further exploration and research. May it serve as a stepping stone for future research and spark meaningful conversations."



Acknowledgement

The insights presented in this thesis are not the result of individual effort alone. I would therefore like to take this opportunity to express my sincere gratitude to all those who supported and inspired me throughout this journey.

First and foremost, I am deeply thankful to my three graduation supervisors at TU Delft. My sincerest thanks go to Dr. ir. Sultan Çetin, whose weekly supervision provided both structure and critical depth to my work. Her guidance challenged me to sharpen my thinking, while our open discussions helped me refine ideas and steer the thesis towards meaningful outcomes. Her encouragement and dedication throughout this project have been truly inspiring.

I am also grateful to Dr. ir. Ruben Vrijhoef for his constructive feedback during our monthly progress meetings. His technically grounded perspective enriched the analytical depth of this research and ensured its relevance in science.

My appreciation extends to Dr. ir. Erwin Heurkens, who took on the role of chair within my graduation committee. His oversight during the pivotal stages of my thesis ensured academic integrity and helped guide the process to its successful conclusion.

I am extremely thankful for the opportunity to graduate at EDGE. The expertise and support I received from colleagues during my time there have been invaluable. In particular, I would like to thank my company supervisor, Constantijn Berning, whose practical insights and exceptional commitment to my progress significantly elevated the quality of this work.

I also wish to thank the many professionals and experts who generously contributed their time to interviews, expert panels, and informal consultations. Their practical perspectives were crucial in bridging the knowledge gap addressed in this research.

On a personal note, I want to thank those closest to me, my father, mother, brother, and girlfriend, for their unwavering support and belief in me throughout this entire journey. Their presence gave me strength during both the difficult moments and the milestones along the way. I am equally grateful to the rest of my family and close friends for their continued support throughout my journey.

I must express my deepest gratitude to one person in particular: my mother. Without her, I would not have had the values, ambition, or confidence to pursue a university education, let alone graduate as an engineer. Her unconditional belief in me, combined with the countless hours she devoted to my growth, have been the true foundation of all my achievements. Alongside her, I am equally grateful to my father, whose quiet strength and inspiration have deeply shaped my character and drive. Together, they not only created the opportunities I've had, but more importantly, shaped the person I've become.

Lastly, I am grateful for the opportunity to conduct research at a university that embraces innovation, sustainability, and critical-thinking. This journey has not only shaped my academic and professional development, but also embedded personal values that will stay with me for the rest of my life.

Thank you all.

Executive Summary

Climate change is one of the most pressing challenges of our time. Addressing it requires more than transitioning to renewable energy; it also demands a significant reduction in the use of virgin construction materials and a stronger commitment to circular thinking. The Ellen MacArthur Foundation has demonstrated that circular economy strategies can substantially reduce emissions across material-intensive industries. Its 2021 report estimates that circular practices could lower global emissions from cement, steel, plastic, and aluminum by up to 40% by 2050, three of which are core to the construction sector. This thesis investigates how circular construction strategies can contribute to reducing upfront embodied carbon (UEC) during the early design phases while maintaining financial feasibility.

As European and national regulations and guidelines become increasingly stringent, through the introduction of Paris Proof thresholds and mandatory environmental assessments for building permits, there is a growing demand for tools that can interpret and balance environmental and financial performance. In response, this thesis explores the following main research question: *How can a framework be developed to evaluate the impact of circular construction strategies on upfront embodied carbon reduction and financial feasibility during early design phases?*

To answer this question, the research presents the development and validation of the Circular-Carbon Framework (CCF): a decision-support tool designed to help design teams evaluate circular strategies across three interrelated performance indicators, carbon, cost and circularity. The CCF addresses both a scientific and practical gap by integrating these variables into a single, transparent model that is open-source, user-friendly, and interpretable for all members of a multidisciplinary design team.

A mixed-methods approach was employed. First, a structured literature review revealed the absence of integrated tools that assess circularity alongside carbon and cost during early design. Based on these findings, the CCF was developed and informed by qualitative data from semi-structured in-

terviews with material suppliers and design team members. An expert panel was then engaged to refine the framework. Finally, the model was tested in a real-life case study. This case involved the development of EDGE Coolsingel 75, an office building used to evaluate the model's usability and performance.

The research scope focused on the structure and skin layer of buildings, which together contribute roughly 75% of total UEC. Within these layers, the highest-emitting materials were analyzed. For the structure: concrete, reinforcement steel, structural steel, and engineered timber were considered. For the skin: aluminum, glazing, and architectural steel were assessed. Each material was evaluated for circular strategies aimed at improving performance across all three indicators.

The findings of the case-study reveal that circular strategies have strong potential to reduce UEC and lower material costs, though their effectiveness is highly context-dependent. In some cases, increasing circularity leads to lower carbon emissions but introduces cost increases; in others, the inverse holds true. The CCF enables users to explore these trade-offs systematically and supports integrated decision-making at the material level. The tool also addresses a key limitation in current design practice: the lack of quantifiable data and early-stage collaboration on circularity between design team members.

To explore how circularity can contribute to Paris Proof compliance, the model compares a conventional concrete base case with four circular strategies applied to the highest-emitting structural and skin materials. The analysis confirms that circularity can be a lever to meet carbon goals, but results are material- and project-specific, underscoring the importance of early, data-informed design decisions.

In addition to the main finding, the study identified several enabling conditions for circular strategies to effectively reduce UEC and meet Paris Proof targets. From a regulatory standpoint, stronger alignment between the MPG assessment, NMD data, and broader EPD datasets is needed to ensure

environmental assessments are objective and consistent.

From the perspective of material suppliers, earlier engagement in the design process could unlock valuable expertise on materials and circularity. While this can deliver notable carbon and cost benefits, it is often resisted by project developers, owners, and contractors due to the perceived lock-in effect, an issue that requires targeted solutions. Another finding is that material reuse is one of the most circular strategies available; however, its practical application remains limited for most materials due to regulatory, supply-chain, and technical barriers. Overcoming these constraints is essential to fully leverage its potential in reducing UEC.

From a design team perspective, the findings reveal that circularity is not always well understood, and its role in reducing UEC is often overshadowed by carbon and cost considerations. This disconnect limits the effective integration of circular strategies. Greater flexibility in the design process, such as introducing a VO+ time window, could create space for implementation. A dedicated decision-support tool, addressed in this study through the CCF, can help align stakeholders, facilitate transparent discussions, and guide circular strategy selection.

Despite its contributions, the research has limitations. The study is based on a single case study, which restricts generalizability across different project types. Moreover, the interviews predominantly involved sustainability-driven firms, potentially biasing the input toward favorable views on circularity. On the modeling side, the CCF sim-

plifies complex real-world dynamics and relies on assumptions that may not always reflect actual construction conditions. Additionally, challenges related to inconsistent Environmental Product Declarations and fluctuating market prices complicate the accurate quantification of both circularity and cost.

This thesis proposes several recommendations to advance the integration of circular strategies in early-stage building design. Scientifically, further research should develop standardized methods for quantifying circularity indicators and test the CCF across diverse building typologies to enhance its generalizability. In practice, design teams are encouraged to pilot the CCF within integrated design workflows and foster stronger cross-disciplinary collaboration, particularly at the material level. From a policy perspective, circularity should be more embedded into national environmental assessment frameworks, such as the MPG, while efforts must also be made to align the Nationale Milieu Database with Environmental Product Declarations to ensure comprehensive and transparent evaluations of material performance.

In conclusion, this thesis demonstrates that circularity, when supported by transparent and integrated tools like the CCF, has the potential to significantly reduce UEC while maintaining financial feasibility. Nevertheless, unlocking its full potential requires more structured data implementations, enhanced collaboration among design teams, and new regulatory frameworks that formally incorporate circularity into building performance assessments.

Abstract

The building sector is under increasing pressure to reduce upfront embodied carbon (UEC) in order to meet climate goals. Paris Proof threshold values are becoming increasingly stringent, placing new demands on design teams to evaluate material choices not only for environmental performance but also for financial feasibility. This thesis presents the Circular-Carbon Framework (CCF), a decision-support model developed to assess circular construction strategies based on three key indicators: carbon, cost and circularity. The model addresses a gap in current practice by enabling integrated trade-off analysis during the early stages of building design. A mixed-methods approach was used, including a structured literature review, semi-structured interviews, expert validation, and a case study of a commercial office project. The scope was limited to structure and skin materials, which together account for the majority of UEC. Results indicate that circular strategies can support reductions in both UEC and cost, though outcomes vary depending on material type and project context. The CCF enables design teams to systematically explore these trade-offs and make informed decisions aligned with Paris Proof requirements. The thesis concludes with scientific, practical, and policy recommendations to advance the integration of circularity in sustainable building design.

Keywords: Upfront embodied carbon, cost, circularity, early design phase, Paris Proof, Circular-Carbon Framework

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1

Introduction

1.1. Research Context

The construction industry is under increasing pressure to decarbonize, as climate change intensifies and international carbon regulations tighten. In alignment with the Paris Agreement, national policies are becoming more ambitious in targeting the environmental impact of buildings. In the Netherlands, the construction sector accounts for approximately 11% of national CO₂ emissions and consumes half of all raw materials, positioning it as a critical area for climate action. Projections indicate that the Netherlands will exceed its CO₂ budget for limiting global warming to 1.5°C by 2026, to 1.7°C by 2029, and to 2.0°C by 2043, unless immediate and significant emission reductions are achieved in the built environment (Gemeente Amsterdam et al., 2023).

In this context, circularity may become a strategic necessity rather than a voluntary commitment. The urgency is compounded by multiple interrelated trends: declining availability of raw materials, increasing material costs, rising societal demand for sustainable development, and growing interest in bio-based construction solutions (Gemeente Amsterdam et al., 2023; Kanters, 2020). These developments signal the need for a systemic transformation of the construction sector, particularly in the way buildings are designed and materials are selected.

A significant portion of a building's total life cycle emissions comes from embodied carbon, which is largely determined during the early design phases. Therefore, DT members such as architects, project developers and advisors are increasingly required to rethink traditional design processes. The chances of meeting Paris Proof targets for upfront embodied carbon (UEC) depends largely on the capacity of design teams (DTs) to engage in proactive, early-stage decision-making around materials and circular design strategies. Achieving these targets requires not only compliance with regulatory frameworks but also maintaining financial feasibility and architectural quality.

This research addresses the role of circular construction strategies as a means to reduce UEC in building projects. It aims to develop a decision-support model that integrates circularity with carbon performance and financial feasibility. By equipping DTs with a structured and practical tool, this study contributes to a more realistic pathway for aligning construction practices with climate goals.

1.2. Literature Exploration

1.2.1. Research Background

To understand the rationale and scope of this research, it is essential to provide a brief theoretical and contextual background. This study revolves around balancing three interrelated variables that are critical to the feasibility of construction projects: Carbon, Cost, and Circularity. Each of these elements plays a pivotal role in shaping sustainable decision-making within the built environment.

This section introduces and defines the carbon, cost, and circularity using insights from academic literature and current practice. Additionally, it outlines the regulatory frameworks and assessment tools currently in use to evaluate and guide sustainability performance in construction. Together, these foundations provide the necessary context for understanding how a proposed decision-support model operates and why it is needed.

Carbon

Within a building's lifecycle (Figure 1.2), two types of carbon emissions arise: embodied carbon (EC) and operational carbon (OC). EC refers to the greenhouse gas emissions generated during the production, transportation, installation, maintenance, and disposal of building materials (Lambert & Lewis, 2024). In contrast, OC accounts for the emissions resulting from the energy required to operate the building (DGBC, 2021). Together, these emissions constitute the whole-life carbon footprint of a building.

This research specifically examines EC, thereby refining the scope of the study. This refinement is based on several key arguments. First, recent construction efforts have predominantly focused on reducing operational energy consumption. Measures such as the Nearly Zero-Energy Building (BENG) standards have played a central role in achieving progress in this area. However, according to the World Economic Forum, the share of emissions associated with building materials, referred to as embodied emissions, has become increasingly significant. As shown in figure 1.1, embodied emissions are expected to account for 74% of total emissions from new buildings by 2030. This projection underscores the urgent need to address and reduce these emissions (Cutler et al., 2022; DGBC, 2021; Schroeder & Foulkes, 2024).

In addition, EC emissions are generated during the construction phase and become locked-in once the building is completed. This is in contrast to OC, which can be gradually reduced over time through energy efficiency measures (Esau et al., 2021; Lützkendorf & Balouktsi, 2022).

Finally, OC varies significantly due to user behavior, management decisions, and financial constraints. Although buildings may be designed for efficiency, actual emissions depend on the actions of investors, building managers, and tenants. Their differing priorities can often lead to suboptimal performance. Tracking these influences is further complicated by evolving stakeholder interests. In contrast, EC is more stable and objectively measurable, as it depends primarily on material choices and construction methods rather than human behavior. As a result, prioritizing EC in carbon accounting offers a more reliable and measurable approach to emissions reduction (C. Hay, *personal communication*, 2025).

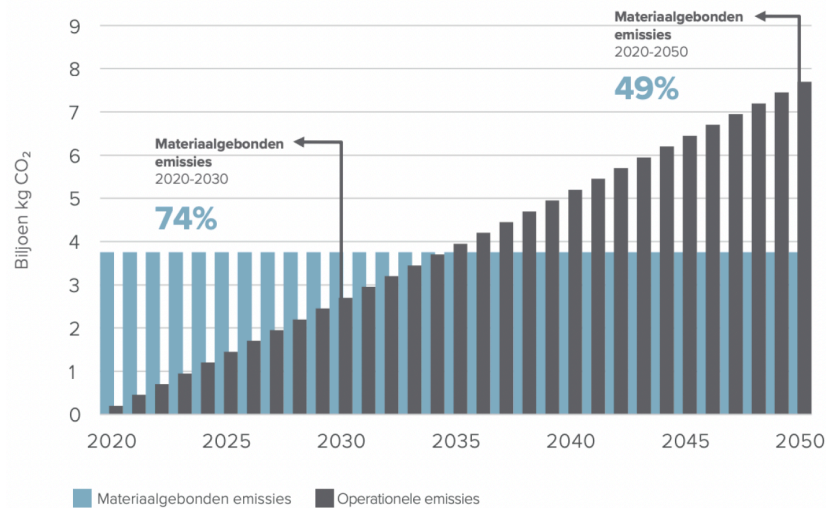


Figure 1.1: Total cumulative global emissions from new construction between 2020 and 2050 under a business-as-usual scenario. Embodied emissions (blue) and operational emissions (grey). Adapted from (DGB, 2021).

While the concept of EC is now clearly motivated, it can be further specified. To fully understand EC and refine the scope of this research, figure 1.2 illustrates the building lifecycle as structured into four main phases, ranging from material supply (A1) to product disposal (C4). These phases represent the critical stages in a building's existence. Summing the emissions from all these stages results in the total EC (excluding B6 and B7).

Evaluating total EC is challenging due to the complexity and variability across projects. Therefore, this study narrows its scope to upfront embodied carbon (UEC), which covers emissions in stages A1 to A5. Given the material-focused nature of this research and the greater ease of generalization, the analysis further concentrates on stages A1–A3: raw material supply, transport, and manufacturing. These stages contribute most to UEC and are critical to address early in the design phase.

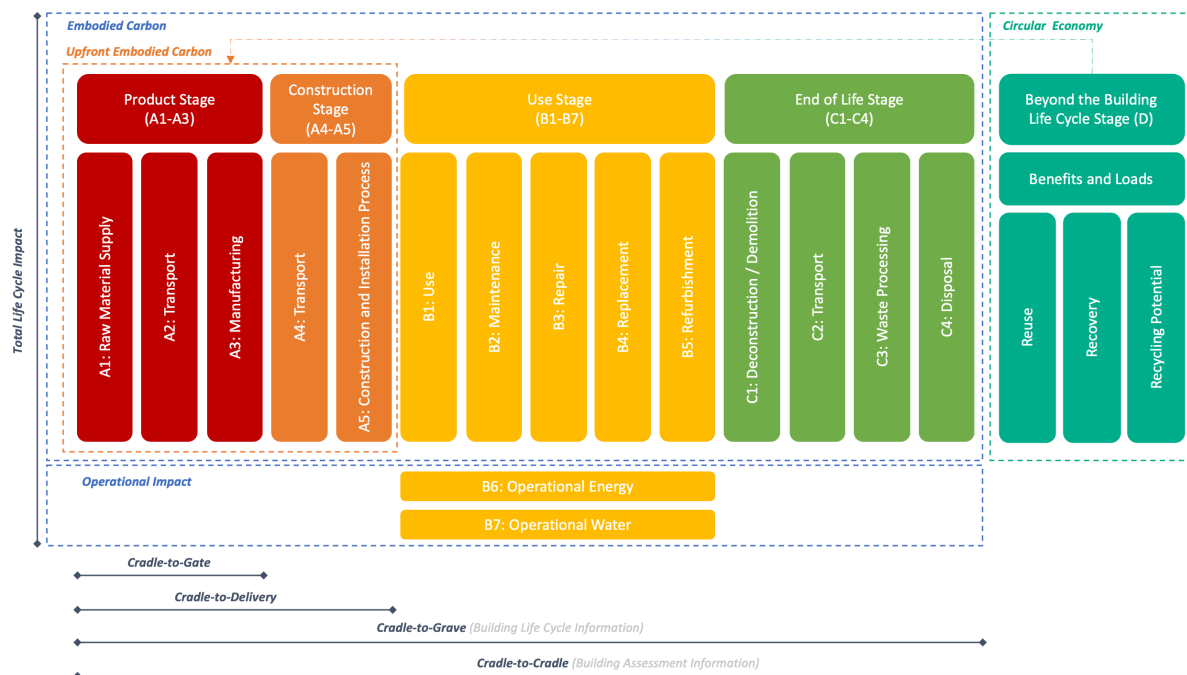


Figure 1.2: Building Lifecycle Diagram. Adapted from EN 15978:2011. Modified by author.

In addition to the four core lifecycle phases, a fifth stage introduces the principles of the circular economy, which are central to this research (Module D). This stage considers the potential for materials to be reused, recovered, or recycled in future construction projects. Circular strategies aim to improve resource efficiency, reduce construction waste, and facilitate material recovery. However, their direct impact on UEC emissions can vary across applications, which highlights the importance of further evaluation.

To understand how UEC can be effectively reduced thru the making of a new model, it is essential to identify the phases within the building process where the most impactful interventions can be made. Specifically, understanding how circular strategies can influence the reduction of UEC requires knowing where the greatest window of opportunity lies. According to World Green Building Council (2023), up to 80% of the potential CO₂ reduction can be achieved during the initiation and design phases. This underscores the necessity of evaluating carbon reduction opportunities during these early stages, as later phases offer significantly less flexibility for implementing impactful changes. Therefore, a structured and early-stage approach to assessing carbon reduction opportunities is crucial.

Figure 1.3 illustrates the overall development process of a building project, which is divided into successive phases that shape both technical decisions and stakeholder engagement. The phases highlighted in blue represent the design stages, during which key decisions regarding material use, circularity, and emissions performance are typically made. The earlier these decisions are implemented, the greater their potential impact on reducing UEC and influencing the overall carbon footprint of the building.

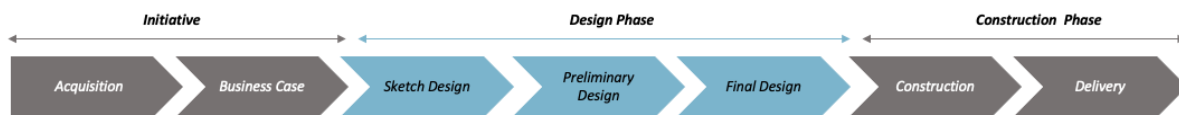


Figure 1.3: Building phases. Adapted from EDGE.

Circularity

The concept of the circular economy is applicable across a wide range of industries, including manufacturing, logistics, clothing, construction and mining. Its broad scope makes defining circular economy inherently challenging. Kirchherr et al. (2017) initially identified 114 definitions, a number that expanded to 221 in their 2023 revision (Kirchherr et al., 2023). Rather than proposing a single, definitive definition, their study analyzes these variations to understand common themes. Kirchherr et al. (2023) present the following meta-definition:

The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the ‘end of life’ concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities.

This meta-definition provides the guiding framework for this research, recognizing that a universally accepted definition of circular economy may never be established (Kirchherr et al., 2023; Nobre & Tavares, 2021).

Since circular economy is not exclusively applicable to the construction sector, it is essential to establish a universally accepted meta-definition of circular construction. Although the study by Ossio et al. (2023) attempts to provide such a definition, it has not been universally adopted by researchers. Therefore, a clear and widely accepted definition of circular construction has yet to be formulated (Nußholz et al., 2023). This results in the need for more practical frameworks that can serve as reference points to precisely define the scope and principles of circular construction.

The leading frameworks that guide the implementation of circular principles are the R-ladder, Circular Strategy Framework by Çetin et al. (2021) as well as the circular strategies from Eberhardt et al.

(2022).

R-Ladder The R-ladder, illustrated in figure 1.4, provides a hierarchical framework for implementing circular economy principles. It ranks circular strategies from R0, the most circular, to R9, the least circular, prioritizing material retention and resource efficiency. This structured approach is widely applicable across various industries and serves as one of the primary tools in guiding the construction sector away from traditional linear models toward a system that maximizes material value throughout the building lifecycle. (C. Zhang et al., 2022)

Despite its potential, applying the R-ladder to the construction industry presents several challenges. In sectors like consumer goods, circular strategies can be implemented through relatively short lifecycle loops, such as plastic bottle recycling (TNO, 2024). However, the built environment differs significantly due to its long asset lifespans, complex material compositions, and diverse stakeholder involvement, making strict adherence to the R-ladder difficult. Additionally, the framework does not provide explicit implementation pathways, creating barriers to adoption and limiting its practical applicability in the built environment (Norouzi et al., 2021).

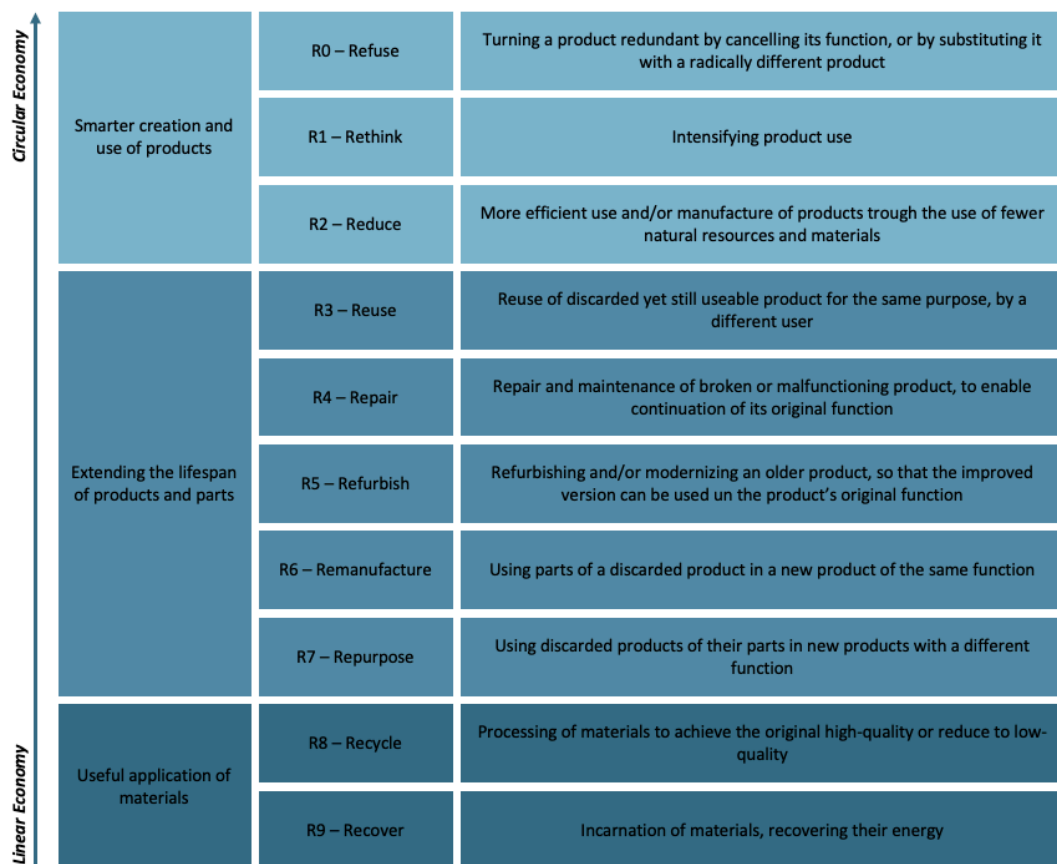


Figure 1.4: R-ladder. Adapted from (Potting et al., 2017).

Circular Strategy Framework The CSF consists of circular strategies aimed at transitioning the built environment toward greater resource efficiency. Similar to the R-ladder, its primary objectives are to reduce resource input, extend the lifespan of buildings and materials, and close material loops to minimize waste. However by providing a more specific and structured framework, project developers can implement these strategies more effectively, increasing their adoption and practical applicability. (Çetin et al., 2021)

As can be seen in Figure 1.5, the circular building strategies are structured around four core principles.

1. **Regenerate** – Aiming to create a positive environmental impact by using renewable resources, promoting biodiversity, and enhancing the built environment.
2. **Narrow** – Focuses on reducing primary resource inputs by optimizing material use and improving efficiency.
3. **Slow** – Aiming to extend the lifespan of buildings and their components through durable design, easy maintenance, and adaptability.
4. **Close** – Ensuring that materials are continuously reused, recycled, or repurposed instead of being discarded.

Core Principle	Circular Building Strategy	Description	Example
Regenerate	Stimulate human nature co-habitation and local biodiversity	Create spaces for human nature interaction and biodiversity	Green roof project
	Use healthy and renewable resources	Eliminate toxic contents, use bio-based materials, and produce with renewable energy	Producing insulation panels from mycelium
	Enhance indoor and outdoor environment	Improve the indoor environment and regenerate degraded outdoor spaces	Transformation of misused urban areas into public spaces
	Exchange excess resources	Exchange surplus resources produced by regenerative buildings	Exchanging renewable energy within the neighborhood
Narrow	Reduce primary resource inputs	Minimize primary resource use and waste	Minimize primary resource use and waste
	Design for high performance	Optimize buildings and systems for fewer resource	Optimization of lightweight structures
	Improve efficiency	Enhance performance of building systems and operations to minimize resource consumption	Deep energy renovation
Slow	Design for long life	Design buildings with durable materials, consider ease of maintenance and repair, and design for emotional attachment	
	Design for reversibility	Design buildings and products for multiple life cycles with deconstruction and transformation strategies	
	Lifetime extension	Extend the service time of buildings and components by restorative activities	
	Smart use of space	Deliver new functionalities to underutilized buildings, and land through adaptive reuse and flexibility	Flexible office spaces
	Deliver access and performance	Provide access, functionality or services without offering ownership of buildings and building products	Pay-per-lux model for lighting
	Reuse	Bring resources back into the economy with a minimum of resource input	Construct indoor partitions from old windows during façade renovation
Close	Recycle	Convert reclaimed resources into similar or lower quality ones with considerable energy and water input	Recycling concrete aggregates
	Urban mining	Extract materials from the urban environment that are not designed for reuse or recycling	Urban mining project
	Industrial symbiosis	Initiate synergistic interactions between different industries to recover waste and by-products	Industrial symbiosis for recycled aggregates
	Track and trace resources	Track and trace resources from extraction/reclamation until end-of-use stages and in further cycles	Track and trace resources from extraction/reclamation until end-of-use stages and in further cycles
Collaborate (as supporting strategy)	Support supply chain collaboration	Work with partners in the existing supply chain to slow, close, narrow and regenerate resource loops	Reverse logistics
	Create knowledge and value networks	Identify and develop new networks for collaboration to implement ambitious CE visions	Buyer group is established to foster circular procurement

Figure 1.5: Circular Strategy Framework (CSF). Adapted from (Çetin et al., 2021). Modified by author.

In addition to the R-ladder and the CSF, this research incorporates circular strategies derived from the work of Eberhardt et al. (2022). This study offers a valuable contribution by focusing on the practical implementation of circularity within the built environment. The strategies are categorised by their scale of application, building, component, and material level, and are further assessed based on their level of technological readiness, as identified in the literature. This classification provides a meaningful complement to the more conceptual approaches offered by the R-ladder and CSF.

Cost

While this research primarily focuses on the relationship between circularity and carbon reduction, cost remains a critical factor influencing the feasibility of implementing circular strategies. The financial feasibility of a project determines the extent to which circular interventions can be accommodated within its scope. Therefore, cost is introduced as a boundary condition within the assessment framework, shaping the practical applicability of carbon reduction strategies.

Regulations and Guidelines

To position this research within the broader framework of circular construction, it is crucial to identify the key regulatory instruments and assessment frameworks that shape sustainable practices in the built environment. These instruments not only establish the legal and methodological foundation for environmental evaluation but also guide the implementation of circular strategies in practice. Understanding

these frameworks is essential for aligning the research with current standards and policy developments at the global, European, and national levels.

Table 1.1 provides an overview of the most relevant regulations, guidelines, and certification schemes. It categorizes them by governance level, clarifies their respective subjects and objectives, and highlights their significance in the context of this study. This structured overview serves as a reference point for the regulatory landscape in which this research is embedded, supporting the development and evaluation of circular strategies for EC reduction.

Table 1.1: Overview of primary regulations, guidelines and certification tools. Own illustration.

Level	Instrument	Subject	Aim	Source
Global	Regulation	Paris Agreement	International climate treaty regarding CO ₂ reduction target in the built environment	(United Nations, 2025)
Global	Regulation	ISO 14040/44 and EN 15978	Official framework for Life Cycle Assessment	(ISO Standards, 2025; NEN, 2025)
EU	Regulation	Circular Economy Action Plan	Action plan regarding circular economy	(European Union, 2023)
EU	Regulation	Levels	Framework for sustainable buildings, designed to evaluate and report the sustainability performance of buildings	(European Union, 2024)
Netherlands	Regulation	MilieuPrestatie Gebouwen	Measures the environmental impact of building materials, with lower values indicating greater sustainability, serving as a key tool in design and sustainability requirements	(Rijksdienst voor ondernemend Nederland, 2017)
Netherlands	Regulation	Nationale Milieu Database	Providing standardized environmental data for calculating the environmental performance of buildings	(NMD, 2025)
Netherlands	Guide	Dutch Green Building Council	Knowledge and network organization accelerating the sustainability transition of the Dutch built environment	(DGBC, 2025)
Netherlands	Certification	BREEAM-NL	Certification method for a sustainable built environment is a standardized framework used to assess and verify the sustainability performance of buildings	(BREEAM, 2025)

1.2.2. Research Problem

To support the transition toward circular construction and Paris Proof buildings, the industry relies on a growing set of digital tools and frameworks. These tools aim to enhance decision-making by providing insights into environmental performance, material usage, and circular potential, especially during the early design phases where most of a building's environmental impact is determined.

While several emerging technologies, such as Artificial Intelligence, Digital Twins and Internet of Things, show strong potential to support circular construction, this study focuses exclusively on tools that are already widely adopted across the industry (David et al., 2025; Yu et al., 2022). This choice for established systems like BIM and material passports have proven practical applications and offer more accessible data for analysis. By narrowing the scope to these tools, this research aims to address the practical implementation challenges and specifically fill the existing gaps in how current frameworks support circularity and UEC reduction. Although emerging technologies are promising, significant gaps remain in terms of data integration and decision-making, both in renovation and new construction contexts. (Çetin et al., 2022)

BIM is an integrated process for generating and managing project data within a three-dimensional digital environment. It is utilized throughout various project phases, including planning, design, construction, and operation (Autodesk, 2024). BIM enables the tracking of both physical and functional characteristics of a project, facilitating collaboration among stakeholders in the design and construction phases. Additionally, it supports sustainable construction by providing a platform to implement and assess different sustainability strategies.

Several obstacles hinder BIM in the effectiveness of implementing circular construction. Firstly, BIM is mainly used for design and visualization rather than material tracking, deconstruction planning, and circularity assessments. Advanced functionalities like 4D (time-based scheduling) and 5D (cost-based estimation) are underutilized. Secondly, the lack of standardization leads to inconsistent material tracking and data loss, as no universal standard integrates circular economy principles into BIM. Third, poor data management further limits the role of BIM. Within BIM product life-cycle data are often missing or incomplete, and cloud-based data sharing is not widely adopted, affecting the design phases. Finally, the financial integration is missing. Clients often prioritize short-term costs over long-term circular benefits, slowing BIM adoption in circular construction. (Kioumars Mahdi & Shafei, 2025; Liu et al., 2024; Mcneil-Ayuk & Jrade, 2024)

Material passports are increasingly used in circular construction and asset management to document material composition, CO₂ storage, and disassembly potential. Systems such as Madaster and the Building Circularity Index (BCI) serve as repositories of building material data, offering circularity indicators that assess reuse potential and other lifecycle characteristics (BCI, 2025; Heisel & Rau-Oberhuber, 2020; Madaster, 2025). However, these tools are typically applied after project delivery, meaning they primarily function as post-construction databases rather than integrated design systems. As such, their current use supports circularity assessment retrospectively rather than guiding material selection or circular decision-making in the early design phases, where the greatest impact on reducing UEC can be achieved (Figure 1.6).

In addition to material passport systems, other software tools are used by architects to support carbon-conscious design. A notable example is the LEVS Carbon Tracker, which is employed to optimize carbon reduction strategies within financial constraints. However, the tool presents several limitations in terms of collaborative usability. It is not open-access, lacks multi-user functionality, and requires direct collaboration with their design office. These constraints limit its broader applicability, particularly when the objective is to enable independent and transparent use by all members of the DT.

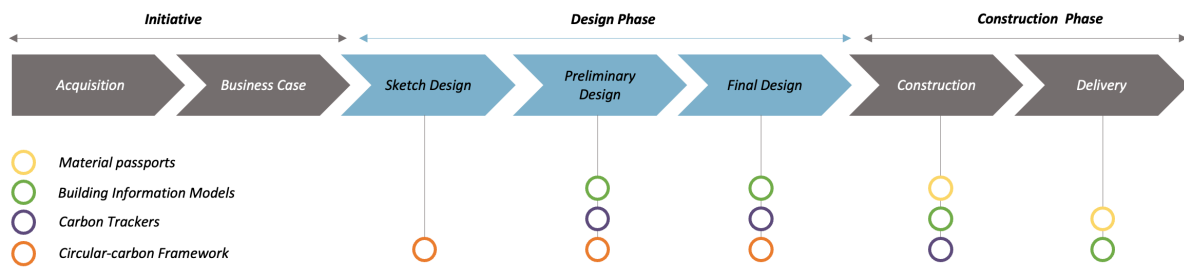


Figure 1.6: Building phases and tool comparison. Own illustration.

Although various literature and tools exist to support circular construction and the reduction of EC, both research and practice still lack an integrated approach that aligns circular strategies with measurable carbon reduction and financial feasibility. Current models often focus on identifying circular solutions or providing qualitative assessments but do not offer a structured method to quantify the trade-offs between carbon, cost, and circularity. This missing connection is particularly critical for aligning new construction projects with Paris Proof targets, which require significant reductions in upfront emissions.

Moreover, several practical barriers persist. The limited accessibility of material passports, fragmented data environments, and the absence of integrated, structured datasets hinder the effective application of circular principles in real-world projects (Marchi et al., 2024; Mikulėnas & Šeduikytė, 2025). As regulatory pressure to reduce EC increases, real estate developers are increasingly expected to adopt sustainable design approaches. However, without clear and accessible insights into the carbon and cost implications of circular strategies, decision-making in practice remains uncertain.

This challenge is most acute in the early design phases, where environmental performance is largely determined, but data is limited. This situation is referred to in this research as the *early-decision paradox*, which describes the difficulty of making informed design choices at a point when their long-term impact is greatest. Although circularity is widely acknowledged as a pathway to reduce embodied emissions, there is a lack of practical, data-driven methods to apply circular strategies effectively in early-phase design processes (Charef, 2024; Santos et al., 2025; Tirado et al., 2022).

To address this gap, this study investigates how circular strategies can be used to reduce UEC in alignment with Paris Proof carbon goals, while simultaneously assessing the financial feasibility (Figure 1.7). By quantifying the impact of specific circular strategies between carbon, cost, and circularity, in collaboration with the DT, this research aims to support more transparent and informed decision-making in the early design stages. In doing so, it contributes to bridging the gap between theoretical circular potential and practical implementation.

These objectives are captured in the main research question of this study:

How can a framework be developed to evaluate the impact of circular construction strategies on upfront embodied carbon reduction and financial feasibility during early design phases?

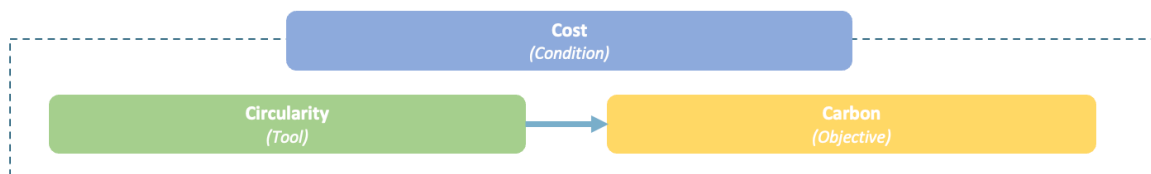


Figure 1.7: Schematic representation of the relationship between Carbon, Cost and Circularity. Own illustration.

1.3. Research Questions

Research Question:

How can a framework be developed to evaluate the impact of circular construction strategies on upfront embodied carbon reduction and financial feasibility during early design phases?

To support the main research question, four sub-questions have been formulated:

Sub Research Questions:

1. What are the contextual foundations necessary to develop a framework that integrates carbon, cost, and circularity?
2. What circular construction strategies can be categorized and applied across different design phases to support early-stage decision-making?
3. How can a multi-layered framework be developed to systematically structure and quantify the relationships between circular strategies, upfront embodied carbon, and financial feasibility?
4. How can the Circular-Carbon Framework be applied to support design teams in selecting circular strategies that aim for Paris Proof building performance while maintaining financial feasibility?

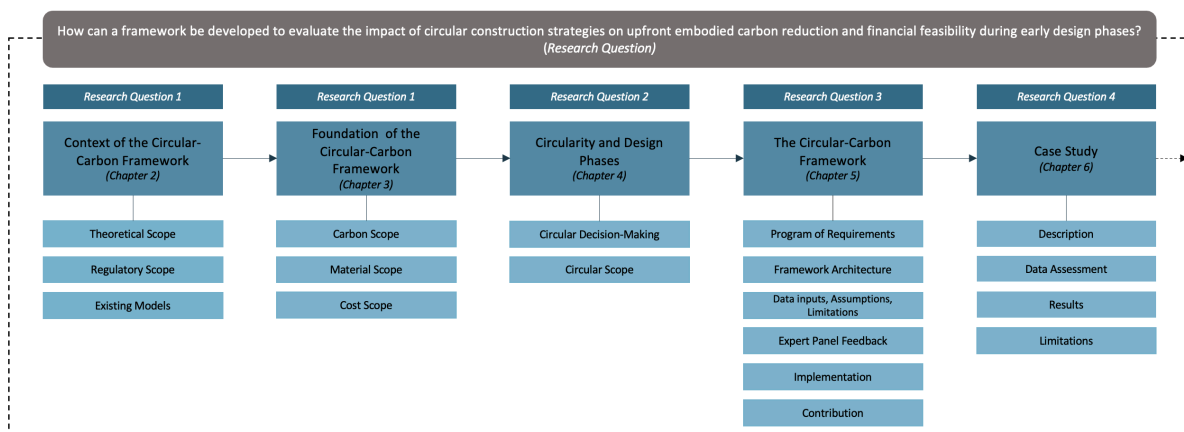


Figure 1.8: Conceptual Model Research Questions. Own illustration.

1.4. Research Design

1.4.1. Research Method

Literature Review

The literature review will focus on the collection and analysis of non-numerical data to understand basic circular economy concepts within the construction industry. The methodological approach used is action research, which integrates theoretical insights with practical applications to drive (social) change (Bhandari, 2025).

To build this foundation, the research begins with a structured review of the literature, which identifies gaps and defines the scope of the study. The identification of a literature gap has motivated this research. The literature review follows a systematic approach comprising four stages: (1) designing the review, (2) conducting the review, (3) analyzing findings, and (4) synthesizing and presenting results (Snyder, 2019). However, similar to the research topic itself, this process should be circular rather than linear, ensuring an iterative refinement of insights.

Using this method presents certain limitations, primarily due to the lack of stakeholder engagement, which can reduce its relevance. Another critical limitation of literature research is selection bias, which occurs when the chosen articles are not representative of the overall body of evidence. Although increasing the volume of reviewed literature may mitigate this issue to some extent, it remains constrained by the availability of research. Many relevant studies are inaccessible due to paywalls and restricted access to journals, which constitutes a third limitation. Lastly, literature research is susceptible to publication bias, wherein studies with positive and statistically significant findings are more likely to be published than those reporting negative or non-significant results. (Haddaway et al., 2020)

Interviews

To gain deeper insights, semi-structured face-to-face interviews will be conducted with professionals across the real estate value chain. This qualitative method allows respondents to answer open-ended questions freely, avoiding restrictive responses (Utibe Monday, 2020). Since the specific knowledge gaps regarding the selection of (combinations of) circular strategies exist among various stakeholders in the real estate value chain, interviews are a suitable method for identifying these gaps.

However, this method introduces another form of bias, known as subconscious bias. Interviewees may only disclose information they are prepared to share, shaping their responses based on personal perceptions of events and opinions. The perceptions can be subjective and may change over time due to evolving circumstances. Additional limitations of this method include its time-consuming nature, particularly in conducting and transcribing interviews. The transcription process can introduce inconsistencies, as errors in interpretation may affect the accuracy of the data and therefore the reliability of the results. (Alshenqeeti, 2014)

Expert Panel

An expert panel will be used to validate the Circular-Carbon Framework (CCF). An expert panel refers to a structured group of individuals selected based on their experience, knowledge, or involvement with a specific topic. Such panels are commonly employed in research to interpret data, validate findings, or refine complex concepts. (D. Walker, 2023)

Using an expert panel is particularly suitable for theoretical validation of the CCF before its application in a case study. As the framework addresses multifaceted themes, namely carbon, cost and circularity, input from professionals with relevant practical expertise helps ensure that the framework is applicable in real-world contexts. The collective discussion among experts can also reveal blind spots or underlying assumptions that may not be evident in a purely theoretical design. Based on this feedback, the framework can be revised and improved to enhance its clarity, robustness, and usefulness.

Nonetheless, the expert panel method also presents certain challenges. It is often time-consuming and resource-intensive, requiring careful planning to ensure timely execution. Additionally, strong and conflicting opinions among panel members may hinder consensus. To address this, the composition of the panel should be carefully considered to achieve a balanced representation of perspectives. More-

over, facilitation strategies should be employed to prevent dominant voices from overshadowing other valuable input. (D. Walker, 2023)

Case Study

A case study will be conducted as part of this research. A case study is a detailed investigation of a specific group, location, or organization, among other subjects (McCombes, 2019). In this study, the selected case will be the project development of one of EDGE's projects. After developing the CCF, the model will be practically validated by applying it to a real-world project.

One of the key advantages of case study research, especially in exploratory studies, is its flexibility and capacity for in-depth analysis. A well-executed case study can enhance readers' understanding by engaging them in knowledge construction as if they had experienced the case firsthand. This is precisely the objective: to create a model that project developers can utilize, guiding them toward more sustainable yet financially viable development. (Marrelli, 2007; Patton, 2002)

However, case study research presents several challenges. First, due to its specificity, the number of cases studied is typically small, making it more difficult to generalize findings. Second, the assessment and interpretation of data are influenced by the researcher's knowledge and those involved in constructing the study, introducing the potential for subjective bias (Pelto & Pelto, 1978). Finally, translating the findings into a coherent and well-structured narrative can be a complex process, requiring consideration of both the data and the overarching research objectives. (Marrelli, 2007)

Operational Model

The operational model serves as a guiding framework for this research. Based on Yin (2003), the operational model is structured into three distinct phases (Figure 1.9).

The first phase, Define and Design, establishes the foundation of the study by outlining its structure and research framework. This phase ensures a clear direction for subsequent research activities.

The second phase, Prepare, Collect, and Analyze, focuses on data collection through a combination of literature review and interviews. The collected data will inform individual reports addressing specific sub-research questions. Additionally, it will support the development of the CCF, which will be validated through an expert panel and case study to assess its strengths and weaknesses.

The third phase focuses on restating the key findings of the sub-research questions, followed by answering the main research question. This is complemented by a discussion, reflection, and a set of recommendations.

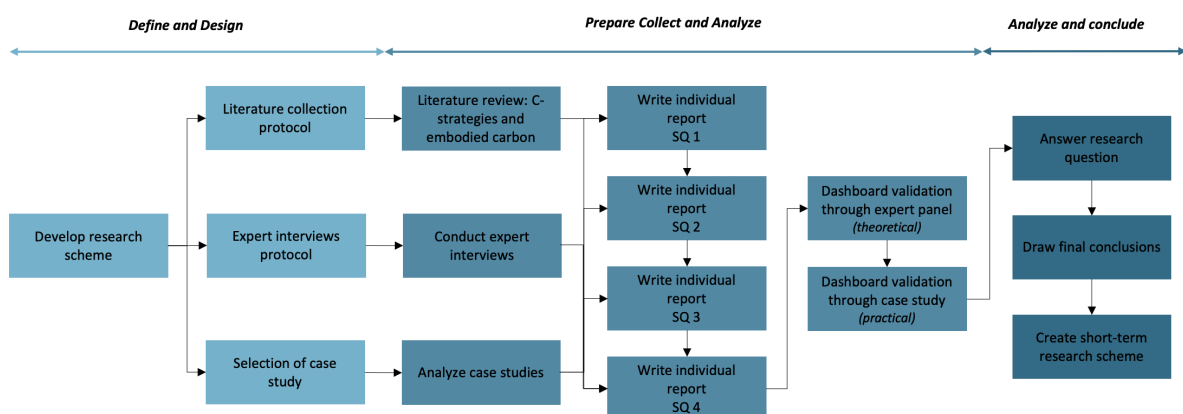


Figure 1.9: Operational model. Based on (Yin, 2003). Modified by author.

1.4.2. Data Gathering and Analysis

Literature Review

The foundation of this study is based on an extensive review of the scholarly literature. The primary data sources include Google Scholar, Scopus, Researchgate and the TU Delft library, ensuring access to high-quality and peer-reviewed academic publications. In certain cases, additional data sources may be used; however, these will only be used after a critical assessment of their credibility and relevance. This approach ensures a robust theoretical framework while mitigating the risks of selection bias and unreliable information.

In addition to primary literature, secondary sources will also be utilized. This will involve document analysis from professional institutions, including governmental bodies (e.g., the European Union), national governments, and independent organizations such as BREEAM-NL. These sources will provide industry-specific insight and practical frameworks relevant to circular construction practices.

Interviews

To complement the literature research, semi-structured interviews will be conducted with key stakeholders from various sectors within the real estate value chain. Each professional will be represented to understand the diverse perspectives on the challenges and opportunities of the implementation of circularity data. The primary interviewees will include material suppliers, architects, structural engineers, project developers, as well as cost and sustainability advisors. These interviews will form the basis for this research. The contact with these stakeholders will be established through EDGE's business relations and personnel, covering a significant part of the interviewees. Additional interviews will be organized through personal connections ensuring diverse representation of relevant stakeholders.

To ensure the quality and relevance of the collected insights, interviewees will be selected based on the following criteria:

- **Minimum of five years of professional experience:** preference will be given to candidates with more extensive experience.
- **Involvement in the design or realization of office buildings:** ensuring practical, project-based knowledge.
- **Strong knowledge of circularity and carbon reduction strategies:** guaranteeing expertise on the research topics.

These criteria aim to guarantee that the interviews yield informed, practical, and contextually grounded perspectives.

For the analysis of the interviews, it is essential to accurately summarize and anonymize the interview recordings while ensuring that the original meaning and context remain intact. The primary focus will be on identifying recurring concepts and themes across different interviews through cross-case analysis and systematic categorization (Talja, 1999). By grouping responses based on emerging concepts, insights are gained into how different stakeholders perceive key aspects of circular construction processes and financial feasibility.

Furthermore, newly collected interview data will serve as a feedback loop for the literature review, allowing an iterative approach to refining theoretical frameworks and identifying gaps that may not have been initially considered. This iterative process will be particularly crucial for addressing sub-questions one to four, as it will provide deeper empirical grounding for the research findings.

Expert Panel

To ensure the development of a robust and practically applicable dashboard, it is essential to establish a credible expert panel composed of professionals from diverse sectors and areas of expertise. Key stakeholders from the DT will be invited to participate, including the project developer from EDGE, a architect, cost advisor, sustainability consultant, and structural engineer. This panel will serve as a critical layer for evaluating the dashboard's structure, relevance, and usability within real-world design

processes. Conducting the session in person is preferred, as it facilitates dynamic discussion and more nuanced feedback. No video or audio recordings will be made; instead, the outcomes of the session will be documented through a summarized, anonymized report to preserve confidentiality while capturing key insights.

Case Study

The CCF will be used for case study analysis and is modeled in Microsoft Excel. This software was chosen because of its built-in functionalities that align well with the research requirements, as well as its wide user base, which facilitates future adoption of the model by other stakeholders.

The case study that could be incorporated to validate this model practically is for example EDGE Coolsingel Rotterdam. This new construction project, located at Coolsingel 75, features a relatively straightforward building structure, which makes it a suitable case to systematically analyze various combinations of circular strategies (Edge, 2024). Additionally, a substantial amount of tracked carbon and circularity data is available, enabling a comprehensive evaluation of circular strategies.

Furthermore, the financial aspects of the project are already well-documented, as the early design phases have been completed and the project is currently in the construction phase. This availability of material cost data improves the reliability of the case study, making EDGE Coolsingel a good project to assess the validity and applicability of the CCF.

Data Management Plan

To ensure the safe and responsible handling of research data, the DMPOnline platform provided by TU Delft will be utilized throughout the project. This platform offers guidance on the secure collection, documentation, and storage of data during the research phase and after the project's completion, thereby supporting long-term data preservation and accessibility. The Data Management Plan will be reviewed by a data steward, as well as by relevant committee members, to ensure compliance with the academic standards for data management.

The research will involve three main types of personal or project-related data: interview data, expert panel data, and project documentation. All data types will be documented in an anonymized and/or generalized format to protect the confidentiality of participants and project stakeholders while retaining the value of the information. All confidential data will be securely stored on the TU Delft Data Storage (U:) drive, which meets TU Delft's requirements.

Use of Artificial Intelligence

Throughout this thesis, ChatGPT (OpenAI, Model version-4) was used as a supportive tool to enhance the research and writing process. The tool contributed to brainstorming activities, including the setup of chapters, paragraph structuring, and the organization of tables. Additionally, it was used to help rewrite draft sections into more formal and academic English to improve readability and clarity.

ChatGPT was also employed in the preparation of the interview process. It supported the development of the interview setup and the drafting of interview questions, including those used for the expert panel feedback sessions. Furthermore, ChatGPT was used to assist in rewriting interview summaries, strictly in anonymized form. At no point were company names, personal identifiers, or any sensitive information uploaded into the chat environment, in order to fully protect the privacy of the participants.

ChatGPT was used exclusively as a language and ideation tool between April and August 2025. It was never applied to generate original content, perform data analysis, or formulate conclusions. All interpretations, structuring of arguments, and final content remain the sole responsibility of the author. The use of AI was conducted in line with TU Delft's academic integrity policies.

At all times, the generated output was critically assessed, fact-checked, and edited by the author to ensure academic integrity, originality, and accuracy. To the best of my knowledge, ChatGPT was never used in a way that would risk unintentional plagiarism.

1.5. Research Rationale

Research Objective

This research aims to support early-phase decision-making within DTs, specifically in balancing UEC, material cost, and circularity. Rather than creating a document that remains on a bookshelf, this research seeks to fill a critical knowledge gap in decision-making processes related to circularity and CO₂ emissions during the early design phases.

Research Context

Currently, there is no tool available to track project-specific CO₂ emissions per circular strategy during the design phases while also considering the associated material costs. Although industry professionals are aware of the possible circular strategies and their cost implications, no structured model has been developed to systematically integrate this information into the decision-making process. While specialized consultancy firms possess expertise in this area, access to such insights should be available to all key stakeholders in the construction industry, including project developers, project owners, contractors, and architects.

By making this data accessible and optimizing its usability, all potential combinations of circular strategies can be tested within a project, allowing for an informed selection based on the EC impact relative to cost increases. Although front-runner projects, such as those developed by EDGE, may derive less direct value from this model due to their advanced sustainability approaches, the broader industry stands to benefit significantly. This is where substantial progress in sustainability can be achieved at an industry-wide scale.

Deliverable

The final deliverable of this research is the CCF, a structured approach designed to support decision-making in early-phase building design by integrating circular strategies with carbon and cost considerations. The framework aims to fill a critical knowledge gap by enabling project stakeholders to compare and evaluate circular options based on their potential to reduce UEC while maintaining financial feasibility.

At the core of the CCF is a decision-support dashboard, developed as a practical tool to operationalize the framework. This interactive, Excel-based dashboard allows users, primarily DT members, to input project-specific data and explore which combinations of circular strategies best align with their project's objectives. By evaluating trade-offs between carbon, cost and circularity the dashboard serves as the primary interface for applying the framework in practice.

While the underlying structure of the framework remains consistent, the dashboard is designed to accommodate varying project inputs, making it adaptable to different real estate contexts. It draws on expert interviews, literature, and industry data to ensure the included strategies and assessment logic reflect current practice and practical feasibility.

1.6. Research Relevance

Project management has long been framed by the Triple Constraint Model, also known as The Iron Triangle, which was introduced in 1999. This model emphasizes three fundamental success criteria in project management: Cost, Time, and Quality, all defined within a specific scope (Atkinson, 1999). The degree to which these criteria are optimized determines the likelihood of project success. Although these principles remain relevant today, the specific content and focus of these criteria have evolved, particularly in the face of current challenges such as sustainability, climate goals, and circularity in construction.

A major driving force behind this research is the increasing regulatory and societal pressure at global, European, and Dutch levels to achieve the CO₂ reduction targets. This necessitates new tools that can steer and assess the new criteria for project success. It creates a need for tools that can assess project success by steering and evaluating circular construction implementation toward sustainable goals.

1.6.1. Scientific Relevance

Despite the increasing focus on circular construction through regulations, frameworks, and certification schemes, its consistent implementation across the industry is not yet standard practice. While several frameworks exist to map circular economy strategies, they typically remain descriptive and do not assess how these strategies function as tools for reducing UEC while staying within financial feasibility.

Currently, no framework quantitatively evaluates the extent to which circular strategies contribute to UEC reduction in real design contexts. This research addresses that gap by introducing a model that explores how circularity can be used as a lever to reduce carbon emissions, rather than treating it as a standalone goal. Scientifically, this is particularly relevant: Which circular strategies actually reduce UEC? Is this true for all strategies, or only for specific types? These questions remain largely unanswered in existing literature.

In addition to filling this practical and theoretical gap, the proposed framework aligns with existing models of project success (Atkinson, 1999; PMI, 2021) by offering structured, decision-oriented guidance for practitioners. It also contributes to academic discourse on material traceability, digitalization in construction, and the operationalization of circular economy principles (Çetin et al., 2021; Naji et al., 2024; Rodrigo et al., 2024; Z. Zhang et al., 2024). Finally, the framework may offer a foundation for future methodological innovations aimed at enhancing sustainability performance in the built environment.

1.6.2. Practical Relevance

The practical relevance is divided into three levels defining its relevance:

1. **Project level (*Micro*):** The CCF supports DTs in using circular strategies as tools to reduce UEC while maintaining financial feasibility. It enables early-phase comparison of strategies, helping project developers make better-informed decisions aligned with Paris Proof goals.
2. **Industry level (*Meso*):** By translating abstract circularity principles into a practical and repeatable decision-making tool, the framework helps make circular implementation more realistic, applicable, and generalizable across different projects. This supports broader adoption of circular strategies within the construction industry.
3. **Societal level (*Macro*):** By enhancing circular implementation, this study hopes to contribute to a more sustainable and cleaner living environment, aligning with broader societal goals for resource efficiency and environmental preservation.

Developing the proposed framework creates a crucial intersection between science and practice by identifying circular strategies from literature that can be effectively applied in real projects. This research will enhance understanding of key design decisions and support the transition to a circular economy in the built environment.

2

Context of the Circular-Carbon Framework

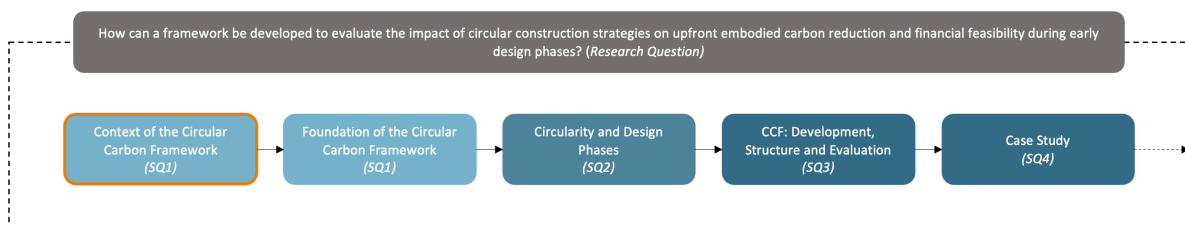


Figure 2.1: Chapter 2 roadmap. Own illustration.

2.1. Introduction

This chapter defines the contextual foundation for the development of the Circular-Carbon Framework (CCF). It begins by examining the theoretical basis in which the model is conceptually grounded, focusing on the integration of Carbon, Cost, and Circularity as central design variables. The Value-Driven Design methodology is introduced as a guiding structure to support multi-criteria decision-making during early design stages.

In addition, the chapter explores the regulatory environment that informs and constrains the application of the CCF. This includes an analysis of relevant policy frameworks, performance thresholds, and certification systems that are essential for aligning the model with current sustainability requirements.

Finally, a review of existing models is presented to identify current limitations in supporting design teams (DTs). This comparative analysis clarifies the specific contribution of the CCF and the gap it aims to address. Together, these elements establish a comprehensive foundation for the development of a practical, data-driven decision-support tool for sustainable construction design.

2.2. Theoretical Scope: Value-Driven Design

The objective of this research is to develop a decision-support tool that guides circular construction design. Given the complexity of sustainability-related challenges, this involves more than merely combining environmental and financial indicators. Core objectives such as reducing upfront embodied carbon (UEC), enhancing material circularity, and ensuring financial feasibility are intrinsically interconnected and frequently involve trade-offs. Addressing these goals in a structured and balanced manner requires the development of a design model grounded in a sound theoretical framework.

In the absence of such a foundation, design models risk becoming overly simplistic by treating key objectives in isolation, or inconsistent by lacking a clear and systematic approach to comparing alternative design options (Gorschek et al., 2014). This issue is especially critical during the early design stages, when decisions remain flexible but the availability of reliable data is limited. Under such conditions, a methodology that integrates system-level thinking with value-based reasoning is essential.

To address this need, the research adopts Value-Driven Design (VDD) as the overarching framework. VDD provides a structured approach to evaluating design alternatives based on multiple performance variables. Within the context of this study, these variables include Carbon, Cost, and Circularity. (Movaffaghi et al., 2020)

Originally developed within the aeronautical industry, the VDD methodology is particularly well-suited to complex project environments where multiple stakeholders often hold differing interpretations of value (Castagne et al., 2009; Collopy & Hollingsworth, 2009). This is also the case in the construction sector, where perspectives on sustainability, functionality, and cost efficiency frequently diverge. Instead of relying on a fixed, one-size-fits-all definition of value, the VDD framework enables a context-specific interpretation that reflects the priorities of the DT and client, sustainability objectives, and project-specific adaptability requirements (Keeney, 1992).

Figure 2.2 illustrates the conceptual model of VDD. The model represents the design process as an iterative cycle. These variables represent the parameters that define the initial configuration of the design. The cycle then proceeds through configuration, analysis, and evaluation of attributes, ultimately feeding back into the value assessment. This continuous feedback loop emphasizes that high-quality design solutions emerge through multiple iterations and progressive refinement of design decisions.

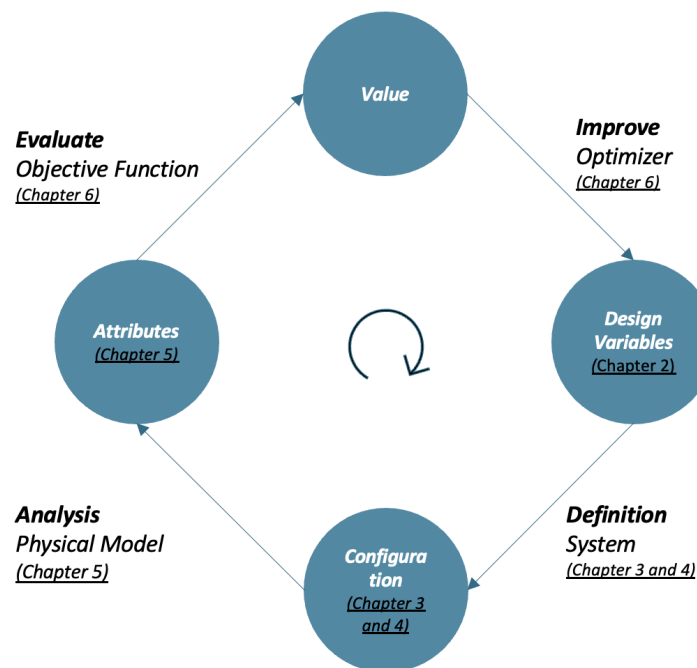


Figure 2.2: Value driven design conceptual model. Adapted from (Collopy & Hollingsworth, 2009).

The development and structure of this thesis are directly aligned with the phases of the VDD model, a methodology used to guide decision-making through the iterative formulation and evaluation of value-driven criteria. Each chapter contributes to a distinct phase within the VDD cycle, progressively translating abstract sustainability goals into a functional and evaluative decision-support tool: the CCF.

The first phase of the VDD model, Design Variables, is addressed in chapter 2. This chapter introduces the three fundamental criteria Carbon, Cost and Circularity. These variables define the design space. Furthermore, the chapter contextualizes these variables within current regulations, certification system, and existing models, thereby establishing their relevance and interdependence in practice.

The second and third phase, definition and configuration, are addressed in chapters 3 and 4. Chapter 3 focuses on carbon and cost variables, qualitatively introducing their corresponding attributes and determining the material scope by identifying elements that contribute most to UEC and material cost. Chapter 4 introduces the final variable, circularity, and its attributes. It explores how circularity is interpreted and applied in practice, identifies key roles within the DT, and outlines primary strategies. Together, these chapters define a clearly bounded system in which all three variables are structured into a operational indicator set.

The fourth and fifth phases, Analysis and Attributes, are presented in Chapter 5. In this chapter, the insights from previous chapters are synthesized into a general form of the CCF. The three variables, along with their corresponding attributes, are structured into the CCF model and tested against a selection of structural and skin materials (Figure 2.3). The attributes are quantitatively defined and integrated into the framework. This chapter marks the completion of the general CCF model.

The sixth phase, Evaluate and Improve, is presented in Chapter 6 through the application of a case study. The general CCF model is tested in a real-world context to assess its practical applicability. This phase yields two types of results. First, it evaluates whether the CCF functions as intended when applied in practice. Second, it provides conclusions specific to the case study, identifying which circular strategies perform best across the three variables and assessing whether the model can effectively support design teams in decision-making.

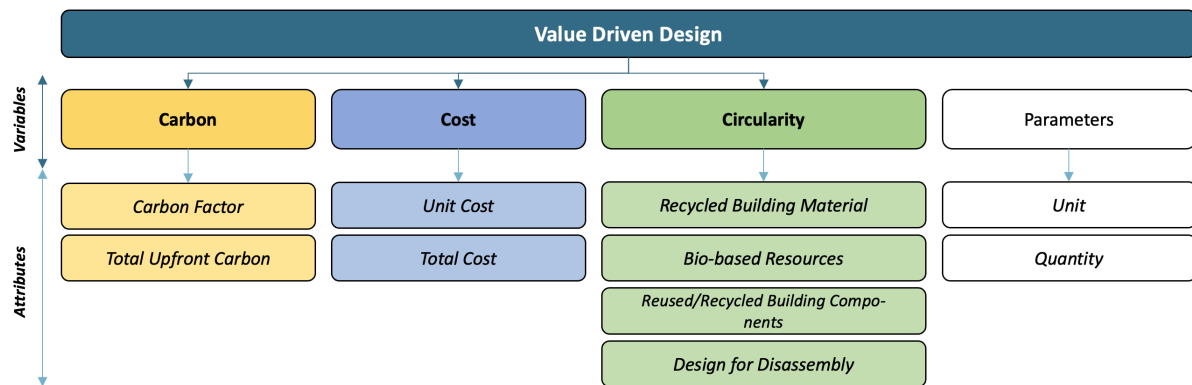


Figure 2.3: Overview of the variables and attributes of the value driven design model as adapted for the CCF. Own illustration.

2.3. Regulatory Scope

The title of this thesis, *From Data to Paris Proof*, implies that enhanced data utilization can accelerate progress toward achieving Paris Proof threshold values. To understand how such threshold values are operationalized, it is essential to first explore the regulatory and methodological pathway that guides this transition. This begins with an overview of the multilevel policy framework, from global agreements to national instruments and practical tools, represented in the Road to Paris Proof figure.

Following this, special attention is given to the Paris Agreement, which forms the foundation of the long-term climate objectives. Understanding how its global targets were translated into national threshold values for the Dutch built environment is critical. Once these values are established, they can be integrated into the the CCF.

2.3.1. Regulations and Tools

To comprehend the road to the Paris Proof objectives, it is essential to examine the various policy instruments operating across different governance levels, and to understand the positioning of the CCF within this trajectory (Figure 2.4).

At the global level, the Paris Agreement serves as a foundational policy, reflecting a collective acknowledgment of the climate crisis and the need for coordinated international action. This agreement has catalyzed subsequent policy development across lower governance levels.

At the European level, the European Green Deal serves as the overarching strategic framework introduced by the European Commission in 2019. Its principal objective is to achieve climate neutrality within the European Union by 2050. This wide-ranging strategy encompasses several sectors, including energy, industry, mobility, agriculture, and the built environment. One of its key targets is the reduction of net GHG-emissions by at least 55% by 2030 compared to 1990 levels (European Council, 2025). Within this context, the Circular Economy Action Plan plays a critical role, aiming to close material loops in Europe, with the construction sector identified as a major contributor. The plan strongly aligns with the goals of this research, particularly in promoting reuse, circular design, and the evaluation of environmental impacts over the building life cycle (European Union, 2023). Complementary to this, the Levels framework was developed as a tool to measure and report on the sustainability performance of buildings. It emphasizes quantifiable indicators across environmental, social, and economic dimensions over the full life cycle of buildings (European Union, 2024).

At the national level in the Netherlands, three interrelated policy instruments translate European ambitions into binding regulations. First, the *'Besluit Bouwwerken Leefomgeving'* (BBL), in effect since 2024, serves as the legal framework establishing technical requirements for both new and existing buildings. As part of the Environmental and Planning Act, the BBL stipulates minimum standards concerning safety, health, usability, energy efficiency, and environmental performance (Rijksdienst voor Ondernemend Nederland, 2025). It embeds the *'Bijna EnergieNeutrale Gebouwen'* (BENG) and *'MilieuPrestatie Gebouwen'* (MPG) requirements as statutory obligations. Although BENG, mandated since 2021 for all new constructions, focuses on energy use during the operational phase, it is included here for completeness (Rijksdienst voor Ondernemend Nederland, 2017). The MPG regulation, by contrast, directly assesses the environmental impact of construction materials based on life cycle assessment (LCA) methodology, thereby aligning closely with the subject of this study. Since 2018, MPG compliance has been required for new residential buildings and large office developments (Rijksdienst voor ondernemend Nederland, 2017). These assessments depend on data derived from the Nationale Milieudatabase (NMD), which contains standardized profiles of building materials compiled in accordance with strict LCA protocols. Together, LCA methodology and NMD constitute the technical foundation for validated MPG calculations, thereby establishing the MPG as a key legal indicator of building sustainability (NMD, 2025).

Digital tools such as BIM and material passports provide critical input for conducting LCAs and generating MPG assessments. BIM models facilitate the visual representation and quantification of material specifications, while material passports offer structured data on the origin, composition, and circularity attributes of building components (Autodesk, 2024; BCI, 2025; Heisel & Rau-Oberhuber, 2020;

Madaster, 2025). The integration of these tools enhances data quality and improves the reliability and efficiency of LCA-based environmental evaluations.

In addition to these established tools, the CCF is introduced as a complementary decision-support model. Its purpose is to assist DTs in optimizing circular performance in relation to UEC reduction and material cost during the early design phases. By promoting informed design decisions, the framework aims to improve environmental outcomes for buildings, thereby enhancing the quality of the MPG. In turn, this aligns with the strategic ambitions of the European Green Deal and ultimately supports progress toward the overarching goals of the Paris Agreement, illustrating the bottom-up contribution of practical tools to global climate commitments.

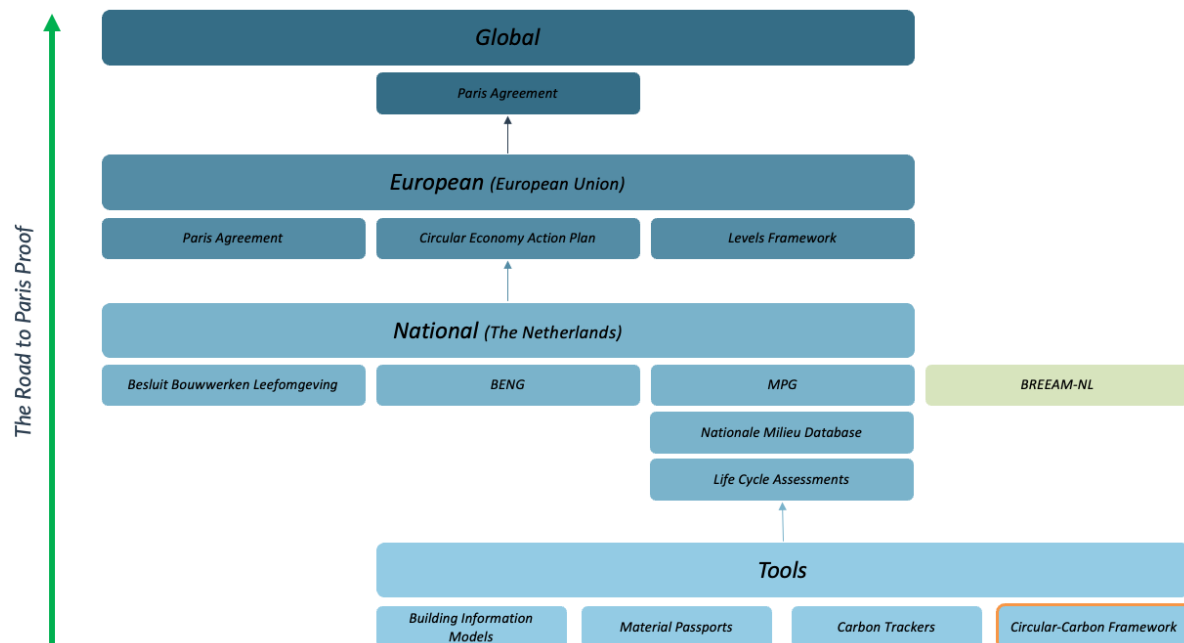


Figure 2.4: The road to Paris Proof: Positioning the CCF within the multilevel policy and tool landscape. Own illustration.

2.3.2. BREEAM-NL Certification

BREEAM is an internationally recognized sustainability assessment framework used to evaluate the environmental performance of buildings. It provides a set of structured criteria across various categories such as energy, water, materials, and waste, with the aim of promoting more sustainable design, construction, and operational practices. The Dutch version of BREEAM, known as BREEAM-NL, is tailored to local regulations and environmental priorities. (BREEAM-NL, 2025)

Within this framework, the Materials (MAT) category explicitly addresses both EC and circularity as fundamental components of sustainable construction. It aims to promote environmentally responsible material choices and integrate life cycle thinking across the design and construction phases. The category is grounded in LCA methods and supports the use of Environmental Product Declarations (EPDs) to quantify and minimize material-related environmental impacts. (BREEAM-NL, 2025)

- **MAT 01** evaluates the total environmental impact of building materials using the MPG indicator, with additional points awarded for the inclusion of material passports (covering at least 80% of materials), the specification of materials using Category 1 data from the NMD, and the integration of installation materials into the LCA assessment.
- **MAT 03** focuses on the responsible sourcing of construction materials, awarding credits for the use of certified sustainable products (e.g., FSC, PEFC), the development of a procurement strategy for ethical sourcing, and ensuring that at least 40% of the material shadow costs are associated with products that have verified sustainability credentials.

- **MAT 05** encourages the selection of durable and robust materials that can resist wear, impact, and environmental degradation, thereby reducing the frequency of replacement and extending the lifespan of building components.
- **MAT 06** promotes material efficiency by rewarding early-stage design strategies that minimize material consumption without compromising performance. This includes structural optimization, reduction of over-specification, and the integration of material efficiency objectives into the Program of Requirements (PvE).
- **MAT 07** incentivizes design for disassembly and adaptability by encouraging construction methods and documentation that enable future dismantling, reuse, or functional adaptation of building components, supporting long-term circularity and end-of-life resource retention.

In conclusion, the analysis of the MAT criteria in BREEAM-NL shows that the system offers strategic guidance but lacks the specificity needed to support DTs in identifying the most effective circular and low-carbon interventions in early design phases. While the MPG score introduces a performance-based structure, the certification remains largely checklist-driven rather than serving as a design-support tool, offering limited assistance in translating circular principles into concrete design actions. Nonetheless, the criteria outlined in BREEAM provide a useful reference to ensure that the CCF aligns with and covers relevant circularity aspects, reinforcing its applicability within existing sustainability certification contexts.

2.3.3. Paris Proof

The Paris Agreement, adopted by a large number of countries including the Netherlands, sets the objective of limiting global warming to a maximum of 1.5°C. This target corresponds to a GHG-emission budget of 400 Gt CO₂-equivalent. In the Netherlands, the Dutch Green Building Council (DGBC) played a central role in translating this global target into national objectives for the construction sector. Based on the country's share of the global budget, an estimated national carbon budget was determined, ultimately resulting in an allocation of 100 megatons of CO₂-equivalent for the Dutch construction sector. The DGBC further refined this figure into specific threshold values for various construction categories, thereby establishing the Paris Proof performance standards that now serve as essential guidelines within the built environment. (Nossek et al., 2022; Spitsbaard & van Leeuwen, 2021)

Tables 2.1 and 2.2 present the specific threshold values for material-related emissions in new construction and renovation projects, categorized by building type. These values correspond to life cycle stages A1–A5 and are expressed in kilograms of CO₂-equivalents per square meter (kg CO₂-eq/m²) of gross floor area (GFA) (Figure 1.3).

In practical terms, all upfront carbon emissions associated with material use must remain below these thresholds for a project to be considered aligned with the Paris Proof targets for climate neutrality in the built environment.

Table 2.1: Paris proof threshold values for new construction in material-related emissions (kg CO₂-eq. per m² GFA) from 2021 to 2050. Adapted from (Nossek et al., 2022).

Building Type	2021	2030	2040	2050
Residential (single family)	200	126	75	45
Residential (multi family)	220	139	83	50
Office	250	158	94	56
Retail	260	164	98	59
Industry	240	151	91	54

Table 2.2: Paris proof threshold values for renovation in material-related emissions (kg CO₂-eq. per m² GFA) from 2021 to 2050. Adapted from (Nossek et al., 2022).

Building Type	2021	2030	2040	2050
Residential (single family)	100	63	38	23
Residential (multi family)	100	63	38	23
Office	125	79	47	28
Retail	125	79	47	28
Industry	100	63	38	23

This research focuses specifically on office buildings, which are therefore highlighted in grey. The threshold values used correspond to the period from 2021 to 2050, provided at ten-year intervals, and represent material-related carbon reduction targets on a broad scale. However, the development of projects within these intervals requires more precise threshold values. Since project timelines are often subject to delays, whether legal, financial, or societal, a fixed and reliable moment in time is needed to determine which threshold value applies. The delivery date is not suitable for this purpose due to its uncertainty. Therefore, the DGBC has determined that the moment the environmental permit is granted should serve as the reference point. This is the value a project must adhere to. For example, if the environmental permit for a project is granted in 2027, the 2027 threshold value applies, regardless of whether the building is completed in 2029 or 2031. (DGBC, 2021)

To accommodate this need for year-specific data, table 2.3 presents a linear interpolation of the threshold values for office buildings between 2025 and 2030. This approach has been adopted because this time horizon is relevant to the period in which this research is being conducted. These values will be integrated into the CCF and will act as reference points to clarify both the current CO₂-eq emissions in the baseline scenario and the target emissions defined by the Paris Proof threshold. This will help illustrate the gap that needs to be closed and demonstrate how the implementation of circular construction strategies can contribute to reaching Paris Proof levels of UEC. As shown in the table, buildings delivered in 2025 should aim for 209 and 105 kg CO₂-eq. per m² GFA for new construction and renovation, respectively.

Table 2.3: Linear interpolation of Paris Proof threshold values for material-related emissions (kg CO₂-eq. per m² GFA) for office buildings. New construction and renovation from 2025 to 2030. Own illustration.

Office	2025	2026	2027	2028	2029	2030
New	209	199	189	178	168	158
Renovation	105	100	94	89	84	79

2.4. Review of Existing Models

Despite the growing importance of balancing carbon, cost, and circularity, there remains a notable absence of practical models that can support DTs in simultaneously evaluating these interconnected variables during the early design phases. Literature research and interviews with industry professionals reveal that while general frameworks exist, no low-threshold, user-friendly tool is currently available to facilitate informed decision-making that integrates these three factors within financially feasible boundaries. As Paris Proof threshold values become increasingly stringent, this gap in practical guidance presents a significant barrier to achieving the ambitious sustainability targets set for the built environment. Consequently, proactive engagement from project developers and design stakeholders is essential; however, their efforts are currently not sufficiently supported by tailored, integrative tools.

Numerous sustainable building models and tools have been developed in recent years. However, these tools often address only a single dimension of sustainability and lack comprehensive integration of carbon, cost, and circularity considerations. Moreover, many fail to meet the specific needs of DTs identified during the interviews, or they are positioned at a different stage of the project timeline, such as post-delivery. A comparison of the boundaries and limitations of these models is provided in table 2.4, which will further illustrate the specific gaps that remain unaddressed in current practice.

Table 2.4: Comparison of existing models on their integration of CO₂, Cost, and Circularity. Own illustration.

Model	CO ₂	Cost	Circularity	Main Limitation
BIM	✗	✗	✗	Provides data management; requires external tools for carbon, cost, and circularity evaluation
BCI	✓	✗	✓	Focuses only on circularity and carbon indicators but no cost integration
(LEVS) Carbon Trackers	✓	✓	✓	Lacks open-source access, multi-user functionality, accessibility, and detailed material parameterization
Material Passports	✓	✓	✓	Used after project delivery; limited design-phase decision support

To address the limitations of existing building models, the CCF will be developed. The primary objective of the CCF is to provide a parametric, data-driven methodology designed to support DTs during the early stages of the architectural design process. Grounded in both academic literature and interviews from DT members, the framework will facilitate a systematic evaluation and integration of the three core criteria: carbon, cost and circularity. By aligning with current regulatory developments, the CCF aims to function as a practical decision-support tool, enabling DTs to make informed and balanced design choices at an early stage.

2.5. Conclusion

SRQ 1: What are the contextual foundations necessary to develop a framework that integrates carbon, cost, and circularity?

This chapter has established the external contextual foundation required for the development of the CCF. By analyzing the theoretical, regulatory, and practical landscape, it defined the environment in which the CCF will operate and the gaps it aims to fill.

The Value Driven Design (VDD) methodology serves as the guiding framework for structuring and developing the CCF. Central to this methodology is the treatment of carbon, cost, and circularity as the core design variables, each with their own attributes and performance indicators. VDD structures the thesis around iterative phases, definition, configuration, analysis, and evaluation, ensuring a systematic progression from conceptual criteria to a functional decision-support tool. By continuously balancing these three variables, the methodology enables informed trade-offs between environmental impact, financial feasibility, and circular performance. As such, it ensures that the CCF is both academically robust and practically oriented toward multi-criteria decision-making in early design phases.

The regulatory analysis positioned the CCF within global, European, and national sustainability frameworks, with the Paris Agreement forming the overarching objective. European initiatives, such as the Green Deal, the Circular Economy Action Plan, and the LEVEL(s) framework, were identified as key enablers, while national instruments like MPG and BBL translate these ambitions into enforceable requirements. Moreover, the Paris Proof benchmarks for UEC highlight the growing pressure on the built environment to achieve significant reductions in material-related emissions, emphasizing the need for innovative and integrative tools like the CCF.

The review of existing models confirmed that current tools often fail to combine the carbon, cost, and circularity in an actionable way during early-stage design. While many models provide valuable insights into isolated aspects of sustainability, they lack the integrative and user-oriented approach necessary to guide DTs effectively. This identified gap underscores the relevance and necessity of the CCF as a data-driven decision-support tool tailored to early-phase design.

Together, these insights form the external contextual foundation of the CCF. They define its methodological backbone, clarify its position within the regulatory environment, and demonstrate its added value in comparison to existing models.

3

Foundation of the Circular-Carbon Framework

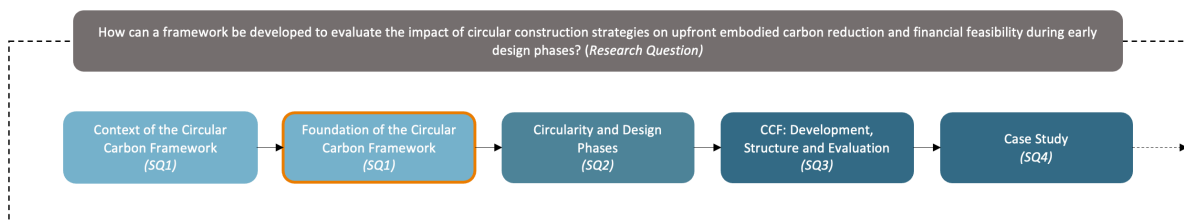


Figure 3.1: Chapter 3 roadmap. Own illustration.

3.1. Introduction

As the construction industry faces increasing pressure to meet climate goals, reducing upfront embodied carbon (UEC) during the early design phase has become a critical priority. This chapter marks the beginning of a structured approach to support sustainable decision-making by focusing on circular strategies that reduce UEC while ensuring financial feasibility.

The chapter begins by defining carbon within the context of this thesis, with a particular focus on UEC and its role in design-phase decisions. It then introduces the shearing layers framework to differentiate various parts of a building according to their functional role and carbon impact. This analysis establishes the initial scope of the CCF by identifying which layers are included and which are excluded based on their relevance to UEC.

The selected shearing layers are then examined at the material level. A detailed analysis is conducted to identify which materials contribute most significantly to UEC. This provides the foundation for exploring how circular strategies can lower UEC.

The chapter concludes by defining the cost scope of the CCF. It outlines the distinction between capital expenditure and operational expenditure, with an emphasis on capital expenditure due to its relevance in early design stages.

This chapter establishes a clear foundation for the CCF by identifying high-impact building layers, analyzing carbon-intensive materials, and defining the cost variable to evaluate circular strategies during the early stages of building design.

3.2. Carbon Scope

Carbon is the first key variable within the Value-Driven Design (VDD) methodology. While carbon dioxide (CO₂) is essential to natural processes, elevated atmospheric concentrations have severe environmental impacts. The construction sector is a significant contributor to these emissions, responsible for approximately 11% of total emissions in the Netherlands (Gemeente Amsterdam et al., 2023). To support meaningful reduction strategies thru circularity, this section defines carbon and clarifies how it is integrated and applied within the CCF.

3.2.1. Defining Carbon

In the construction industry, carbon emissions are generally categorized into two primary types: operational carbon (OC) and embodied carbon (EC). Operational carbon refers to greenhouse gas (GHG) emissions generated during a building's use phase, primarily resulting from energy and water consumption for heating, cooling, lighting, and other building services (DGBC, 2021). These emissions are accounted for within life cycle stages B6 and B7 (Figure 1.2).

EC includes all GHG-emissions associated with the extraction, production, transportation, installation, maintenance, and end-of-life treatment of building materials. It represents the total carbon footprint of a building across its entire life cycle, independent of operational energy use (Lambert & Lewis, 2024). EC is typically divided into three categories: emissions prior to use, emissions during use, and emissions after use. Emissions occurring before the building becomes operational are referred to as UEC and include life cycle stages A1 to A5, which cover raw material extraction, transport, manufacturing, and construction activities (Figure 1.2).

Given the focus of this thesis on early design-phase decision-making and material selection, the scope of analysis is limited to stages A1 to A3: raw material supply, transport, and manufacturing. This boundary aligns with the purpose of the CCF, which supports material-related decisions during the design phase when most construction details are not yet defined. Moreover, this scope corresponds with the structure of widely used data sources such as Environmental Product Declarations (EPDs) and the Nationale Milieudatabase (NMD), in which life cycle stages are reported separately. Since A1 to A3 specifically capture material-related emissions, they provide the most relevant and consistent basis for carbon assessments in this research.

The material-related emissions data used in this thesis are derived from EPDs and the NMD, and are expressed through carbon factors. The *carbon factor*, which represents the first attribute of the VDD-Framework, quantifies the amount of carbon emissions associated with one unit of a specific material. The unit of measurement varies by material type; for example, emissions for concrete are reported per cubic meter (m³), whereas those for steel are calculated per metric tonne. The specific role and application of carbon factors within the CCF will be further explained in Chapter 5.

3.2.2. Building Layers

In order to understand which parts of a building contribute most significantly to UEC, a more detailed examination of its different layers is required. The layered structure illustrated in figure 3.2 provides an overview that divides the building into distinct layers, each with specific functional roles, material compositions, and renewal cycles. This differentiation forms the foundation for optimizing circular and low-carbon design strategies by enabling targeted interventions that correspond to the expected lifespan and replacement frequency of each layer.

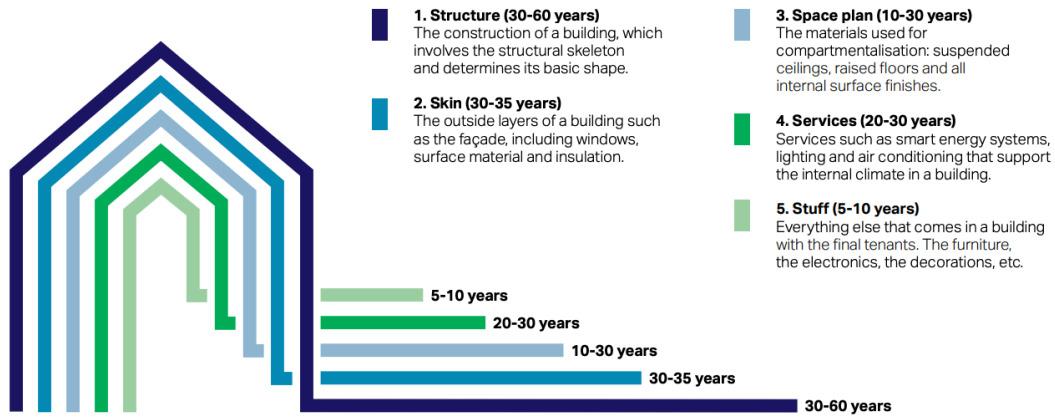
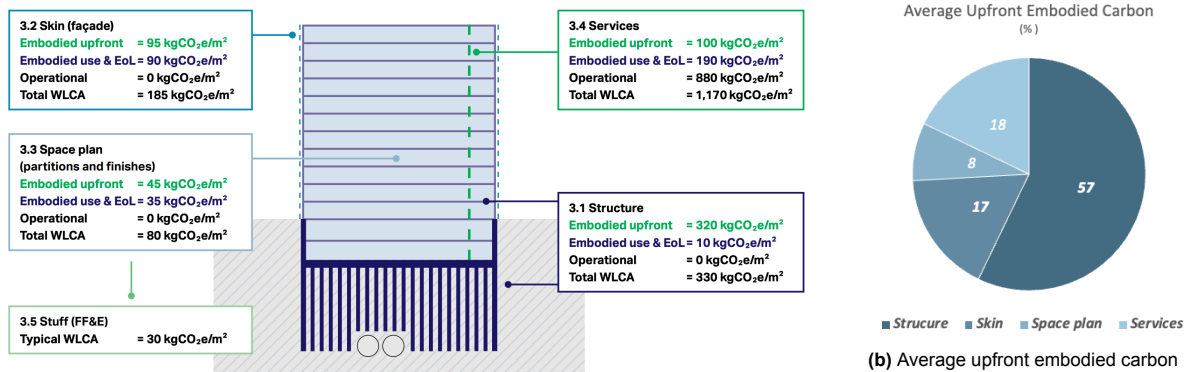


Figure 3.2: Building shearing layers. Adapted from (Bevan et al., 2023).

To determine which building shearing layers are relevant for inclusion in the CCF, it is necessary to understand their respective contributions to the UEC. Figure 3.3a provides a breakdown of average carbon emissions per building layer, based on data from the World Green Building Council. Since this research focuses on the A1–A3 life cycle stages, the values highlighted in green are the most relevant for analysis.

Using this data, the pie chart in figure 3.3b was developed to visualize the relative contribution of each layer to total UEC. As shown, the structure and skin layers together account for the majority of emissions. Consequently, layer 3.5 'Stuff' is excluded from the analysis due to its tenant-specific nature and limited relevance to the actual building structure.



(a) Average carbon footprint per shearing layer. Adapted from Bevan et al. (2023).

(b) Average upfront embodied carbon footprint per building layer. Based on Bevan et al. (2023). Own illustration.

Figure 3.3: Comparison of average upfront embodied carbon footprint across the shearing layers.

As illustrated in figure 3.3b, structure and skin are the dominant contributors to upfront carbon emissions. This is quantitatively confirmed by the formula below, showing that these two layers together account for approximately 74% of the total UEC. This substantial share justifies prioritizing them within the CCF because it aligns with the research's focus on strategies that target carbon-intensive building elements. Research from Cottafava and Ritzen (2021) even estimates the combined EC impact of structure and skin to exceed 81%, further emphasizing the critical importance of addressing these high-impact layers in circular low-carbon strategies.

$$UEC_{\text{Structure} + \text{Skin}} = \frac{UEC_{\text{Structure}} + UEC_{\text{Skin}}}{UEC_{\text{Total}}} = 74\% \quad (3.1)$$

Note

1. UEC = Upfront Embodied Carbon (kg CO₂-eq)
2. UEC_{Total} = Structure + Skin + Space Plan + Services (kg CO₂-eq)

These findings are further supported by large-scale European data shown in figure 3.4. Based on a study conducted by One Click LCA, which analyzed the EC profiles of 3,737 buildings, office buildings show the highest average UEC intensity. The structure and skin layers in office buildings can approach 450 kg CO₂-eq/m². This underscores the relevance of selecting office buildings as the primary building type for this research.

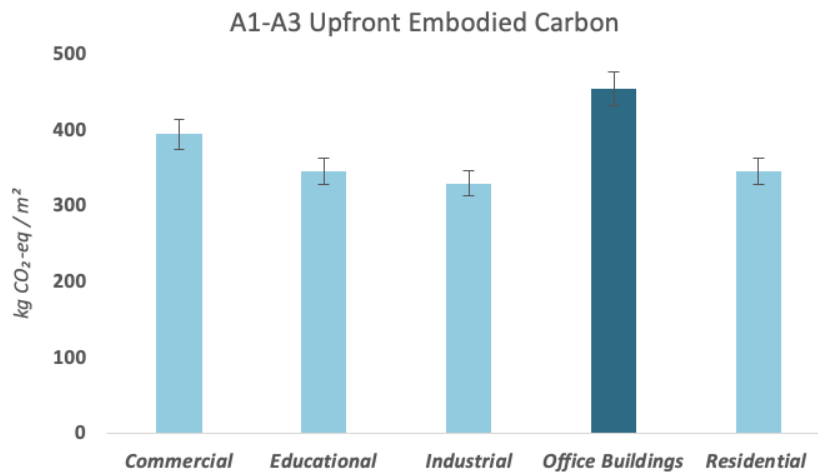


Figure 3.4: Upfront embodied carbon comparison between five building types. Adapted from (*Embodied Carbon Benchmarks for European Buildings*, 2021). Modified by author.

The preceding analysis provides a clear quantitative reason for prioritizing the building's structure and skin in the effort to reduce UEC through the implementation of circular strategies. The specific approach to achieving this reduction will be detailed in the following sections. However, before elaborating on these methods, it is necessary to explicitly justify the exclusion of the *space plan* and *services* layers from the scope of this framework.

The *space plan* has been excluded primarily due to its relatively minor contribution to UEC, approximately 8%. In addition to its limited impact, the space plan encompasses a wide range of design variations, particularly in floor finishes and interior layouts. This extensive variability presents significant challenges in integrating it into a generalized model such as the CCF.

The *stuff* layer, which consists of tenant-owned items such as desks, chairs, and accessories, is excluded for two primary reasons. Firstly, the diversity of products within this category is too extensive. Secondly, it is highly tenant-specific and therefore falls outside the defined scope of UEC.

The *services* layer, although responsible for nearly 20% of total EC over the building's lifecycle, contributes only 4.9% to UEC (Figure 3.5). Despite its considerable influence on the overall EC, its limited relevance to UEC renders it outside the primary focus of this study.

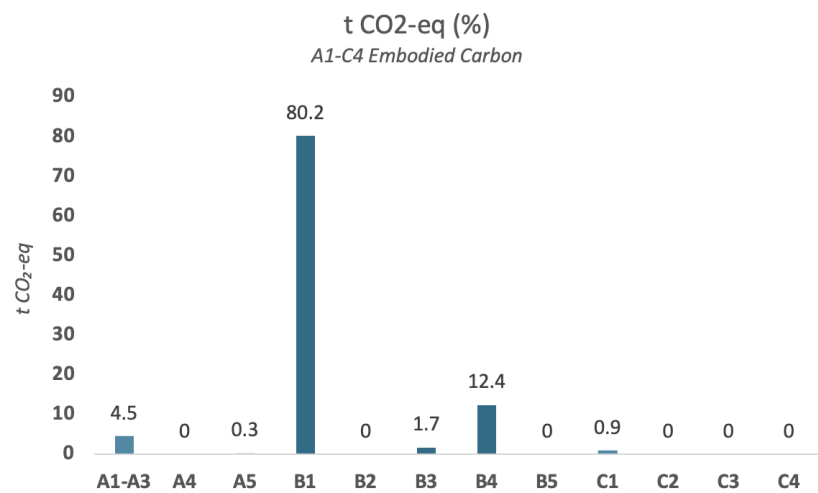


Figure 3.5: Embodied carbon of the services layer across the entire building lifecycle. Adapted from Bevan et al. (2023). Modified by author.

This section defined the material scope necessary for developing a circular approach to reducing UEC. By analyzing the layered composition of buildings and their respective contributions to UEC, it was determined that the structure and skin layers are the most carbon-intensive. Together they accounting for approximately 74% of total emissions. This insight forms the foundation for the CCF, as it ensures that the framework targets the shearing layers with the highest potential for carbon reduction through circular strategies. The layers space plan, services, and stuff were excluded from the scope due to their relatively minor impact on UEC, high variability, or tenant-specific nature, making them less suitable for the first version of the CCF.

The following two paragraphs will examine the structure and skin layers in material detail and aim to identify circular implementation strategies as the first part of the CCF.

3.3. Material Scope: Carbon, Cost and Circularity

3.3.1. Structure

The concept of building layers was initially conceptualized by Francis Duffy in 1990 through the 4S framework and was later extended by Brand (1994) into the more comprehensive 6S framework. Within this framework, the structural layer is considered the foundational 'bones' of a building, encompassing all primary load-bearing components that support the entire structure (Brand, 1994). As illustrated in figure 3.6, this layer can be further divided into two main components: the substructure and the superstructure. The substructure includes all foundational and load-bearing elements located at or below ground level, while the superstructure comprises the load-bearing components situated above ground. Together, these elements form the essential structural system responsible for transferring all vertical and lateral loads from the building's various layers safely into the ground.

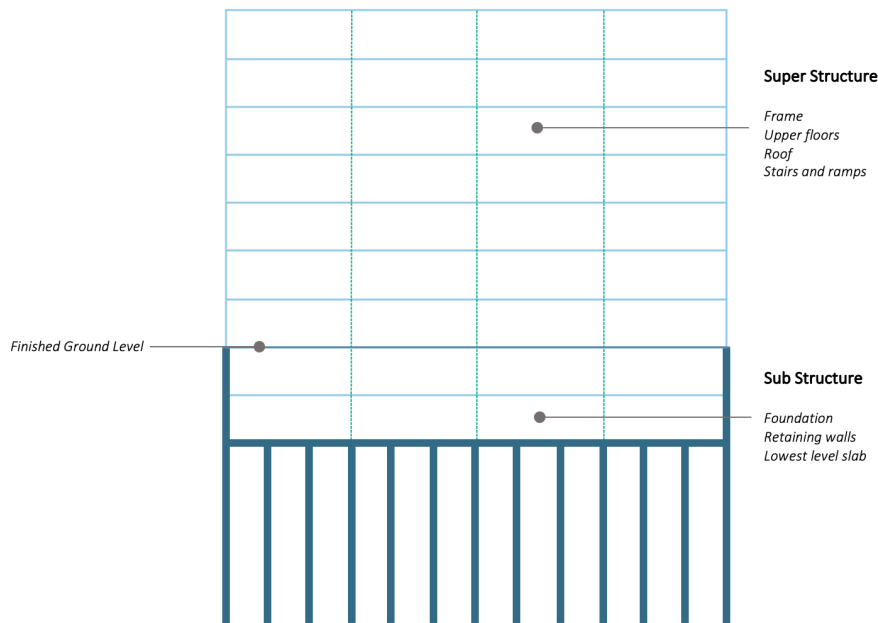


Figure 3.6: Schematic representation of the building structure, divided into substructure and superstructure. Adapted from Bevan et al. (2023). Modified by author.

As illustrated in figure 3.3b, the structural layer of buildings accounts for approximately 55% of total UEC, contributing up to 320 kg CO₂-eq. per m² (GFA). According to table 2.3, office buildings that receive their environmental permit in 2025 are expected to meet a target average of 209 kg CO₂-eq. per m² (GFA) for material-related emissions. Bridging this significant gap necessitates a fundamental transformation in conventional construction practices. To explore potential pathways for reducing these emissions, it is essential to examine the material composition contributing to the structural layer's carbon footprint. Figure 3.7 presents the UEC emissions associated with various building materials. Notably, approximately 55% of these emissions are attributable to steel and concrete, which dominate the structural framework. Consequently, these materials, along with load-bearing timber as a potential low-carbon alternative, will be further analyzed in terms of their carbon impact and circular construction potential.

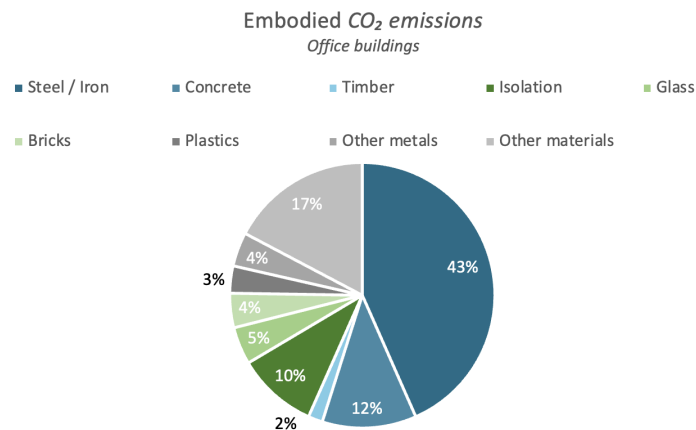


Figure 3.7: CO₂ emissions per building material. Adapted from Arnoldussen et al. (2020). Modified by author.

Reinforced Concrete

Concrete is a widely used construction material composed of cement, sand, gravel, and water. Variations in the composition and proportion of these raw materials influence not only the mechanical properties of the final product but also its environmental impact, particularly in terms of emissions. While structural concrete exhibits high compressive strength, it performs poorly under tensile stress. To address this limitation, steel reinforcement bars (rebars) are embedded within the concrete matrix before it sets, resulting in reinforced concrete capable of withstanding both compressive and tensile forces. (Guo, 2014)

Figure 3.8 illustrates the distribution of material composition and corresponding carbon impact for reinforced concrete. Subfigure (a) presents the material breakdown by mass (in kilograms), highlighting that sand, aggregates, and cement constitute the majority of the mixture. However, mass alone does not reflect the environmental impact associated with each component. Subfigure (b) therefore depicts the same material constituents, but categorized according to their contribution to the overall EC (in kg CO₂-equivalent). Together, cement and steel reinforcement account for approximately 95% of the total material-related carbon emissions in reinforced concrete. As such, circular strategies aimed at reducing EC should primarily focus on minimizing the use of these two high-impact materials.

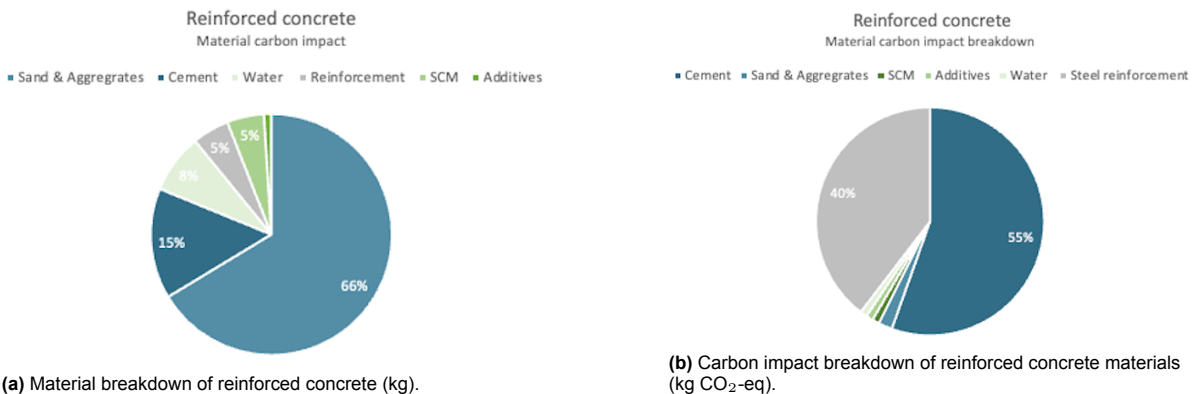


Figure 3.8: Material and carbon impact breakdown of concrete. Adapted from Bevan et al. (2023).

Understanding which implementation strategies effectively reduce the reinforcing steel and cement content in concrete is crucial for lowering EC. OneClick LCA offers a structured overview of such strategies. The interventions that align with principles of circularity are presented below (Tsikos, 2024):

- **Avoid overdesign of structural elements:** Use only as much concrete as structurally necessary

to prevent waste.

- **Rationalize the consideration of live loads during design:** Use realistic load assumptions to avoid oversizing while still allowing flexibility for future use.
- **Design for material efficiency:** Optimize structural spans and use efficient elements like hollow core slabs or composite decks to save material.
- **Avoid over-specifying concrete's compressive strength:** Adjust concrete strength to match the specific structural needs instead of using unnecessarily high grades throughout.
- **Use alternative binders:** Replace part of the cement with supplementary cementitious materials (SCMs) like Fly-Ash, GGBS or calcined clays to lower EC.

Green reinforced concrete offers a promising alternative to conventional (Portland-based) cement concrete, with studies by Fattah et al. (2017) and Huang et al. (2025) showing minimal differences in cost and structural performance. However, widespread adoption remains limited due to several barriers: limited long-term durability data, supply chain constraints for SCMs, lack of standardization, and low stakeholder awareness.

To gain a better understanding of the practical use of reinforced concrete and the implementation of circular strategies, an interview was conducted with the technical manager of a leading Dutch concrete supplier. Since concrete is produced locally and its composition depends on region-specific raw materials and practices, insights from a domestic expert provide useful context. A detailed summary of the interview is available in appendix C.

Concrete mix design is highly case-specific and project-dependent. Common strength classes include C30/37 and C35/45, while higher grades such as C45/55 are typically used for foundations or substructures in aggressive environments. Each building consists of a unique set of mixtures, specified by the structural engineer and, in consultation with the contractor, implemented during execution.

In terms of circularity, the company currently replaces around 30–40% of natural aggregates with certified recycled concrete granulate. This material is obtained through partnerships with demolition contractors and supports circular material flows. Although the concrete binder is not yet fully recycled, the reuse of aggregates contributes to resource efficiency. Geopolymer concrete was discussed as a promising low-carbon alternative. However, while beneficial in terms of EC, it remains approximately twice as expensive as standard concrete (€250–260/m³ versus €120–160/m³), and requires significant adjustments in safety protocols and execution method, factors that currently limit its scalability.

An important insight from the interview concerns the under utilization of supplier expertise during early project phases. In approximately 90% of projects, the company is only involved after the concrete specifications are already defined in the tender. The interviewee emphasized that earlier engagement during the sketch or preliminary design phase would allow for more sustainable choices. For instance, designing for strength at 56 or 92 days, rather than the standard 28 days, enables reductions in cement content (aligned with the Reduce principle), which also leads to cost savings without compromising structural performance.

To overcome these barriers, DTs and developers are encouraged to actively involve suppliers earlier in the process. When environmental and financial criteria are aligned, green concrete alternatives can be a viable and impactful choice. The CCF model can support the evaluation of such strategies, helping teams make informed decisions during early design stages.

Structural Steel

With 17% steel is the second biggest contributor in terms of material carbon impact after cement (66%). Steel's primary purpose in the building industry is to form a skeleton that holds everything together (E.g., columns, beams and floor systems). Weaker structural steel is also used as a reinforcement material to counter concrete's low tensile strength and ductility, it is then called reinforced steel. (Srikanth & Asmatulu, 2013)

To reduce carbon emissions associated with steel production, various green steel alternatives are emerging in the market. Although no universally accepted definition of 'green steel' exists, this study adopts a broad interpretation of the term. It includes the indicators (Assunção et al., 2022; Muslemanni et al., 2021; NUCOR, 2025):

- Steel produced through low-emission technologies such as electric arc furnaces (EAF)
- Steel composed of recycled scrap metal
- Below-average GHG-intensity
- Supported by Environmental Product Declarations (EPDs)
- Compliant with climate-related regulations

To complement these findings, an interview was conducted with a leading steel distributor that holds approximately 33% of the Dutch steel market. The company is primarily engaged in the procurement of raw steel and aluminum, supplying these materials to metal processing firms. As the construction sector increasingly demands sustainable material solutions, distributors are adapting their operations to align with broader environmental goals. A detailed summary of the interview is provided in Appendix C.

The insights derived from this interview reflect broader industry trends in the steel supply chain. Recycling is widely applied as the dominant circular strategy, often through closed-loop systems where steel scrap from production processes is compressed and reintroduced into the supply chain. In contrast, the direct reuse of structural or façade-grade metals remains rare due to a combination of regulatory, logistical, and technical challenges.

In terms of UEC, there is a growing industry-wide shift toward transparent carbon accounting using cradle-to-gate assessments. These calculations typically rely on EPDs, supplemented by data from internal processing and transport emissions. The EC of steel products can vary significantly, ranging from approximately 0.52 to 3.6 tCO₂/tonne, depending on the production method and the proportion of recycled content.

Low-carbon steel products generally command a cost premium of 10–20% over conventional alternatives. As a result, procurement strategies are increasingly focused on maximizing CO₂ savings per euro spent. However, the absence of a standardized and transparent system to compare suppliers based on both EC and cost continues to present a major challenge for the industry.

A second interview with another steel supplier provided further insights into the operational realities of circular steel implementation. Similar to the first interviewee, this supplier confirmed that recycling remains the dominant circular strategy, whereas the reuse of structural steel components is more complex due to disassembly challenges, certification requirements, and logistical complexity. Although tools such as EPDs and internal carbon accounting systems are in place, the integration of these tools into early-stage design decisions is still limited. The interviewee emphasized that without explicit contractual requirements or strong client demand, circular strategies are often deprioritized during material selection.

An interesting contradiction emerged regarding the financial feasibility of low-carbon steel alternatives. While the first supplier indicated that green steel products typically come at a 10–20% cost premium compared to conventional steel, the second supplier reported that their low-carbon offerings do not entail significantly higher prices. This discrepancy underscores the absence of a transparent and standardized framework for comparing suppliers on both circular, carbon and cost performance, further complicating informed decision-making in early design phases.

This gap reinforces the importance of early-stage collaboration between DTs and suppliers to identify and pursue optimal material choices. By specifying low-carbon steel options early in the design phase, DTs can play a critical role in aligning project outcomes with circularity and carbon reduction objectives.

Timber

Timber has traditionally been used in construction, but recent advancements in engineered timber have significantly expanded its structural applications. As a renewable resource with a comparatively low environmental footprint, timber offers notable advantages in the context of climate mitigation, particularly through carbon sequestration, reduced embodied emissions and circularity. Engineered timber products such as Cross-Laminated Timber (CLT), Glue-Laminated Timber (GLT), and Laminated Veneer Lumber (LVL) have demonstrated the mechanical performance required for structural use in medium- to high-rise buildings. These materials combine strength, dimensional stability, and design flexibility, enabling timber to function as a viable and sustainable alternative to conventional load-bearing materials such as concrete and steel in modern construction. (Bukauskas et al., 2019; Duan et al., 2022; Tupenaite et al., 2023)

Timber offers significant potential to replace carbon-intensive materials such as steel and concrete. However, its environmental benefits are not guaranteed and depend heavily on how the material is managed throughout its lifecycle. Carbon sequestration is only effective if end-of-life scenarios are considered from the design phase onward. To ensure a meaningful reduction in EC, timber must be applied in ways that enable reuse and recycling, particularly through design for disassembly. If the material is ultimately incinerated, its carbon advantage is lost. Therefore, DTs must prioritize strategies that preserve timber's circular potential from the outset (Bevan et al., 2023).

Similar to concrete and steel constructions, timber structures are also governed by standardized product requirements. The specifications for commonly used engineered wood products, as well as their permissible applications, are outlined in European standards: EN 14080 for glued laminated timber (Glulam), EN 16351 for cross-laminated timber (CLT), and EN 14374 for laminated veneer lumber (LVL). According to these standards, the most frequently used timber species for structural applications include Norway spruce, Scots pine, Douglas fir, silver fir, and larch.

Lin et al. (2025) presents a literature review on end-of-life (EoL) scenarios for engineered timber, highlighting their circularity potential. To support low-carbon, circular construction, DTs should incorporate the circular EoL hierarchy during the design phase. Achieving higher-tier outcomes, such as reuse and recycling, requires design for disassembly, though this is often limited by technical, financial, or policy constraints. Modular design and prefabrication can enhance reuse potential.

The circular EoL hierarchy is as follows:

- Adaptive reuse of entire structures
- Component reuse
- Recycling
- Incineration with energy recovery
- Landfill

3.3.2. Skin

While the structural system of a building comprises its primary load-bearing components, the skin refers to the external envelope that separates the interior environment from external conditions. This layer includes elements such as external walls, windows, insulation systems, and roofing components (Brand, 1994). In contrast to structural systems, building envelopes exhibit considerably greater variation in design and configuration, thereby increasing the complexity of identifying circular, low-carbon alternatives. To ensure the CCF remains applicable, the focus is placed on materials commonly used in office building façades that contribute significantly to EC emissions: aluminum, steel, and glazing (Dodd & Vinson, n.d.; Pomponi & D'Amico, 2017). Although bricks and cement exhibit high levels of carbon emissions, these materials are relatively specific in application and are not commonly used in mid- to high-rise office buildings. If the market demonstrates strong interest in the CCF, the model could be expanded to incorporate these additional materials, thereby enabling the implementation of a broader and more diverse range of circular strategies.

It is essential to recognize that, unlike structural components, the carbon dynamics of the skin involve a more complex interaction between EC and OC. Although this study primarily addresses the reduction of EC in the early design stages, it is important to acknowledge that strategies for enhancing low EC do not always lead to lifecycle carbon efficiency. For instance, selecting high-performance insulated glazing may result in increased UEC, but this is often offset by significant reductions in operational emissions throughout the building's use phase. (Dodd & Vinson, n.d.)

Aluminum

Façade systems are available in a wide variety of forms and materials, thereby increasing the complexity of decision-making for DTs when selecting appropriate façade systems for commercial buildings. In total, there are at least sixteen distinct façade construction possibilities, designated as WT01 through WT16. These configurations are categorized into subgroups based on the primary material used in the façade system. This research examines façade systems from the perspective of their material contribution to EC emissions and their circularity potential. Based on this approach, a study conducted by Arup and Saint-Gobain provide evidence to inform façade system selection. Specifically, aluminum accounts for between 26% and 60% of the UEC of façade systems, with typical commercial building applications approximating 50% of total UEC. (Dodd & Vinson, n.d.)

Expressed differently, and more aligned with the objectives of the CCF, aluminum exhibits a very high carbon intensity, ranging between 67 and 342 kg CO₂-eq. per m². This significant carbon footprint positions aluminum as a critical material requiring circular strategies to effectively reduce EC and, therefore, renders it highly relevant to the CCF framework (Dodd & Vinson, n.d.).

The strategic importance of circular approaches for aluminum to reduce EC is further emphasized by the European Aluminum Association, the official industry body representing the full aluminum value chain in Europe. The association collaborates closely with the European Union to achieve the circular economy goals outlined in the EU Green Deal. A study conducted in collaboration with Delft University of Technology investigated aluminum collection rates, revealing a notably high rate of 95%. (Al-Alimi et al., 2024; EA, 2025).

Aluminum exhibits substantial potential for the reduction of EC, particularly when integrated with strategies such as design for disassembly and high recycling efficiency. Approximately 23% of all aluminum produced is employed within the construction sector. Due to its inherent property of infinite recyclability, around 75% of all aluminum ever produced remains in use today. Recycling aluminum scrap results in a significant reduction in CO₂ emissions, with savings of up to 92% compared to the production of primary aluminum. Moreover, the recycling process consumes only about 5% of the energy required for the production of virgin aluminum, thereby achieving considerable CO₂ savings (EuRIC, n.d.).

This potential is further reinforced by findings from Dodd and Vinson (n.d.), which indicate that aluminum with a 40% recycled content emits approximately 255 kg CO₂-eq. per m², while aluminum with a 94% recycled content emits only 105 kg CO₂-eq. per m². This nearly 60% reduction highlights a substantial opportunity for DTs to incorporate circular strategies targeting EC reductions through increased recycled content in aluminum-based façade systems (Dodd & Vinson, n.d.).

Glazing

Glazing constitutes the second-largest contributor to the UEC of a building's envelope. In façade systems where the contribution of aluminum is relatively low, glazing often accounts for the majority of the remaining UEC. The magnitude of this contribution varies depending on the type of glazing applied, including single, double, and triple glazing, as well as toughened or laminated variants. On average, glazing contributes between 30% and 40% of the total UEC associated with the façade, corresponding to an absolute range of approximately 64 to 175 kg CO₂-eq. per m².

Based on this knowledge, it would be logical to assess whether DTs prefer a higher share of glass or aluminum when considering UEC. The window-to-wall ratio (WWR) concept was developed for this purpose. Generally, as the WWR increases, UEC decreases because glazing typically has a lower EC than non-transparent constructions like aluminum or steel. However, when looking beyond the initial construction phase to later life cycle stages, during component replacement, the trend reverses as

higher WWR leads to increased EC. This is because insulated glazing units, with a typical lifespan of 30 years, require replacement during the 60-year study period, unlike the more durable non-transparent parts. Moreover, in practice, it is often not just glazing but entire façades that are replaced, especially in commercial buildings, suggesting that whole-life EC may be underestimated in such analyses. Therefore, it is unfortunately not that straightforward, and DTs must actively seek both low-carbon and circular options for aluminum as well as steel, ensuring that the total absolute UEC decreases while finding the most suitable solution for each specific project. (Tawfeeq & Qaradaghi, 2024; Troup et al., 2019)

To deepen the understanding of circular strategies for glazing systems, an interview was conducted with the Director of one of the leading flat glass manufacturers, producing approximately 20 kilometers of glass daily and holding a market share of 15%. Given its industry leadership and active engagement in circularity and UEC reduction, this company was deemed an ideal candidate for expert consultation. A detailed summary of the interview is available in appendix C.

Several important findings emerged that were not previously identified through the literature review. Although design for disassembly is widely promoted in academic discourse, its application to existing commercial buildings is highly limited. Much of the glass installed in current building stock was not designed for disassembly, making reuse economically and technically unfeasible due to extensive deconstruction times, installation specificity, and prohibitive costs. As a result, reusing façade glass from older buildings in new developments is unlikely to be a scalable strategy.

The primary focus for circularity should therefore be on recycling glass from end-of-life buildings. Technically, all types of flat glass, except certain colored variants, can be fully recycled. Regarding cost implications, glass products with high recycled content are approximately 15–20% more expensive than conventional alternatives. Nevertheless, this premium is considered acceptable, particularly because, depending on the façade system configuration, the contribution of glazing materials to total façade costs can be substantial.

Architectural Stainless Steel

Steel is utilized in various applications within façade systems, serving both as a support structure and as part of steel frame systems. These applications are prevalent in nearly all commercial buildings. Additionally steel is sometimes employed as an exterior layer to enhance the building's aesthetic appeal. This practice is attributed to steel's visual attractiveness, customization possibilities, and durability, which collectively make it an ideal material for such purposes.

Within façade systems, the contribution of steel to the UEC depends on the specific design selected, typically ranging between 6% and 12%. In absolute terms, this corresponds to approximately 20 to 30 kilograms of kg CO₂-eq. per m². Although steel is not the primary contributor to UEC, it remains a relevant material for reduction efforts through the application of circular strategies. Consequently, steel has been included in the scope of this research. (Bevan et al., 2023)

3.4. Cost Scope

Up to this point, this chapter has introduced the carbon variable alongside the contributions of individual materials. The following section shifts focus to the second key variable: cost. Cost has historically been, and continues to be, a dominant criterion in construction decision-making. No matter how sustainable or technically sound a proposal may be, if the financial feasibility is not valid, the project is unlikely to proceed. Therefore, cost is not treated as a secondary concern in this framework but as an integral and interacting variable within the sustainability assessment.

3.4.1. Cost Integration

In the context of construction economics, cost is generally subdivided into capital expenditures (CapEx) and operational expenditures (OpEx). CapEx refers to the upfront costs required to design and construct a building, including materials, labor, and direct construction costs. OpEx, by contrast, includes recurring costs over the building's life cycle, such as energy use, maintenance, and operational staffing. While both cost types are relevant in sustainable building evaluations, this research explicitly focuses on CapEx, as material costs fall under this category and are central to the CCF. (Ross, 2024)

During the early design phases, different materials and their corresponding prices are assessed and compared. Based on their cost impact, choices are made regarding material selection and usage. However, since the CCF evaluates both cost and carbon simultaneously, it is essential that materials are assessed using consistent units across both variables. To ensure this consistency, all cost values are expressed per unit of material, as provided in EPDs (e.g., €/m², €/kg, or €/m³). These units align directly with the corresponding carbon factors used in the framework.

For the cost output, the model clearly distinguishes between expenditures related to the structure, those related to the skin, and the total expenditures of these two shearing layers combined. This layered breakdown allows for conclusions to be drawn about which components exceed the cost budget and which remain within it. In doing so, the framework supports DTs in identifying where the highest material costs occur and how alternative strategies may affect the overall budget distribution.

While the CCF does not aim to provide a full life cycle cost analysis, it focuses specifically on material cost comparisons during the early design phases. The primary aim of the framework is therefore to facilitate early-stage decisions that are not only low in UEC and high in circular potential, but also financially feasible.

Residual Value

Recent literature increasingly emphasizes the importance of considering the residual or End-of-Life (EoL) value of materials in circular construction. Unlike conventional linear use, where materials are discarded after use, circular strategies often allow materials to retain significantly higher value at the end of their life cycle (Munaro et al., 2020). Nevertheless, the integration of residual value into the CCF is excluded for several reasons, which are grounded in both literature and practice, as well as in the scope and methodological positioning of the framework itself.

First, while the principle of residual value is theoretically compelling, its actual quantification and realization remain highly uncertain. Jiang et al. (2022) and Oliveira et al. (2024) emphasize that the extent to which value is generated, retained, or lost within a circular economy is still poorly understood. Similarly, Wamelink et al. (2023) notes that current knowledge and practical experience are insufficient to reliably assess these value dynamics. Since the CCF is applied in the earliest design phases, when uncertainty is greatest, incorporating EoL value estimations is particularly problematic.

Second, although residual value is often portrayed in literature as a promising opportunity, scholars underline the need for substantial technological and market advancements before it can be operationalized. For instance, Oliveira et al. (2024) and van der Zwaag et al. (2023) argue that realizing residual value requires improved traceability of structural elements to monitor performance and predict future usability. To this end, Oliveira et al. (2024) proposes the use of BIM, Big Data, and RFID sensor technologies to enable such monitoring. While these innovations show potential, their large-scale implementation remains in development, limiting their applicability in current design-phase decision-

making.

Third, in practice, the mechanism of residual value does not yet function effectively. Developers and investors indicate that there is no willingness to pay more for a building based on a potential higher residual value of circular materials. Moreover, a broadly accepted methodology to determine EoL value is lacking, making it unsuitable for reliable financial assessments. Consequently, residual value does not create additional investment space nor provide financing benefits, as banks and investors do not adjust conditions based on speculative future value (*C. Berning, personal communication, 2025*). This absence of a functioning market mechanism and clear financial incentives prevents residual value from being applied as a steering instrument in practice.

Lastly, from the perspective of the CCF itself, which seeks to bridge literature and practice, residual value is not sufficiently mature to be included. During the early design phases, limited to no information is available on future market prices for specific secondary materials. Given this uncertainty, financial feasibility is currently better assessed using initial costs rather than speculative future values. Since this thesis focuses on the A1–A3 life cycle phases and given the lack of reliable data, the residual value of materials falls outside the scope of the present study.

3.5. Conclusion

SRQ 1: What are the contextual foundations necessary to develop a framework that integrates carbon, cost, and circularity?

This chapter has established the internal contextual foundation required for the development of the CCF. Specifically, it addressed the detailed understanding of the three key design variables, carbon, cost, and circularity, as well as the materials they are applied to. These four elements form the starting point for designing the framework and collectively answer the second part of SRQ 1, identifying the internal contextual foundations.

The building layer analysis showed that the structure and skin together account for approximately 74% of total UEC, thereby justifying the focus on these two shearing layers in the CCF. Within the structure, concrete, steel reinforcement, and structural steel were identified as the primary carbon emitters. Insights from expert interviews revealed several effective strategies for carbon reduction, including optimized concrete mixes, the use of green steel, and increased recycling. In addition, engineered timber products, such as CLT, GLT, and LVL, emerged as promising low-carbon alternatives to conventional high-emission materials.

For the skin, aluminum, glazing, and architectural steel were found to be the dominant contributors to façade-related UEC. Increasing the recycled content of these materials presents a realistic strategy for carbon reduction. While re-use is often emphasized in literature, its implementation in practice remains limited. For example, the re-use of glazing is generally infeasible due to a lack of standardization.

The cost variable was limited to capital expenditures directly linked to material selection. By aligning cost per unit with carbon emission factors, the framework enables early-stage trade-offs between environmental impact and financial feasibility. Although residual value and life cycle costs are relevant in broader cost assessments, they were excluded from the CCF due to their limited applicability in current industry practice.

Within the CCF, the variables of carbon, cost, and circularity are evaluated against predefined budget thresholds to determine project feasibility. These budgets act as reference values, enabling design teams to understand where steering is required. The detailed integration approach is further explained in chapter 5.

Together, these insights form the internal contextual foundation of the CCF. They define its material scope, understand its key design variables, and ensure the model is rooted in both practical and academic relevance.

4

Circularity and Design Phases

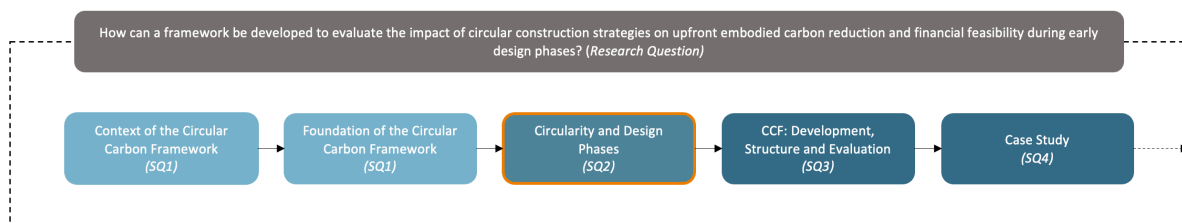


Figure 4.1: Chapter 4 roadmap. Own illustration.

4.1. Introduction

This chapter builds upon the previously defined variables, carbon and cost, and completes the foundation of the Circular-Carbon Framework (CCF) by introducing its third and final variable: Circularity.

The chapter begins by examining the role of individual design team (DT) members in circular decision-making. To gain insight into how circularity is approached in practice, thirteen interviews were conducted with professionals from various disciplines. These interviews provided a deeper understanding of the internal dynamics of the design process and revealed how circular strategies are interpreted, applied, and evaluated. In addition, interviewees shared expectations for new software tools, offering essential input for shaping the functionality and usability of the CCF.

With the practical context established, the chapter proceeds to define circularity as it is applied throughout the CCF. A distinction is made between circular indicators, which serve to measure circular performance, and circular strategies, which aim to influence it.

The chapter concludes by categorizing these strategies based on their applicability across different design phases and their potential impact on UEC and material cost. This final step completes the conceptual foundation necessary for developing the CCF in the subsequent chapter.

4.2. Role of Design Team in Circular Decision-Making

4.2.1. Definitions

Improving the balance between carbon, cost, and circularity in design requires clear insight into the roles of key stakeholders. This section focuses on DT members selected for their significant influence on circular and low-carbon implementation during the design phase. While other roles are present within DTs, their impact on these objectives is comparatively limited. Interviews were conducted with these key actors to explore their responsibilities, drivers, constraints, and the support they require to make informed decisions that promote circularity and reduce UEC.

Project Developer/Owner

The owner, represented by the project developer, initiates and finances the project while defining its strategic objectives. The project developer acts on behalf of the owner, managing approvals, coordinating key decisions, and overseeing daily project activities. Despite operational delegation, ultimate responsibility for project outcomes remains with the owner. Upon project completion, the owner assumes full possession of the asset, ensuring that its operation aligns with the intended functional, financial, and strategic goals. (IKIGAI Consulting, 2023)

Architect

The architect serves as the lead in the design process, translating the client's vision into comprehensive technical drawings and specifications. Their role encompasses ensuring that the design meets functional, aesthetic, and regulatory requirements. Throughout the construction phase, the architect is responsible for supervising compliance with the approved design, managing any necessary changes, and finalizing the documentation required for project handover.

Structural Engineer

Structural engineers are responsible for ensuring the safety, stability, and regulatory compliance of a project, focusing specifically on the design and integrity of all load-bearing elements. They translate architectural concepts into structurally feasible solutions while optimizing material use, constructability, and long-term performance.

Cost Consultant

The cost consultant, often referred to as the quantity surveyor, oversees the financial management of the project to ensure that it remains within the established budget. Their responsibilities include the preparation of cost estimates, facilitation of value engineering processes, management of contract variations, and the provision of financial reporting throughout the project duration. The cost consultant maintains rigorous financial control up to the final account closure.

Environmental Consultant

The environmental consultant is tasked with ensuring that the project complies with sustainability goals and regulatory standards. This role involves guiding material selection, promoting energy-efficient solutions, supporting waste reduction strategies, and managing the processes necessary for achieving relevant sustainability certifications. In new projects EDGE appoint both a sustainability and a circularity advisor to emphasize the distinct importance of each discipline. Through these actions, the environmental consultants contribute to minimizing the environmental impact of the project and enhancing its long-term resilience.

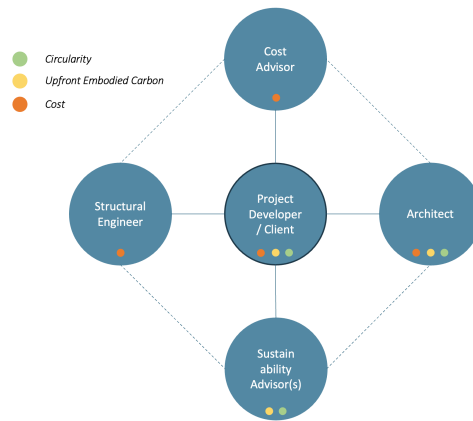


Figure 4.2: Key design team members involved in structural and façade-related decision-making. Own illustration.

4.2.2. Findings from Practice

This section presents a cross-interview analysis of the perspectives of nine key DT members involved in commercial construction projects. The focus lies on identifying areas of conflict and consensus in relation to circular strategies, UEC, and financial feasibility. This is followed by an assessment of how the CCF can support integrated decision-making and overcome structural barriers within current project dynamics. (Appendix C)

1. Points of Conflict

A recurring tension exists between the moment when material and structural decisions are made and the optimal timing for assessing circular or low-carbon alternatives. Both Environmental Advisor 2 and the Structural Engineer emphasized the need for early integration of suppliers and material expertise into the design process. In contrast, Project Developer 1 and the Cost Advisor pointed to practical constraints, noting that financial clarity is often a prerequisite for engaging with such actors. This mismatch frequently leads to suboptimal lock-in of material systems before their carbon or circular implications are fully explored.

Architect 1, Architect 2, and Environmental Advisor 2 consistently promoted sustainable ambitions during the design phase. However, these ambitions are often moderated by more risk-averse perspectives from roles such as the Cost Advisor and Project Developer 2, who prioritize financial certainty. In practice, cost-related feasibility tends to override circular goals, particularly when there is no shared, quantifiable benchmark that simultaneously captures environmental and economic performance.

While EC has become a more standardized and recognized metric (e.g., through Paris Proof or MPG regulation), circularity remains comparatively vague. Environmental Advisor 1 and the Circular Advisor each underscored the lack of consistent definitions and measurable parameters for circularity in the current design landscape. This ambiguity has led to a tendency to prioritize UEC reduction over circular performance, even in contexts where both are interdependent.

2. Dynamics Within the Design Team

Circular and low-carbon ambitions are primarily initiated by environmental advisors and, in some cases, by architects with strong sustainability agendas. However, the degree of influence is highly dependent on the project developer's openness and the financial structure of the project. The Circular Advisor noted that while tools like BCI are becoming increasingly accepted, circular strategies are often deprioritized without clear financial translation.

The KPIs most frequently cited across interviews include EC ($\text{kg CO}_2\text{-/m}^2$), biobased content percentage, disassembly potential (losmaakbaarheid), and financial rest value. These KPIs provide the structure for evaluating performance, yet they vary in use and emphasis depending on the role of the actor.

3. Use of Tools and Software

Multiple advisors referred to software platforms such as the BCI, MPG-calculators, and internal Excel-based tools used for circularity and cost estimation. However, a consistent critique emerged regarding internal tools: while they provide flexibility and customization, they lack transparency and standardization. This opacity can hinder collaboration, especially when comparing scenarios or communicating assumptions across disciplines. The CCF, in contrast, was welcomed as a transparent, comparative, and structured method to integrate circularity, UEC, and cost in early-phase discussions.

4. Circular Strategies in Practice

Interviewees reflected on which strategies are actionable and which remain aspirational. Strategies such as reuse of structural components, design for disassembly, and the incorporation of bio-based materials are recognized for their potential, yet face financial and logistical hurdles. Several stakeholders noted that design-for-long-lifespan strategies, such as flexible floor plans and adaptable structures, are often overlooked, despite offering significant circular potential. Conversely, some strategies such as 'urban mining' and high-integrity reuse are still hampered by lack of standardization and cost-effectiveness.

Architect 2 introduced a noteworthy approach: a 'VO+ phase' in which additional flexibility is preserved to continue integrating circular strategies and even re-evaluate existing material inventories. This adaptive design phase allows for dynamic collaboration and late-stage integration of reclaimed or alternative materials, underscoring that some circular gains can be made beyond schematic design.

5. Gaps in Data, Supply Chains, and Certification Tools

A consistent barrier identified by Environmental Advisor 2 and Project Developer 2 is the incomplete integration of EPD in current workflows. While the NMD is referenced for impact data, EPD coverage remains partial and varies significantly in quality. As a result, accurate material assessment often requires assumptions or workarounds, complicating the ability to benchmark or compare.

Additionally, many stakeholders raised concerns about the availability and readiness of circular material supply chains. There is a notable lack of scalable, standardized circular material streams capable of supporting commercial construction timelines. Even when a strategy like structural reuse is desired, the sourcing, certification, and logistical coordination often remain unresolved, leading to conservative choices. This highlights that supply-side readiness, not just design ambition, is a key bottleneck.

6. Involvement of Material Suppliers

Interviews with material suppliers, specifically in the domains of concrete, steel, and glass, highlighted their strong interest in earlier involvement within DTs. Suppliers emphasized that early dialogue would allow them to optimize product specifications (e.g., low-carbon concrete mixes or recycled steel profiles). While this sentiment was echoed by DT members like Environmental Advisor 1 and the Structural Engineer, concerns were also raised. Developers and cost advisors noted that early supplier involvement could limit market competitiveness and undermine procurement through tender processes. This reveals a systemic tension between optimal material performance and traditional procurement mechanisms.

7. Market Appetite for Decision-Support Tool

Importantly, all interviewees, regardless of discipline, expressed interest in a robust, user-friendly DT tool that could support structured, early-phase material decision-making. Such a tool, if capable of comparing circular strategies across carbon, cost, and implementation feasibility, would fill a critical gap in current design processes. Several respondents pointed out that while existing tools help quantify impacts, they rarely support integrated, cross-disciplinary collaboration.

Conclusion

The interviews reveal a nuanced and evolving design culture that is simultaneously ambitious and constrained. While awareness of UEC and circularity is rising, implementation is often hindered by misaligned incentives, fragmented data, and inconsistent ownership of sustainability decisions across roles.

Based on the interviews, for the CCF to function effectively in real-world projects, DTs require more than technical guidance. They need:

- **Open-source accessibility:** The tool must be openly available and usable by all disciplines, allowing team members to collaboratively define and explore circular strategies without license or platform barriers.
- **KPIs:** Decision-making should be grounded in clear, cross-disciplinary key performance indicators, such as EC per m², circularity potential, and cost efficiency, that facilitate consistent interpretation and transparent trade-offs.
- **Usability:** The tool must be relatively easy to use, enabling all disciplines (not just specialists) to input, update, and reflect on material choices and impacts during active project phases.
- **Design-phase guidance:** The tool should clarify which circular strategies are realistically implementable in each design phase, from SO through VO, (VO+), and DO, so teams can time decisions appropriately and avoid late-stage inefficiencies or missed opportunities.

These needs outline the functional and collaborative conditions required for the CCF to succeed. The following chapters address several of these priorities, particularly by exploring how the tool can guide early design-phase decisions around circular strategies, UEC, and financial feasibility.

4.3. Circular Scope

4.3.1. Defining Circularity

In the introductory chapter, circularity is defined both in the broad context of the circular economy and in terms of its application to building strategies. While circularity remains an evolving concept, it is essential to establish a clear and consistent definition within the scope of this research and, specifically, within the CCF. (Marin & De Meulder, 2018)

To achieve this, the CCF operationalizes circularity in the early design phase of buildings. The framework does so by distinguishing between two essential and interdependent components: circular strategies and circular indicators.

Circular strategies represent the practical design interventions that DTs can adopt to lower UEC through circularity. These strategies function as the actionable input of the framework. While the theoretical range of such strategies is extensive, the CCF identifies a curated set of seven strategies in this chapter that are most relevant and feasible during the early design phases. Importantly, the CCF remains flexible: additional strategies can be introduced as long as they result in measurable changes in one or more of the circular indicators.

Circular indicators, on the other hand, represent the quantifiable outputs of circular strategies. They reflect measurable characteristics of material use and design decisions that contribute to circular outcomes. These indicators form the analytical backbone of the CCF and are used to evaluate and compare the circular potential of different design alternatives. Their selection is grounded in both academic theory and practical models from industry, ensuring their relevance to real-world construction processes.

Together, the indicators and strategies provide a structured yet adaptable method for DTs to implement and evaluate circular decisions. The following sections introduce these two concepts in detail, first by explaining the fixed set of circular indicators, followed by an overview of the circular strategies that can activate them in practice.

4.3.2. Circular Indicators

To evaluate circularity in a measurable and project-specific way, this thesis introduces a set of circular indicators that quantify the impact of circular strategies on UEC. These indicators form the output of the CCF and serve as the basis for assessing and comparing different design decisions.

A variety of frameworks have been developed to support the transition toward a more circular built environment. Among the most influential are the Circular Strategies Framework (CSF) and the R-Ladder, both of which serve as foundational tools in identifying and prioritizing circular actions (Figure 1.4 and 1.5). To ensure a robust and applicable CCF, this study also incorporates insights from Het Nieuwe Normaal (HNN), the Building Circularity Index (BCI), and Madaster (Figure 4.3). (HNN, 2025; van Grinsven et al., 2024).

The selected circular indicators are drawn from both theoretical principles and practical assessment tools. The CSF and R-Ladder provide the overview for circular indicators, while HNN, BCI and Madaster supply quantifiable criteria rooted in Dutch construction practice. The interviews were also used to reflect real-world design processes and the challenges faced by DTs.

Within the CCF, these indicators represent the quantifiable output of circular strategies and form the basis for evaluating their effect on UEC. To maintain analytical focus, only indicators with a direct impact on UEC were included. All circular strategies, whether predefined or project-specific, must ultimately translate into a measurable shift in one or more of these indicators to be evaluated within the framework. These indicators are operationalized through the Circular Index Meter (CIM), which enables consistent and transparent comparison of circular outcomes across different design alternatives.

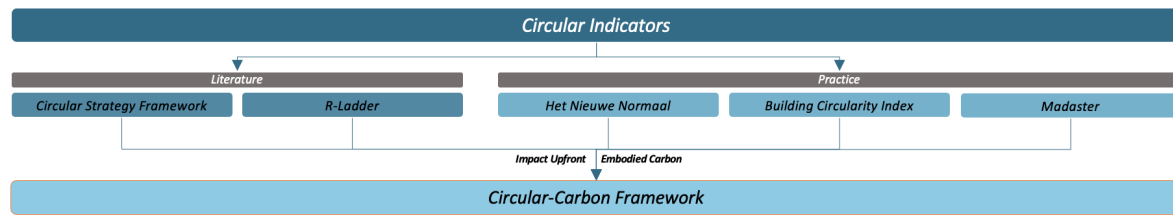


Figure 4.3: Overview of literature-based and practice-based sources used to define circular indicators in the CCF. Own illustration.

Table 4.1 presents the primary quantifiable circularity indicators considered in this thesis. Their inclusion within the CCF is based on two criteria: the accessibility of the required data and the alignment of these indicators with the outcomes of the circular strategies discussed in the following paragraph. For each material applied, the percentages of reused, recycled, and bio-based content are tracked, along with the associated material disassembly potential.

While platforms such as BCI and Madaster also include the percentage of downcycled material in the input phases (A1–A5), these materials typically do not re-enter the building's structural or skin layers, which is the focus of this research. Such inputs are more commonly applied in the space plan and service layers, components that fall outside the scope of this study. Similarly, indicators related to the building's end-of-life phase, such as potential for reuse, recycling, or downcycling, are acknowledged but excluded due to the research's emphasis on early design-stage decisions. The selection of indicators was further informed by the analysis of EDGE's projects, which provided practical insight through their implementation in platforms Madaster and the BCI. By critically reviewing these platforms and grounding the selection in real-world project data, the indicators presented in Table 4.1 are deemed the most relevant and applicable quantitative measures for integration into the CCF.

Table 4.1: Circular indicators used within the CCF to assess the integration of circular strategies in building design. Own illustration.

Abbr.	Circular Indicators	Definition	Source
RBC	Reused Building Components	The share of products reused for the same purpose by a different user, without major reprocessing	CSF and R-Ladder & Madaster
RBM	Recycled Building Material	The conversion of reclaimed materials into lower-grade or functionally reduced applications, typically requiring substantial energy or water input	CSF, R-Ladder, BCI, HNN & Madaster
BBR	Bio-based Resources	The extent to which materials are sourced bio-based and produced using renewable energy	CSF, BCI, HNN & Madaster
DFD	Design for Disassembly	The extent to which the building is designed to allow components and materials to be easily taken apart, removed, and reused or recycled at the end of their service life, minimizing waste and facilitating circular use.	CSF, BCI, HNN & Madaster

4.3.3. Circular Strategies

Within the CCF, circular strategies provide the DT with a structured menu of potential approaches to reduce UEC. These strategies guide how circularity can be implemented in the early design phase, ranging from for example, long-life design to bio-based construction.

The strategies included in this thesis represent the most dominant and UEC-relevant approaches identified through literature from Çetin et al. (2021) and Eberhardt et al. (2022) complemented by expert interviews with DTs. However, the CCF is explicitly designed to be open-ended: DTs are encouraged to develop project-specific strategies beyond those predefined, as long as their effects can be expressed through the circular indicators.

In this way, circular strategies act as starting points for circular design thinking, they are not prescriptive, but rather inspire and structure decision-making. What matters for the model is that any strategy, whether standard or custom, leads to a quantifiable change in the circular indicators.

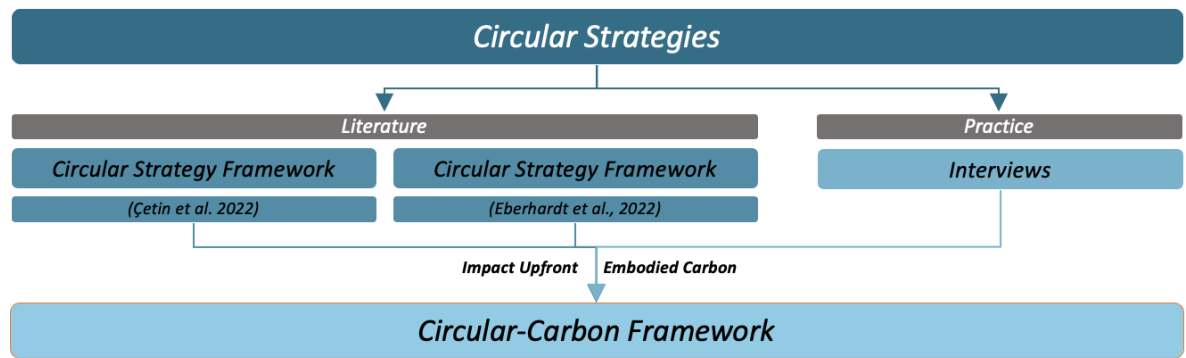


Figure 4.4: Overview of literature-based and practice-based sources used to define circular strategies in the CCF. Own illustration.

Table 4.2 presents the set of circular strategies usable for the CCF to evaluate their influence on UEC in the built environment. Each of these strategies has been selected based on their frequent appearance in literature, particularly the works of Eberhardt et al. (2022) and Çetin et al. (2021), where they are consistently associated with measurable circular outcomes and carbon reductions. While other circular strategies do exist, those included in this table form a representative menu of widely cited and practically applicable options for early design-phase decision-making.

These strategies are assessed through the circular indicators outlined in the previous section, such as the percentage of reused, recycled, and bio-based content, as well as the disassembly potential of materials. These indicators allow for a quantifiable evaluation of strategy implementation and enable comparison across different design options.

To maintain flexibility, the CCF includes an open category, PSA (Project-Specific Additions), allowing DTs to define and upload custom strategies specific to their case. These can be compared to the predefined options using the same circular indicators, ensuring consistency in assessment while supporting project-specific adaptation.

Table 4.2: Circular strategies used within the CCF to assess the integration of circular principles in building design. Own illustration.

Abbr.	Circular Strategy	Definition	Source
BBM	Bio-based Materials	Use of renewable, organic materials to replace conventional ones to lower EC.	(Çetin et al., 2021) & (Eberhardt et al., 2022)
CMO	Component and Material Optimization	Minimizing both the quantity and variety of materials and components used in construction.	(Eberhardt et al., 2022)
DHP	Design for High Performance	Early-stage optimization of building performance to reduce resource demand and improve efficiency.	(Çetin et al., 2021)
DR	Design for Reversibility	Enabling disassembly and adaptability to support reuse and multiple life cycles.	(Çetin et al., 2021)
PRC	Promote Recycling	Convert reclaimed resources into similar or lower quality products to retain material value.	(Çetin et al., 2021) & (Eberhardt et al., 2022)
PRU	Promote Reusing	Bring materials back into the economy with minimal reprocessing or additional resource input.	(Çetin et al., 2021) & (Eberhardt et al., 2022)
RED	Material Efficiency (Reduce)	Minimizing the use of raw materials and natural resources through efficient design and manufacturing.	(Çetin et al., 2021)
PSA	<i>Project-Specific Additions</i>	<i>Placeholder for DTs to integrate case-specific strategies relevant to their unique project context.</i>	<i>Design Team</i>

Designing for circularity requires not only knowing what to do, but also when to do it. Many strategies lose feasibility or become significantly more expensive if considered too late in the process. To clarify this timing, a Strategy–Design Matrix has been developed. Grounded in interview findings, it outlines which circular strategies align best with each design phase. Before introducing the matrix, a brief explanation of the typical focus and decisions made in each phase will provide context.

The Sketch Design (SO) phase focuses on translating the client's ambitions into a basic spatial and conceptual design, where key decisions about form, orientation, and function are still open, making it the most impactful phase for integrating circular strategies. In the Preliminary Design (VO) phase, the concept is developed further with structural grids, material choices, and layout refinements, limiting flexibility but still allowing for strategic adjustments. By the Final Design (DO) phase, technical details, product specifications, and construction methods are fixed, leaving minimal room for major circular interventions without affecting cost or feasibility. (Valdes, 2024)

Table 4.3 serves not only as an overview of circular strategies and their estimated impact, but also as a guiding tool for DTs. It supports the mapping of which strategies are most suitable during different design phases and encourages teams to elevate project-specific ambitions in a structured way.

The timing of implementation varies significantly between structural components and skin or finishing elements. For example, choosing a low-carbon concrete alternative must typically occur early in the design due to its structural implications, whereas switching to recycled glass or different façade cladding is often feasible in later stages.

Ultimately, it is up to the DTs to assess the project’s specific needs and context, and to use this table accordingly to maximize circular potential. The table illustrates, in broad terms, when and where circular strategies can still be meaningfully applied, helping to embed circularity at the right moment in the design process.

Table 4.3: Strategy Design Matrix: Integration of circular strategies across design phases and their estimated impact on upfront embodied carbon and cost. Own illustration.

Abbr.	Sketch Design	Prelim. Design	Final Design	UEC Reduction	Cost Increase
BBM	High	Low	Low	+++	+++
CMO	High	Medium	Low	++	-
DHP	High	Medium	Low	++	-
DR	High	Medium	Low	+	++
PRC	High	High	Medium	++	++
PRU	High	High	Medium	+++	+
RED	High	High	Medium	+++	-
PSA	N/A	N/A	N/A	N/A	N/A

4.4. Conclusion

SRQ 2: What circular construction strategies can be categorized and applied across different design phases to support early-stage decision-making?

This chapter builds upon the internal foundation of the CCF by identifying and categorizing the circular strategies that guide early-stage decision-making. While indicators help measure circular performance, it is the strategies themselves that drive design interventions. This distinction is crucial. Through literature review and expert interviews, this chapter develops a structured overview of circular strategies, organized across design phases. The result is a Strategy-Design Matrix that clarifies not only what strategies are available, but also when they can be most effectively implemented.

The DT plays a pivotal but often constrained role in advancing circular decision-making. While awareness of circularity is growing, interviews revealed that implementation is hindered by misalignment between sustainability ambitions and financial certainty, as well as a lack of transparent metrics and standardized tools. The CCF addresses these barriers by offering a structured, KPI-driven framework to support early integration of circularity in the design process. For the framework to be successful, DT members emphasized the need for open access, usability, and clear phase-specific guidance.

A key distinction in the CCF is made between circular indicators and circular strategies. The indicators: Reused Building Components, Recycled Building Material, Bio-based Resources, and disassembly potential, function as quantifiable outputs to assess circularity. They allow for systematic measurement and performance comparison across design options.

In contrast, circular strategies represent design interventions that actively reduce UEC and material cost. These include for example: material reduction, re-use, recycling, and adoption of bio-based alternatives. To accommodate project-specific innovation, the CCF includes a dedicated category for Project Specific Additions (PSA), allowing DTs to formulate custom strategies aligned with circular principles.

Answering the sub question, circular strategies can be categorized across different design phases using the Strategy-Design Matrix developed in this chapter. This matrix links each strategy to the design phase in which it is most effective, early stages such as SO and VO offer the highest potential for impactful interventions, while the DO phase introduces more constraints. While this thesis has used literature to identify and structure a set of key circular strategies, it is important to note that, in theory, the number of circular strategies is unlimited. Their applicability is highly project-specific and context-dependent, which is why the framework also includes a category for Project Specific Additions (PSA) to allow flexibility in practical implementation.

By mapping strategy application to project phase, and ensuring their alignment with measurable indicators, the CCF ensures that circular design remains both structured and adaptable, maximizing impact while preserving flexibility.

5

The Circular-Carbon Framework: Development, Structure and Evaluation

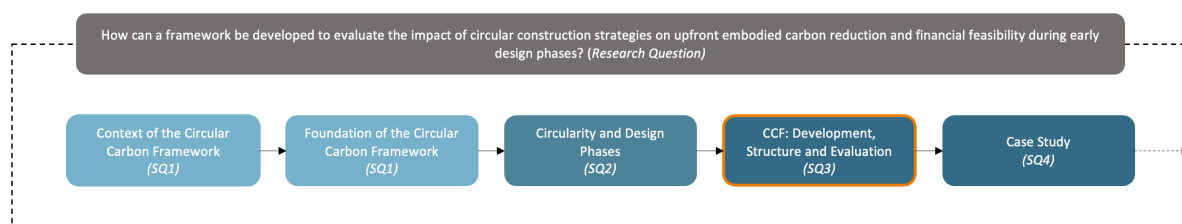


Figure 5.1: Chapter 5 roadmap. Own illustration.

5.1. Introduction

To ensure clarity and maintain continuity, this chapter begins with a brief recap of the previous chapters, which together laid the foundation for the Circular-Carbon Framework (CCF). Chapter 2 introduced the theoretical background and presented the Value Driven Design (VDD) framework. This framework defines three core variables: carbon, cost, and circularity. Each variable is accompanied by a corresponding set of attributes, as illustrated in figure 5.2. The chapter also established the regulatory context and introduced the Paris Proof benchmarks. It concluded with a review of existing models and clarified the distinct position of the CCF in comparison to existing approaches.

Chapter 3 focused on defining the carbon scope. It specified the building layers considered within the analysis, namely structure and skin, and identified the relevant material categories included in the framework. The chapter also introduced the cost variable, explaining how cost is interpreted and delineated within the CCF model.

Chapter 4 examined the roles and responsibilities of design team (DT) members in early design phases. Their influence on circular and low carbon strategies was explored to strengthen the understanding of the final core variable, circularity. The chapter refined the definition of circularity and introduced the circular indicators and strategies operationalised within the framework.

This chapter presents the full development structure and interpretation of the CCF. The variables and attributes introduced in the preceding chapters are now systematically integrated within a coherent framework. Each layer of the framework is subsequently examined in detail to clarify its function and

interrelations within the overall structure.

At this point, the reader is encouraged to open the model and begin exploring the individual sheets. The color scheme used in figure 5.2 is consistently applied in the framework itself to support intuitive navigation through the model.

By the end of this chapter, the reader will have a comprehensive understanding of the model’s configuration, including the internal logic of its layered structure, the required data inputs, and the underlying assumptions and limitations. The chapter concludes by explaining how the model is positioned within the broader academic context and highlights the novelty and scientific contribution of the CCF.

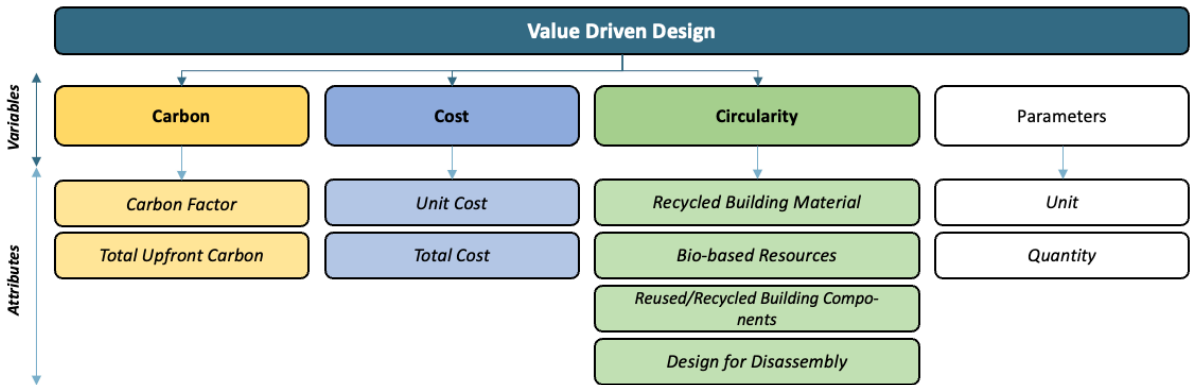


Figure 5.2: Overview of the variables and attributes of the value driven design model as adapted for the CCF. Own illustration.

5.2. Program of Requirements

Before constructing the CCF model, a Program of Requirements (PoR) is needed to understand what must be included in the CCF. A PoR in software development offers several advantages. Firstly, it serves as the basis for verification and validation, ensuring that the model is assessed against its initial requirements. Secondly, a well-structured PoR helps capture and formalize specific constraints early in the project. Finally, a clear PoR facilitates shared understanding, reduces duplication, and improves integration of diverse contributions (M. Chawan & More, 2011).

This PoR defines the functional, technical, user-related, and contextual specifications that guide the development and use of the CCF. The requirements are derived from various sources within this research: literature, interviews, and (policy) frameworks. The requirements are categorized into functional, technical, and user requirements, as well as specific requirements per model layer.

1. Functional Requirements

- **Decision support:** The model must serve as a practical decision-support tool that enables users to compare and enhance multiple circular design strategies based on the carbon, cost, and circularity performance.
- **Circular strategy assessment:** The model must allow for the evaluation of circular design strategies: reuse, recycle, bio-based and design for disassembly. These strategies should be assessed either quantitatively or semi-quantitatively.

2. Technical Requirements

- **Reproducibility:** All outputs of the model must be reproducible and traceable based on transparent and verifiable inputs, with explicit source referencing.
- **Modularity and scalability:** The model must have a modular structure and be scalable for different building layers and materials.
- **Alignment with existing frameworks:** The backbone of the CCF must be based on well-established literature for designing each of the carbon, cost, and circularity variables. These include:
 - The R-ladder of circularity (TNO, 2024)
 - The Circular Strategy Framework (Çetin et al., 2021; Eberhardt et al., 2022)
 - The Paris Proof CO₂ budget (DGBC, 2022)

3. User Requirements

- **Accessibility:** The model must be accessible to users from different technical backgrounds, including architects, engineers, advisors, and clients. The interface should be intuitive and clearly structured.
- **Result visualization:** Outputs must be visualized in a comprehensible manner through dashboards to support interpretation and decision-making.

4. Assumptions and Design Conditions

- **Design-phase applicability:** The CCF is intended for use during the design phases and therefore relies on conceptual (ex ante) rather than detailed (ex post) data.
- **Material focus:** The model's primary scope is on materials with the highest UEC impact, particularly the skin and structure of the building.
- **Validated data sources:** All calculations must be based on validated and commonly accepted datasets, such as national LCA databases (e.g., NMD) or specific EPDs.

5. Model Components and Specific Requirements

To ensure clarity regarding the structure and logic of the CCF, four core model components are defined, each with its own set of specific requirements.

5.1. Input Parameters

- The model must map relevant design variables and their parameters, including:
 - Project information
 - Material selection
 - Carbon, cost, and circularity data
 - Chosen circular strategies
 - All necessary inputs to assess the subsequent model layers

5.2. Comparison Model

- The comparison module must allow for the parallel analysis of multiple circular design strategies.
- Each variant must be evaluated against a uniform set of Key Performance Indicators (KPIs), including:
 - UEC
 - Material cost
 - Circularity Index Meter (CIM-Score)
- Outputs must be represented to enable direct comparison between scenarios

5.3. Decision Dashboard

- The dashboard must provide a clear visual representation of performance per design scenario.
- Core functionalities include:
 - Comparative display of UEC emissions, cost, and circularity level (per m²)
 - Highlighting the best-performing variant based on selected KPIs regarding to the budgets

5.4. Data Sources

- All calculations must rely on verified and publicly accessible datasets, such as:
 - National Environmental Databases (e.g., NMD)
 - EPDs
- The source and version of each data point must be clearly stated within the model.

5.3. Framework Architecture: Structure and Logic

5.3.1. Overall Model Setup: The Circular-Carbon Framework

In the preceding chapters, the variables and attributes underpinning the CCF have been defined and discussed in detail. This chapter aims to consolidate these elements into an integrated framework structure. The CCF is organized into four distinct but interrelated layers, as illustrated in figure 5.3.

Layer 1, Input Parameters, captures the fundamental project-specific information required for analysis. Layer 2, the Comparison Sheet, serves as the technical core of the framework, where the DT formulates and evaluates different circular strategies against carbon, cost, and circularity. Layer 3, the Decision Dashboard, synthesizes outputs from the comparison layer into a more accessible and interpretable format to support decision-making. Finally, Layer 4, Sources, comprises the data inputs necessary to inform the framework, including EPDs and cost datasets.

This section provides an overview of the four foundational layers that constitute the basic structure of the framework. A general interpretation of these layers is presented to establish conceptual clarity. However, due to the increased complexity and level of detail associated with Layers 2 and 3, a more comprehensive explanation is provided separately in paragraph 5.2.2 and 5.2.3, respectively.

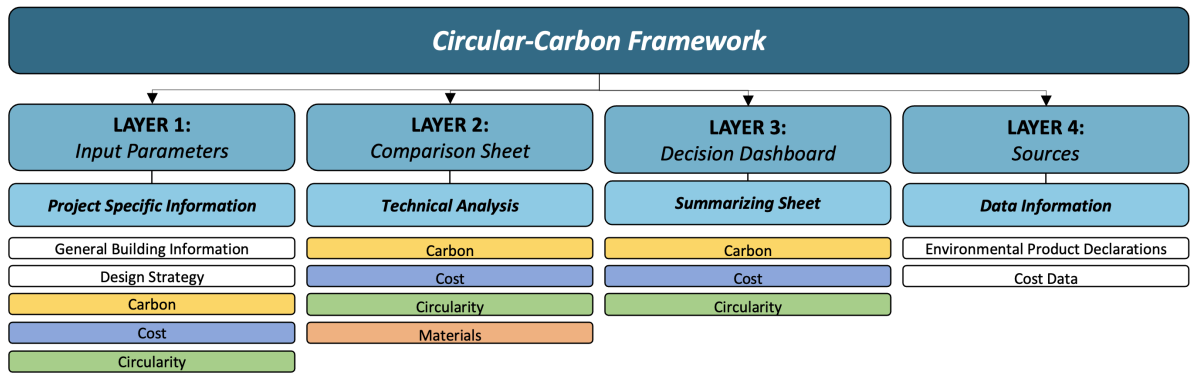


Figure 5.3: Conceptual model representing the structure and components of the CCF. Own illustration.

Layer 1: Input Parameters

Layer 1 of the is the *Input Parameter Sheet*. The primary purpose of this sheet is to clearly define the project context in which the analysis is conducted. By establishing these parameters, the framework ensures that all subsequent calculations and evaluations are based on a consistent and project-specific foundation. The input parameters are divided into five distinct categories (Figure 5.4):

- **General:** This category captures the basic characteristics of the project, including its name, location, design phase, gross floor area (GFA), building type, number of floors, year of permits issuance, completion year, and the primary structural and façade systems. Such information is standard practice in environmental assessments and facilitates a more accurate and contextual interpretation of the results.
- **Design Strategy:** This section identifies the specific circular design strategy under consideration. It reflects the DTs chosen intervention aligned with carbon, cost and circularity objectives.
- **Carbon Indicator:** The carbon indicator describes the parameters required for the assessment of UEC. It is divided into qualitative and quantitative components. The qualitative inputs include the definition of the system boundary in terms of life cycle stages, the EPD database used, and the applied functional unit. The quantitative aspect focuses on the carbon budget allocated to the project, which is derived from Paris Proof targets and serves as a benchmark to guide low-carbon design decisions. A more detailed explanation of the methodology will follow in the subsequent sections.
- **Cost Indicator:** The cost indicator outlines the financial inputs underlying the assessment. Similar to the carbon indicator, it begins with qualitative inputs such as the unit cost definitions and the selected currency. This is followed by quantitative data, where a total project budget is specified. The budget is then split up into specific categories, including separate allocations for the building's structural and skin layer. Within each of these categories, the budget is further refined to budget exclusively for material-related costs. A more detailed explanation of the methodology will follow in the subsequent sections.
- **Circularity Indicator:** The circularity indicator defines how circularity is measured within the assessment framework. This is done through the CIM-meter, which provides a quantifiable value to assess and compare circular strategies. Similar to the other indicators, a minimum required value for circularity is inputted, functioning as a threshold. This value is divided across the building's skin and structural layers, allowing for targeted circularity goals. The CIM serves as a tool to measure circular design decisions. A more detailed explanation of the methodology will follow in the subsequent sections.

Category	Parameter	Description	Value	Unit
General	Project Name	Own entry	-	-
	Project Location	Own entry	-	-
	Project Phase	Own entry	-	-
	Gross Floor Area (GFA)	Own entry	-	m ²
	Building Type	Own entry	-	-
	Number of Floors	Own entry	-	-
	Year of Permits Issuance	Own entry	-	-
	Year of Completion	Own entry	-	-
	Structural System	Own entry	-	-
	Façade System	Own entry	-	-
Design Strategy	Circular Strategy	Own entry	-	-
Carbon Indicator	CO ₂ Boundary (Life Cycle Stages)	A1-A3	-	-
	EPD Database	EPD International	-	-
	Functional Unit	Used functional Unit	-	kg CO ₂ -eq/m ²
	Paris-Proof Embodied Carbon Threshold	Used Paris-Proof Threshold Value	250	kg CO ₂ -eq/m ² GFA (A1-A3)
	Carbon Budget (Structure and Skin)	Carbon budget for Structure and Skin	-	-
	Carbon Budget (Structure, 50%)	Carbon budget for Structure	-	kg CO ₂ -eq/m ² GFA (A1-A3)
Cost Indicator	Carbon Budget (Skin, 20%)	Carbon budget for Skin	-	kg CO ₂ -eq/m ² GFA (A1-A3)
	Unit Cost Basis	Snapshot (Not time adjusted)	-	-
	Currency	Euro (€)	-	€
	Total Budget	Total cost budget	€ -	€
	Total Budget (Structure and Skin)	Total cost budget Structure and Skin	€ -	-
	Cost Budget (Structure, 60%)	Cost budget for Structure	€ -	€
	Cost Budget (Skin, 15%)	Cost budget for Skin	€ -	€
	Conversion Factor	Materials vs Labour	0.5	-
	Material Cost Budget (Structure and Skin)	Material budget for Structure and Skin	€ -	€
	Material Cost Budget (Structure, 40%)	Material budget for Structure	€ -	€
Circularity Indicator	Material Cost Budget (Skin, 15%)	Material budget for Skin	€ -	€
	Circularity Framework	Circular Index Meter (CIM-Score)	-	%
	CIM Score	0-100	Own entry	%
	CIM Total Score	0-100	0%	%
	CIM Structure	Circular Index for Structure	0%	%
	CIM Skin	Circular Index for Skin	0%	%

Figure 5.4: Overview of the input parameters in Layer 1 of the general model (screenshot). Own illustration.

Among all input parameters in the CCF, most are self-explanatory. However, three require additional clarification due to their critical role in guiding material selection and evaluating trade-offs: the **carbon budget**, **cost budget** and **circular budget**. These values (highlighted in orange) function as key steering mechanisms that help identify when a particular building layer (e.g., structure or skin) exceeds acceptable limits in terms of environmental or financial impact. They also define the point at which circular strategies are required to restore the project objectives.

Carbon Budget The *carbon budget* indicates the maximum share of the UEC emissions that can be attributed to the structure and skin while remaining compliant with the Paris Proof threshold value. Since a building consists of more components than just structure and skin, a share of the total carbon budget must be reserved for other building layers.

To enable this distribution between the structure and skin, 70% of the total UEC needs to be split between the skin and structure (Figure 3.3a). How this exact distribution takes place is project-specific and is up to the DT to decide how they want to divide it. Assuming a total allowable EC of 250 kgCO₂e/m², this results in, for example:

- **Carbon Budget Structure:** 50% of 250 = 125 kgCO₂-eq/m²
- **Carbon Budget Skin:** 20% of 250 = 50 kgCO₂-eq/m²
- **Carbon Budget Structure and Skin:** 125 + 50 = 175 kgCO₂-eq/m²

If the UEC values for these layers exceed their respective budgets, circular strategies must be applied to reduce emissions and bring the design back within acceptable limits. This corrective mechanism is a central function of the CCF.

Cost Budget The cost budget follows the same logic. It defines the portion of the total construction budget that should be allocated to the structure and skin. These benchmarks ensure that financial fea-

sibility is maintained across all building layers. The cost shares used in the CCF, structure: 40%, skin: 15%, are based on internal project documentation and cost data from commercial building projects.

The cost budget follows the same logic as the carbon budget. First, a total project budget is defined, representing all costs associated with the complete construction project. The model then automatically divides this total into a cost budget for the structure (e.g. 40%) and a cost budget for the skin (e.g. 15%).

Since construction costs do not solely consist of material expenses but also include labour, which often constitutes a significant share, an additional conversion step is required. To account for this, the budget allocated to both the structure and the skin is multiplied by a conversion factor (e.g. 50%), which represents the proportion of the budget attributed to materials. For example, if the conversion factor is 50%, this means that half of the cost is considered material-related, while the other half accounts for labor and other non-material expenses.

After applying this conversion, the final material budgets are determined: one for the structural materials, one for the skin materials, and their sum yields the total material cost budget. When DTs input the total budget, the model automatically performs all necessary calculations. If desired, users can adjust the allocation percentages between structure and skin, or modify the conversion factor to reflect project-specific assumptions.

Circular Budget Finally, a circularity budget needs to be defined. This represents the minimum percentage of circularity that must be achieved within the project. Similar to the carbon and cost indicators, this requirement is subdivided into two specific circularity index values: one for the structure and one for the skin. These values provide targeted circular performance thresholds for the respective building components and serve as input for evaluating compliance with circular design objectives.

Collectively, these project budgets (highlighted in orange) serve as benchmarks against which the different circular design strategies are evaluated. The carbon, cost, and circularity metrics of each design are tested against these predefined budgets. Therefore, in Layer 3 of the model, the structured comparison enables clear and efficient support for decision-making.

Layer 2: The Comparison Model

The Comparison Model forms the mathematical core of the CCF. In this model, the DT specifies the material choices for a particular construction project at the product and material level. The model allows for flexible input of different material specifications that reflect both the base case design (usually corresponding to the first sketch design phase (SO) and alternative circular strategies (Figure 5.5).

Design Phase	Product choice			General Model							Circular Index Meter (CIM)							
	CO2 Related materials		Layer and Type	Unit	Quantity	CO ₂ Factor (kg CO ₂ -eq/unit)	Total Upfront CO ₂ (kg)	Unit Cost (K)	Total Cost (K)	CIM Score	RBM (N)	BBR (N)	RBC (N)	DFD (N)				
				Parameters		Carbon		Cost (Range)		Circularity	A1-A3	A1-A3	Module C/D	Module D				
sq/v/o	Concrete	Structure	CEM 1	m³	-	2.01E+02	-	110-130	-	-	0%	0%	0%	-				
			C20/25	CEM 3/B	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%	-			
			C20/37	CEM 1	m³	-	3.86E+02	-	110-150	-	-	0%	0%	90%	-			
			C20/37	CEM 3/B	m³	-	1.81E+02	-	120-130	-	-	0%	0%	61%	-			
			C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%	-			
			C35/45	CEM 3/B	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%	-			
			C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%	-			
			C40/50	CEM 1 / CM3 (50/50)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%	-			
			PSA 1	PSA 1	-	-	-	-	-	-	-	-	-	-	-			
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-			
sq/v/o	Reinforced Steel	Structure	Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500P / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500A Recycled	tonne	-	4.64E-01	-	680-720	-	-	18%	0%	95%	-			
			Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%	-			
			Rebar	B500C Recycled	tonne	-	4.57E-01	-	680-720	-	-	1%	0%	90%	-			
			PSA 1	PSA 1	-	-	-	-	-	-	-	-	-	-	-			
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-			
			sq/v/o	Structural Steel	Structure	Sections	S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	750-1200	-	-	0%	0%	95%	-
						Sections	S275	tonne	-	2.35E+03	-	750-1200	-	-	0%	0%	95%	-
Sections	S355	tonne				-	2.53E+03	-	750-1200	-	-	0%	0%	85%	-			
Sections	S235 Scrap	tonne				-	5.60E+02	-	770-1220	-	-	100%	0%	100%	-			
Sections	S275 Scrap	tonne				-	5.60E+02	-	780-1280	-	-	100%	0%	100%	-			
Sections	S335 Scrap	tonne				-	5.60E+02	-	1500-2500	-	-	100%	0%	100%	-			
PSA 1	PSA 1	-				-	-	-	-	-	-	-	-	-	-			
PSA 2	PSA 2	-				-	-	-	-	-	-	-	-	-	-			
sq/v/o	Engineered Timber	Structure				CLT	Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%	-
						LVL	Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%	-
			GLT	Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%	-			
			PSA 1	PSA 1	-	-	-	-	-	-	-	-	-	-				
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-				
			sq/v/o/b/o	Aluminum	Skin	Cladding System	EN AW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%	-
						Cladding System	EN AW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%	-
						Structural Framing	EN AW-6062	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%	-
						Window & Wall Systems	EN AW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%	-
						Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%	-
PSA 1	PSA 1	-				-	-	-	-	-	-	-	-	-				
PSA 2	PSA 2	-				-	-	-	-	-	-	-	-	-				
sq/v/o/b/o	Glazing	Skin				Twitec System Glass	Flat Glass	m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%	-
						Saint-Gobain	Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%	-
						Stronglases	Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%	-
			Thermoplastiki	Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%	-			
			Predari Vetri	Double Glass Recycled	m²	-	3.63E+01	-	500-600	-	-	0%	0%	99%	-			
			Stronglases	Insulated Triple Glazing	m²	-	1.58E+02	-	600-700	-	-	50%	0%	65%	-			
			PSA 1	PSA 1	-	-	-	-	-	-	-	-	-	-				
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-				
			sq/v/o/b/o	Architectural Steel	Skin	Hot Dip Galvanized	DX, HX and S Grades	tonne	-	1.98E+03	-	775-810	-	-	60%	0%	95%	-
						Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%	-
Cold-Rolled	DC01, DC03, DC04, DC06	tonne				-	3.39E+03	-	650-800	-	-	22%	0%	95%	-			
Cold-Rolled	Xcarb CR Recycled	tonne				-	7.99E+02	-	710-730	-	-	0%	0%	98%	-			
PSA 1	PSA 1	-				-	-	-	-	-	-	-	-	-				
PSA 2	PSA 2	-				-	-	-	-	-	-	-	-	-				
TOTALS								Carbon Skin		Cost Skin		CIM Skin						
								Total Carbon		Total Cost		Total Circularity						

Figure 5.5: Overview of the comparison model in Layer 2 of the general model (screenshot). Own illustration.

The Comparison Model is organized per material type and includes key parameters:

- **Upfront Embodied Carbon:** expressed in kg CO₂-equivalent per unit;
- **Cost:** unit cost ranges for the respective materials;
- **Circularity Indicators:** RBM (Recycled Building Material), BBR (Bio-based Resources), RBC (Reused/Recycled Building Components) and DFD (Design for Disassembly).

Through this structure, the Comparison Model enables the quantification of key performance metrics, including the total UEC of the design, the total cost resulting from material choices, and the Circularity Index Meter (CIM), which reflects the circular potential of the design. These outputs allow for informed trade-offs between carbon, cost and circularity.

The fundamental principle behind this model is that the DT collaboratively fills in the base case and explores the effects of introducing different circular strategies. If done correctly, a trade-off emerges: some circular strategies achieve significant carbon reduction but may come with higher costs, while

others lower costs but provide less benefit in terms of carbon or circularity. The intention is not only to provide quantitative outputs but also to stimulate informed, critical discussions within the DT concerning material use, sustainability priorities, and feasible interventions.

Layer 3: The Decision Dashboard

The Decision Dashboard is the second layer of the CCF and serve primarily as a simplified and user-friendly interface for decision-makers who may not be directly involved in the technical details of material selection. This layer was explicitly developed based on insights from expert interviews, which emphasized the need for transparent, easily interpretable KPIs to facilitate informed decision-making by non-technical stakeholders, such as project owners, clients, or investors.

While the Comparison Model offers the full technical depth required for DT members to input, calculate, and enhance material choices, the Decision Dashboards translate these technical inputs into clear and actionable information for a broader project audience. (Figure 5.6)

Input	
Gross Floor Area (m²)	X
Conversion Factor (Kg / Gram)	1000

Decision Dashboard 1						Budget
Totals						
Parameter	Unit	Base Case	Strategy 1	Strategy 2	Strategy 3	
Upfront Embodied Carbon kg CO₂		X	X	X	X	X
UEC (Structure)		x	x	x	x	X
UEC (Skin)		x	x	x	x	X
Total cost	€	Y	Y	Y	Y	Y
TC (Structure)		Y	Y	Y	Y	Y
TC (Skin)		Y	Y	Y	Y	Y
Circularity Index Meter		Z	Z	Z	Z	Z
CIM (skin)		Z	Z	Z	Z	Z
CIM (Structure)		Z	Z	Z	Z	Z

Decision Dashboard 2 (Regular)						Budget
Per m²						
Parameter	Unit	Base Case	Strategy 1	Strategy 2	Strategy 3	
Upfront Embodied Carbon kg CO₂ / m² (GFA)		X	X	X	X	X
UEC (Structure)		x	x	x	x	X
UEC (Skin)		x	x	x	x	X
Total cost	€ / m² (GFA)	Y	Y	Y	Y	Y
TC (Structure)		Y	Y	Y	Y	Y
TC (Skin)		Y	Y	Y	Y	Y
Circularity Index Meter	-	Z	Z	Z	Z	Z
CIM (structure)		Z	Z	Z	Z	Z
CIM (skin)		Z	Z	Z	Z	Z

Decision Dashboard 2 (Color coded)						Budget
Per m²						
Parameter	Unit	Base Case	Strategy 1	Strategy 2	Strategy 3	
Upfront Embodied Carbon kg CO₂ / m² (GFA)		< X	< X	> X	> X	X
UEC (Structure)		x	x	x	x	X
UEC (Skin)		x	x	x	x	X
Total cost	€ / m² (GFA)	> Y	> Y	< Y	< Y	Y
TC (Structure)		Y	Y	Y	Y	Y
TC (Skin)		Y	Y	Y	Y	Y
Circularity Index Meter	-	> Z	< Z	> Z	< Z	Z
CIM (structure)		Z	Z	Z	Z	Z
CIM (skin)		Z	Z	Z	Z	Z

Decision Dashboard 3				
Parameter	Unit	Base Case (Concrete)	1. As-Built (Bio-Based)	2. Enhance Recycling 3. Smart Circular
Carbon Efficiency Ratio	Gr CO₂/€ invested	X	X	X

Figure 5.6: Overview of the decision dashboard in Layer 3 of the general model (screenshot). Own illustration.

The dashboards are subdivided into three components:

1. **Decision Dashboard 1 (Totals):** Displays the total values for:
 - Upfront embodied carbon (CO₂);
 - Total cost (€);
 - Circularity index (CIM Score)
2. **Decision Dashboard 2 - Regular (Per m²):** Provides normalized KPIs per square meter of Gross Floor Area (GFA):
 - Upfront carbon per m² (CO₂/m²);
 - Cost per m² (€/m²);
 - Circularity index
3. **Decision Dashboard 2 - Color Coded (Per m²):** Provides normalized color-coded KPIs per square meter of Gross Floor Area (GFA):
 - Upfront carbon per m² (CO₂/m²);
 - Cost per m² (€/m²);
 - Circularity index
4. **Decision Dashboard 3 (Efficiency Ratio):** Introduces a combined carbon-financial indicator:
 - CO₂ per euro invested (kg CO₂/€ invested)

The first three decision dashboards include an additional *Budget* column, highlighted in orange. These budgets represent the maximum allowable values that must be met to align with the overarching project objectives. For all three key variables these budgets are further split-up into separate targets for the structural and skin layers of the building. The definition and allocation of these budgets are established in Layer 1 of the model (Figure 5.4).

By enabling a layer-by-layer comparison for both the structure and skin, DTs can readily identify which variables do not meet the set project targets. This facilitates targeted refinement of specific circular strategies to improve the balance between carbon, cost, and circularity performance in the early design phase. The exact idea behind this set-up is further explained in paragraph 5.3.3.

By summarizing technical outputs into these straightforward metrics, the decision dashboard enable stakeholders to compare different design scenarios quickly, evaluate trade-offs, and make more informed decisions their project objectives. In this way, the two-layered model ensures that both the technical depth required for detailed design analysis and the managerial simplicity needed for high-level decision-making are fully accommodated.

Layer 4: Sources

The final layer of the CCF is the *source data layer*, which plays a critical role in ensuring transparency and reliability when assessing both environmental and financial performance. This layer consists of two core components (Figure 5.7):

- 1. **EPD data** provides the CO₂ emission factors (in kg CO₂-eq per unit) necessary for calculating EC across life cycle stages A1–A3. Additionally, it serves as the basis for the circularity assessment by supplying the required input for the CIM, which includes four circularity indicators. These indicators are derived directly from the content of the EPDs and reflect the material's potential contribution to a more circular built environment.
- 2. **Cost data** represents the material's financial impact and is expressed in unit prices (e.g., €/m³). Ideally, this cost data is directly aligned with the EPD data, allowing for a coherent and consistent assessment. However, in practice, such alignment is often unavailable. In those cases, the framework uses representative average prices sourced from European or Dutch market data, or where available, specific quotes from manufacturers. Clarifying the origin and quality of this cost information is essential, as financial feasibility remains a decisive factor in project decision-making.

Product choice		Input Data Sources		Extra information	
CO2 Related materials	Layer and Type	Unit	CO ₂ Factor (kg CO ₂ -eq/unit)	Unit Cost (€)	Extra information (Unit Cost Related)
		Parameters	Carbon	Cost (Range)	
Concrete	Structure				
	C20/25	CEM 1	EPD - C20/25 - Normal	Avg EU Price C20/25 (Normal)	EPD Registration Number: EPD-IES-0008683-001 (S-P-08683)
	C20/25	CEM 3/B	EPD - C20/25 - Low Carbon	Price Green Concrete	EPD Registration Number: EPD-IES-0017078-001
	C30/37	CEM 1	EPD - C30/37 - Normal	Avg EU Price C20/25 (Normal)	EPD Registration Number: EPD-IES-0018866-001
	C30/37	CEM 3/B	EPD - C30/37 - Low Carbon	Price Green Concrete	EPD Registration Number: EPD-IES-0019951-002
	C35/45	CEM 1	EPD - C35/45 - Normal	Avg EU Prices Estimate	EPD Registration Number: EPD-IES-0018748-001
	C35/45	CEM 3/B	EPD - C35/45 - Low Carbon	Price Green Concrete	EPD Registration Number: EPD-IES-0005141-003
	C40/50	CEM 1	EPD - C40/50 - Normal	Avg EU Prices Estimate	EPD Registration Number: EPD-IES-0018749-001
	C40/50	CEM 1 CEM 3 (50/50)	EPD - C40/50 - Low Carbon	Price Green Concrete	EPD Registration Number: EPD-IES-0019952-002
	PSA 1	PSA 1	-	-	-
Reinforced Steel	Rebar	B500A	EPD - Rebars General	EuroMetal Prices	EPD Registration Number: EPD-IES-0018167
	Rebar	B500B	EPD - Rebars General	EuroMetal Prices	EPD Registration Number: EPD-IES-0018167
	Rebar	B500B / B500C	EPD - Rebars General	EuroMetal Prices	EPD Registration Number: EPD-IES-0018167
	Rebar	B500A Recycled	EPD - B500A - Recycled	Recycled Price Premium	EPD Registration Number: EPD-KIWA-EE-000131-EN
	Rebar	B500B Recycled	EPD - B500B - Recycled	Recycled Price Premium	EPD Registration Number: EPD-IES-0008499-002 (S-P-08499)
	Rebar	B500C Recycled	EPD - B500C - Recycled	Recycled Price Premium	EPD Registration Number: EPD-IES-0004160-002 (S-P-04160)
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
	PSA 4	PSA 4	-	-	-
Structural Steel	Sections	S235 (H, I- and U-Profile)	EPD - S235	Avg Steel Price (I)	EPD Registration Number: EPD-IES-0002936-002 (S-P-02936)
	Sections	S275	EPD - S275	Avg Steel Price (I)	EPD Registration Number: EPD-IES-0004885-001 (S-P-04885)
	Sections	S355	EPD - S355	Avg Steel Price (I)	EPD Registration Number: EPD-IES-0009490-002 (S-P-09490)
	Sections	S235 Scrap	S235 / S500 - Recycled	Scrap Price Premium	EPD Registration Number: EPD-BFS-20130094-0861-EN
	Sections	S235 Scrap	S235 / S500 - Recycled	Scrap Price Premium	EPD Registration Number: EPD-BFS-20130094-0861-EN
	Sections	S235 Scrap	S235 / S500 - Recycled	Scrap Price Premium	EPD Registration Number: EPD-BFS-20130094-0861-EN
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
	PSA 4	PSA 4	-	-	-
Engineered Timber	Structure				
	CLT	Spurce	EPD - CLT - Spurce	CLT Price Range	EPD Registration Number: EPD-IES-0019455-002
	LVL	Spurce	EPD - LVL - Spurce	LVL Price Range	EPD Registration Number: EPD-IES-0009942-003 (S-P-09942)
	GLT	Spurce	EPD - GLT - Spurce	GLT Price Range	EPD Registration Number: EPD-IES-0009942-003 (S-P-09942)
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
	PSA 4	PSA 4	-	-	-
	PSA 5	PSA 5	-	-	-
	PSA 6	PSA 6	-	-	-
Aluminum	Cladding System	EN AW-5005	EPD - EN AW-5005	Aluminum Sheet Price	EPD Registration Number: EPD-IES-0001717-001
	Cladding System	EN AW-1050	EPD - EN AW-1050	Aluminum Sheet Price	EPD Registration Number: EPD-IES-0007644-001
	Structural Framing	EN AW-6060	EPD - EN AW-6060	Aluminum Structural Frame Price	EPD Registration Number: EPD-IES-0018701-001
	Window & Wall Systems	EN AW-6060	EPD - EN AW-6060	Aluminum Window Systems Price	EPD Registration Number: EPD-IES-0007765-002 (S-P-07765)
	Window & Wall Systems	Hydro CIRCAL® 75 Recycled	EPD - Circular Recycled	Hydra Price	EPD Registration Number: EPD-IES-0015123-002
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
	PSA 4	PSA 4	-	-	-
	PSA 5	PSA 5	-	-	-
Glazing	Structure				
	Flat Glass	EPD - Flat Glass	EPD - Flat Glass	EPD - Flat Glass Price	EPD Registration Number: M-EPD-VMG-G8-001007
	Tinted Glass	EPD - Tinted Glass	EPD - Tinted Glass	EPD - Tinted Glass Price	EPD Registration Number: EPD-IES-0000884-003 (S-P-00884)
	Laminated Glass	EPD - Laminated Glass	EPD - Laminated Glass	EPD - Laminated Glass Price	EPD Registration Number: EPD-IES-0010600-002 (S-P-10600)
	Double Glazing	EPD - Double Glazing	EPD - Double Glazing	EPD - Double Glazing Price	EPD Registration Number: EPD-IES-0012612-002 (S-P-12612)
	Double Glass Recycled	EPD - Double Glass - Recycled	EPD - Double Glass - Recycled	Double Glass Choices	EPD Registration Number: EPD-IES-0004026-001 (S-P-04026)
	Triple Glazing	EPD - Triple Glazing	EPD - Triple Glazing	Triple Glass Price	EPD Registration Number: EPD-QKE-20170001-0861-EN
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
Architectural Steel	Structure				
	DX, HK and S Grades	EPD - DX, HK, S	EPD - DX, HK, S	MEPS Avg EU Price	EPD Registration Number: EPD-IES-0008628-001
	Xcabo HIG Recycled	EPD - Xcabo HIG Recycled	EPD - Xcabo HIG Recycled	EuroMetal Price	EPD Registration Number: EPD-IES-0011500-002 (S-P-11500)
	DC01, DC03, DC04, DC06	EPD - DC	EPD - DC	MEPS Avg EU Price	EPD Registration Number: S-P-11863
	Xcabo CR Recycled	EPD - Xcabo CR Recycled	EPD - Xcabo CR Recycled	EuroMetal Price	EPD Registration Number: S-P-11266
	PSA 1	PSA 1	-	-	-
	PSA 2	PSA 2	-	-	-
	PSA 3	PSA 3	-	-	-
	PSA 4	PSA 4	-	-	-
	PSA 5	PSA 5	-	-	-

Figure 5.7: Overview of the sources in Layer 4 of the general model (screenshot). Own illustration.

To enhance transparency, the design template within the framework include dedicated fields for documenting the assumptions, source types, and context behind both data components. This ensures that all inputs can be traced and evaluated, thereby supporting well-informed and accountable design decisions.

5.3.2. Layer 2: Comparison Model (Detailed parameterization)

This subsection provides a comprehensive elaboration of Layer 2 within the CCF (Figure 5.5). It presents detailed information regarding the variables and their corresponding attributes. For each variable, the associated attributes are discussed at the highest level of specificity, including precise definitions, descriptive explanations, applicable formulas, and illustrative examples. This structured approach ensures a clear understanding of the framework's components and their interrelations.

Unit & Quantity

The first column in the table specifies, for each product, the unit of measurement used in the EPDs. It is important to adhere to these units, as the all carbon, cost, and circularity calculations will also be done using these units.

The second column presents the quantity, indicating the amount of each material used in the project. This information is crucial for further specifying the UEC and cost calculations (Table 5.1).

Table 5.1: Parameters used to quantify the material volume or mass required per circular strategy in the CCF. Own illustration.

Parameter	Definition	Description	Example
Unit	Functional unit used for material quantification	Enables consistent comparison across materials	tonne, m ² or m ³
Quantity	Volume or mass of material required in a strategy	Used to calculate total carbon and cost impacts	3 tonne

Carbon

Each material possesses a specific carbon factor, which indicates the amount of CO₂ emissions per unit of the product. In this study, the carbon factor is derived from EPDs; however, it can also be obtained from other environmental databases, such as the NMD. To determine the total CO₂ emissions, the carbon factor is multiplied by the material quantity (Table 5.2).

The total Upfront Embodied Carbon is calculated using the following equation:

$$UEC = \text{Material Quantity} \cdot \text{Carbon Factor} \quad (5.1)$$

Where:

1. UEC = Upfront Embodied Carbon (kg CO₂-eq)
2. Material Quantity (unit)
3. Carbon Factor (kg CO₂-eq/unit)

Table 5.2: Carbon-related parameters used to assess UEC at the material level. Own illustration.

Parameter	Definition	Description	Example
CO ₂ Factor	Embodied carbon per unit of material (kg CO ₂ -eq/unit)	Indicates material's environmental impact intensity	120 kg CO ₂ /m ³
Total CO ₂	Quantity multiplied by CO ₂ factor	Total embodied carbon per strategy	1,500 kg CO ₂

Cost

As outlined in Chapter 3, this study focuses exclusively on the CapEx associated with materials. Consequently, the calculation of material costs is straightforward (Table 5.3):

Material Cost = Material Quantity · Unit Cost

(5.2)

Where:

1. Material Cost = Total material cost (€)
2. Material Quantity = Amount of material (unit)
3. Unit Cost = Cost per unit of material (€/unit)

Table 5.3: Cost-related parameters used to assess material performance in the Coolsingel project. Own illustration.

Parameter	Definition	Description	Example
Unit Cost	Cost per functional unit of material (€/unit)	Enables comparison of financial feasibility across strategies	€150/m ³
Total Cost	Quantity multiplied by unit cost	Total expenditure for the material in a given scenario	€1,875

To assess the financial feasibility of circular construction strategies, this study limits its scope to the capital expenditure (CapEx) associated with material procurement, as outlined in chapter 3. By isolating material-related costs, the evaluation remains focused and methodologically consistent. The calculation of material costs is therefore straightforward and based on a direct multiplication of the material quantity by its respective unit cost, as shown in equation 5.2.

Circularity

Last but not least, the circularity score is captured in the model through the Circularity Index Meter (CIM), which aggregates a set of quantifiable indicators, as introduced in the previous chapter (Table 4.1). Due to the structure of EPDs, the interpretation and processing of these indicators requires further elaboration, as shown in Table 5.4.

Table 5.4: Circularity indicators used in the Circular Index Meter (CIM) to assess the circular potential of individual materials. Own illustration.

Abbr.	Circular Indicator	Definition	Example
CIM	Circularity Index Meter	Aggregated score combining the sub-indicators (RBM, BBR, RBC, DFD) to represent the overall circularity performance of the material	30%
RBM	Recycled Building Material	The percentage of recycled content present at time of procurement, reported in Module A1–A3	0%
BBR	Bio-based Resources	The percentage of bio-based content present at time of procurement, as reported in Module A1–A3	60%
RBC	Reused/Recycled Building Components	The percentage of the material that can be reused or recycled, based on the potential indicated in Module C and D.	20%
DFD	Design for Disassembly	Qualitative individual assessment of the extent to which components can be separated for reuse/recycling at end-of-life (Module D)	40%

RBM is the first sub-indicators, which reflects the percentage of recycled content present in a material at the time of procurement. This value is not always directly presented in the EPD but can be derived from the product stage (Modules A1–A3) using a simple ratio.

The percentage of recycled content is calculated based on the Material for Recycling (MfR), relative to the declared unit of the product. The formula is as follows:

$$\text{RBM (\%)} = \frac{\text{MfR (unit)}}{\text{Declared Unit}} \cdot 100\% \quad (5.3)$$

Where:

1. RBM = Recycled Building Material (%)
2. MfR = Material for Recycling, as reported in the EPD (e.g. 1 kg, 1 m², tonne)
3. Declared Unit = Functional or declared unit in the EPD (e.g. 1 kg, 1 m²,tonne)

To illustrate this method, consider the EPD for *Hydro CIRCAL® 75R aluminium*, which is part of the CCF base model. According to the EPD, the declared unit is 1 kg of aluminium. The reported MfR is 0.799 kg.

Applying the formula:

$$\text{RBM (\%)} = \frac{0.799}{1} \cdot 100\% = 79.9\% \quad (5.4)$$

This implies that approximately 80% of the aluminum content in the product is composed of recycled material at the time of procurement. As such, it is considered a high-performing material with respect to circularity under the RBM indicator. This percentage is subsequently included in the CIM scoring under the RBM category, specifically in the section for *Hydro CIRCAL® 75R aluminium*.

BBR is The second sub-indicator. This metric is relatively straightforward, as it directly reflects the proportion of bio-based content within the building, expressed as a percentage.

RBC is the third sub-indicator. This value is typically derived from EPDs, which summarize the reuse and recycling potential of the reference materials at the end-of-life stage. In most cases, this percentage can be retrieved directly from the EPDs without the need for additional calculations.

DFD is the final sub-indicator. It is the proportion of the building designed for disassembly (DfD). Both academic literature and existing assessment methods consistently recognize the relevance of DfD potential. However, because DfD is highly project-specific, it is the responsibility of the DT to provide an appropriate value for this indicator.

After the DTs have filled in all relevant input fields, the data entry process is complete. The inputs may be based on data from EPDs, material databases, or supplier-specific sources. Once all data is entered, the final CIM-score is calculated. This score is determined using the unweighted average formula shown below:

$$CIM(\%) = \frac{RBC + RBM + BBR + DFD}{4} \quad (5.5)$$

Strategies

Following this step, the model is ready to be applied for the evaluation of different circular strategies. Users may select predefined strategies from table 4.2, or define custom strategies based on project-specific considerations. It is essential, however, that any newly defined strategy is accurately reflected in the circularity indicators. If not, its impact will not be captured within the CCF.

The comparison of strategies entails assessing various material options in relation to the three core variables of the CCF. By adjusting material selections, the DTs can observe how different strategies influence performance across these indicators.

This iterative use of the model enables data-driven decision-making. It highlights which materials demonstrate strong performance across all three variables and which do not. Ultimately, it is the responsibility of the DT to determine the most appropriate material composition, aligning selections with the specific goals and constraints of the project.

5.3.3. Layer 3: Decision Dashboard (Detailed parameterization)

Project stakeholders such as owners or developers play a key role in decision-making but are typically not involved in technical design. For these actors, the comparison model can be unnecessarily complex. As highlighted in the interviews, they benefit from an intuitive and interoperable interface that enables clear interpretation of data and supports strategic decision-making (Figure 5.6).

To address this need, a more clear dashboard model has been developed. This dashboard compares the base case with the promising circular construction strategies, thereby enhancing transparency and supporting informed decision-making. The model includes three decision dashboards:

1. Decision Dashboard 1: Totals

This dashboard displays the variables in absolute terms, including the unit UEC, total material cost, and CIM-score, as defined in the comparative model. These values provide a broad, project-level overview of outcomes. All the variables are evaluated against their respective budget.

2. Decision Dashboard 2 - Regular (Per m²):

To enhance the comprehensibility of Decision Dashboard 1, Decision Dashboard 2 normalizes its indicators by dividing them by the project's GFA. This enables direct comparison with the Paris-Proof budget and improves the interpretability of the cost variable.

3. Decision Dashboard 2 - Color Coded (Per m²):

This dashboard presents exactly the same structure as the regular version but uses color coding to enhance interpretability. If a design metric falls outside the defined budget threshold, the corresponding cell is highlighted in red. If the value is within budget, it is marked green. This visual distinction improves clarity and supports faster decision-making during design evaluation.

4. Decision Dashboard 3: Carbon Efficiency Ratio

Based on input from Interviewee 7, the owner of a leading sustainability assessment tool, this dashboard includes the *Carbon Efficiency Ratio*, calculated by dividing total UEC by total financial investment in euros. This metric offers a financially steerable indicator to support balanced and strategic design choices.

To illustrate the functionality and added value of the carbon efficiency ratio, consider the following example. Suppose a DT is evaluating two alternative circular construction strategies, Strategy 1 and Strategy 2, each constrained by a fixed project budget of €10 million:

- **Strategy 1** results in total EC emissions of 1,000,000,000 grams CO₂. The efficiency ratio is calculated as follows:

$$\frac{1,000,000,000 \text{ gCO}_2}{€10,000,000} = 100 \text{ gCO}_2/€ \text{ invested}$$

- **Strategy 2** results in total EC emissions of 800,000,000 grams CO₂. The efficiency ratio is:

$$\frac{800,000,000 \text{ gCO}_2}{€10,000,000} = 80 \text{ gCO}_2/€ \text{ invested}$$

Although both strategies require the same financial investment, strategy 2 demonstrates greater carbon efficiency by yielding fewer grams of CO₂ per euro spent. This suggests that, from an environmental standpoint, the budget in strategy 2 is utilized more effectively.

By comparing the carbon efficiency ratios of different strategies, DTs can better align environmental performance with financial constraints. As such, this parameter serves as a guiding metric for identifying interventions that maximize carbon reduction per euro invested, thereby supporting more sustainable and cost-effective design decisions.

5.4. Data Sources, Assumptions and Boundaries

5.4.1. Data Sources

As with any model, the reliability of the output depends directly on the quality of the input data. As the well known programming saying goes, '*rubbish in = rubbish out*'. In the case of the CCF, designed for use during the design phase, the accuracy of inputs provided by DTs is essential. The framework aims to balance UEC, cost, and circularity in early stage decision making. Each of these domains relies on distinct yet interconnected data sources.

For carbon-related assessments, EPDs are the preferred source of data. These documents offer verified life cycle information across all product stages and allow for accurate calculation of UEC. In the Dutch context, however, EPDs can only be used in MPG assessments if they are formally included in the NMD. Although EPDs are widely available, their translation into the NMD is sometimes restricted by additional Dutch-specific requirements related to methodology and verification. As a result, many EPDs cannot be used for official assessments (NMD, 2025).

When no valid EPD is available in the NMD, the system falls back on less precise data. Category 2 consists of sector-wide material averages provided by industry branches. Category 3 includes unverified, generic data of the NMD with a standard uplift factor of 30% to account for uncertainty (NMD, 2025). These fallback options reduce the accuracy of carbon assessments and limit product-specific insights. This discourages transparency among material producers. EPDs are often only submitted to the NMD when a product scores well. If performance is poor, producers may prefer to rely on generic Category 2 or 3 data, which can mask true impact and avoid competitive disadvantage. As a result under performing products remain hidden behind industry averages. This may slow market-driven improvements and undermines fair comparison.

Cost assessments depend heavily on the maturity of the design and the structure of procurement. The most accurate data comes from primary sources such as quotations from suppliers. However, in early stages this level of specificity is rarely available. In these cases, cost estimates prepared by internal or external advisors are necessary. These estimates incorporate volume effect and market dynamics, which are not reflected in standard price lists. Although online price references are easy to access, they are generally unreliable due to regional variation, supply fluctuations, and sensitivity to order size.

EPDs were also chosen as the main input for circularity assessments because they provide detailed data on key indicators: recycled content, reuse potential, bio-based material and design for disassembly. This information is essential for the CCF as it determines the circularity score. Although EPDs are the foundation of the NMD, their translation into standardized NMD profiles, especially category 2 and 3, leads to important limitations. These profiles often include end-of-life credits for reuse or recycling, but without verification that these outcomes will actually occur in practice. As a result, circularity values are applied in a generalized way, which can be misleading and inconsistent across projects. By using EPDs directly, the CCF avoids these assumptions and ensures that circular performance is assessed transparently and based on project-relevant information.

Across all three domains, the accurate estimation of material quantities is a foundational requirement. Reliable quantity take offs, especially for high impact materials such as steel and concrete, are critical to improving the accuracy of UEC, cost, and circularity assessments. These estimates, preferably developed with input from cost or engineering advisors, ensure consistency across metrics.

5.4.2. Assumptions

In order to operationalize the CCF within the constraints of available data and the project timeframe, a set of foundational assumptions has been established. These assumptions are essential to ensure internal consistency, interpretability, and reproducibility of the model outcomes. As highlighted by M. Nkwake (2013), the use of explicit and logically sound assumptions is critical for preserving the coherence between data, interpretation, and conclusions.

The model assumes that the environmental performance of materials, in terms of UEC, can be adequately represented by EPDs sourced from either Dutch or European databases. Although Dutch

EPDs would offer the most context-specific accuracy, they are not consistently available for all material types. Therefore, European EPDs are incorporated under the assumption that they provide a suitable approximation of performance under Dutch construction conditions.

The cost values used in the model are assumed to reflect realistic cost levels based on one of three sources: Dutch market data, expert interview inputs, or European market averages. Although an ideal scenario would link EPD data directly to corresponding material costs, this integration is not yet available. Therefore, the model operates under the assumption that the selected cost inputs are sufficiently representative to enable meaningful comparison between materials. Because the CCF is intended as a design-phase decision-support tool rather than a legally standardized calculation system, it is assumed that the relative cost relationships between materials are more important than precise absolute values. The focus, therefore, is on enabling proportional comparison across material options.

Circularity within the model is assessed based on four measurable indicators: reuse, recycling, biobased content, and design for disassembly. These criteria were selected for their relevance to design-phase decision-making and their presence in existing EPD and material documentation. Although they do not represent the full spectrum of circular economy indicators, the assumption is that they provide a sufficiently robust proxy for circular potential at the material level.

Additionally, the model aggregates recycled content into a single category without differentiating between pre-consumer and post-consumer recycled inputs. This simplification reflects the format of most available EPDs and enables uniform processing of data. The model also treats the reported reuse and recycling values in Modules C and D of EPDs as equivalent. However, as illustrated by the R-ladder, reuse generally holds greater circular value due to the direct reintegration of materials into equivalent functions without extensive reprocessing (Figure 1.4). The model assumes that this simplification is acceptable for early-stage decision-making, while recognizing that more detailed assessments may be necessary in later project phases.

These assumptions collectively ensure that the CCF remains operable, transparent, and consistent within the current data environment. While simplifications are inherent to early-stage modeling, each assumption has been carefully constructed to preserve the framework's analytical coherence and practical relevance.

5.4.3. Limitations

British statistician George Box famously stated that “*All models are wrong, but some are useful*” (Box, 1976). A model, by definition, cannot represent the full complexity of reality, if it did, it would no longer be a model but reality itself. Instead, models serve to capture the most relevant aspects of a system to support understanding or decision-making. The CCF is no exception. It is a deliberate abstraction, shaped by practical constraints and methodological choices. This subsection outlines the key boundaries and limitations that define the scope and applicability of the CCF.

A primary limitation of the CCF lies in the availability and consistency of data across its three core indicators. While data on UEC and cost are relatively mature within the construction industry, reliable metrics for circularity are still emerging. The circular economy has only recently become a central topic in design practice, resulting in limited standardized datasets. In theory, EPDs offer a promising starting point for integrating environmental data into design decisions. However, in practice, several obstacles hinder their effective use. Some suppliers are reluctant to disclose EPDs due to competitive concerns, particularly when performance metrics are unfavorable. Others avoid producing EPDs altogether if they anticipate poor sustainability outcomes (*J. Plas, personal communication, 2025*). These limitations reduce transparency and hinder comprehensive data integration across all indicators. The following subsection further explores potential strategies for addressing this issue.

A second key limitation involves the inherent challenge of quantifying circularity. By adopting a numerical framework, the CCF translates all inputs and outputs into measurable values. However, not all circular strategies lend themselves to quantification. Concepts found in frameworks such as CSF and HNN (Çetin et al., 2021; Eberhardt et al., 2022; HNN, 2025) often encompass qualitative or systemic principles that cannot be adequately captured through metrics alone. As a result, the CIM-score

embedded in the CCF offers only a partial representation of a design's true circular potential.

Additionally, the volatility of material prices poses a significant challenge for the model's cost component. As of 2025, global geopolitical instability continues to disrupt market mechanisms, leading to highly variable pricing, particularly for materials such as steel and aluminum (NOS, 2025). Given that design phases typically span between 6 and 18 months, such fluctuations introduce uncertainty that compromises the accuracy of model-based cost projections. Ideally, a more advanced iteration of the framework would incorporate real-time data integration to improve the reliability of financial estimations. Moreover, the exclusion of residual value represents an additional limitation, as both the academic literature and its translation into practice are still in early stages of development and lack robust methodologies for reliable application. Ideally, a more advanced iteration of the framework would incorporate data integration to improve the reliability of financial estimations.

In conclusion, several structural limitations constrain the full effectiveness of the CCF. Certain datasets are available but not openly shared; others remain underdeveloped or fragmented. Connections between carbon, cost and circularity are not yet fully established within current data infrastructures. Nonetheless, the CCF represents a critical first step toward integrated sustainability assessment in early design phases. Achieving the broader industry targets of 50% circularity by 2030 and Paris Proof construction will, however, require systemic data transparency, standardization, and collaboration across the sector.

5.5. Expert Panel Feedback

To validate the initial version of the model, a structured expert feedback panel was conducted. This panel consisted of four key stakeholders typically involved in early-stage design processes: an architect, environmental advisor, cost advisor, and project developer. The primary aim of the panel was to assess whether the model was clear, practically applicable, and aligned with the informational needs and decision-making logic of these expert roles.

Each expert received a dedicated feedback reader, which provided a concise explanation of the model's purpose, logic, and functionality (Appendix D). The reader also included a set of targeted feedback questions, structured around four themes:

1. **Clarity and Structure:** Is the framework understandable and logically structured?
2. **Practical Applicability:** Can the model be used effectively in real-life project settings?
3. **Value for Decision-Making:** Does the model add value in supporting early-phase trade-offs?
4. **General Feedback:** Suggestions for improvements, missing elements, or further refinements.

The detailed expert responses are included in appendix E. This subsection summarizes the key findings and insights derived from the expert panel, which served both as a validation step and as input for further model refinement.

The expert panel confirmed that the CCF fills a critical gap in early design processes, though feedback reflected each expert's priorities. The architect praised the framework's clarity and logic but found the Excel interface overwhelming for first-time users. He valued the Decision Dashboard as a quick, rule-of-thumb tool and suggested a simplified 'Framework Light' for high-level material comparisons (e.g., concrete vs. timber).

The cost advisor confirmed that the framework's goal, trying to minimize UEC within a set ambition, is clear and aligns with current cost advisory practices. Establishing this ambition level, according to the expert, should originate from the client, thereby offering clear direction to the DT. Although the framework is not yet suitable as a direct calculation tool for quantity surveying, it can serve as a valuable complement to cost estimates by enabling the connection between carbon, cost and circularity performance. Opportunities were identified for the CCF to function as a communication tool within DTs, particularly in the comparison of different circular strategies. A cautionary note was raised concerning the risk of overestimating environmental precision during early design phases. To address this, the expert recommended the inclusion of margins or contingency values, such as CO₂ buffers, to accommodate uncertainty. Furthermore, integrating fundamental project parameters, including building height, form factors, and gross floor area (GFA), was advised to enhance interpretability and enable meaningful cross-project benchmarking.

The environmental advisor emphasized technical rigor, urging alignment with the NMD and Paris Proof benchmarks. He called for clearer definitions of circularity indicators such as RBC and DFD, default material quantities per square meter to simplify inputs, and visualizations (e.g., graphs) to enhance result interpretation.

The project developer focused on financial feasibility, viewing cost outputs as the most useful. He proposed expanding cost analysis to include construction, labor, and time factors and envisioned linking the CCF to conceptual BIM models or AI-driven design implementations for dynamic testing of carbon-cost trade-offs.

Each expert viewed the CCF through a different lens: usability for the architect, methodological rigor for the environmental advisor, and financial outcomes for the project developer. The cost advisor added a complementary operational perspective, emphasizing the communicative role of the framework and the need to factor in uncertainty and context-specific parameters. Their perspectives were complementary rather than conflicting. The architect's call for simplicity balanced the environmental advisor's focus on precision, while the developer's emphasis on real-world costs. The cost advisor bridged both commu-

nication and practicality, suggesting the tool's outputs could support early dialogue even without being embedded in current cost workflows.

This interplay highlighted the multi-disciplinary nature of early design decision-making, where technical, financial, and practical considerations must converge. Their combined feedback underscored the need for the CCF to operate as both a transparent, data-driven tool and an accessible, discussion-oriented platform. Where possible, this feedback was incorporated to enhance the latest version of the framework. The dynamic between these perspectives not only pushed the framework toward a more holistic and strategic decision-support role but also served as a robust theoretical validation method across DT disciplines, helping to clarify both the opportunities and challenges in applying the CCF.

5.6. Implementation: Use of the Circular-Carbon Framework

This section describes how the CCF can be effectively applied in the design phases of construction projects. It outlines practical responsibilities, workflow integration, and governance mechanisms necessary for implementation. Moreover, it identifies common challenges and provides recommendations for ensuring usability across different project contexts.

1. Purpose and Scope of Implementation

The CCF is designed for use in the design phases of building projects. It supports DTs in making informed design decisions based on carbon, cost, and circularity metrics. The aim is for DTs to balance these variables in a way that ensures their project remains feasible.

To achieve this, DTs set carbon and cost budgets for the structure and skin of their building, alongside circularity goals. Using various circular strategies, the model challenges DTs to make data informed decisions regarding which strategies to apply, and to understand their impact on carbon, cost, and circularity performance.

In its first version, the model is constructed for commercial new construction projects but may later be extended to renovation, residential, retail, hotel, or even infrastructure developments. While the current version focuses on materials present in the baseline model, in theory, it can be easily extended to incorporate additional materials and project types.

It is important to emphasize that this tool is intended to support DTs in creating circular and feasible (in terms of carbon and cost) projects. It is not designed to replace professionals or existing software tools. Rather, it fills a current gap by offering functionality that does not yet exist. In an ideal future scenario, organizations would use this platform in all of their projects and adopt it as a mandatory design-phase tool.

2. Roles and Responsibilities

If the CCF is reduced to its essentials, it can be seen as a budget-tracking tool. However, it goes beyond conventional budget tracking by incorporating not only financial budgets but also carbon and circularity budgets. It monitors how well a project performs against the Paris Proof CO₂ threshold and evaluates the implementation of circular strategies to aim for low-carbon and financially feasible outcomes. Material choices form the core of tracking across all three variables.

Based on the DT feedback analyzed in chapter 4, it is assumed that the cost advisor should be responsible for managing the CCF. This is because the cost advisor is most experienced in handling budgets and assumptions. Managing the CCF would be an additional responsibility aligned with their existing role, including tasks such as tracking material costs.

Although the cost advisor manages the CCF, the rest of the DT plays an equally important role in providing accurate data. The architect and structural engineer are responsible for specifying materials, the environmental advisor must deliver reliable environmental data, and the developer must ensure overall consistency and completeness of inputs.

3. Workflow Integration

The CCF should be applied from the sketch design (SO) phase, once an initial set of drawings has been prepared. This information can be uploaded to the CCF to establish a baseline scenario, from which various circular strategies can be explored. Ideally, the final strategy is selected early in the design process, within the defined budgets, as this typically accelerates project development.

In its first iteration, the model will be developed in Excel, which limits its open-source capabilities. During this phase, a shared project drive should be used to ensure that all team members have access to the model. Ultimately, a standalone application of the CCF is desirable. This would allow for integration of real-time data on materials, costs, and carbon profiles, with plug-ins rec-

ommended to enhance usability. Until that point, inputs from the DT should be revisited iteratively during model use to ensure realism and practicality.

4. Governance and Maintenance

The CCF requires regular updates to maintain its accuracy and relevance. This includes updates to data sources, such as material costs, and alignment with any revised policy targets, including Paris Proof budgets. Keeping the CCF current is critical, as the principle 'rubbish in = rubbish out' applies strongly here.

During DT meetings, the CCF should always be part of the agenda. The time spent on it can vary depending on the extent of changes. Regardless of the duration, all updates should be shared with the team and properly documented.

5. Implementation Challenges and Recommendations

High-quality, project-specific data may not always be available during the early design phases. As a mitigation strategy, default values based on previous projects, national averages, or proxy data should be used, with transparency regarding the underlying assumptions.

Not all DT members may be familiar with the CCF or with carbon, cost, and circularity assessments. In that case, teams could either contract experienced professionals or provide training to team members before implementation.

Early-phase projects are often constrained by time. To address this, repetitive tasks should be automated and standardized input templates should be used. For example, some architects work with standard material palettes that can be pre-loaded into the model.

Before applying the CCF, it is important to be transparent and open about the goals of the project. Some projects may aim for high circularity, while others may prioritize financial feasibility due to tight cost constraints. The model must not be used to manipulate inputs for strategic advantage; instead, the CCF should be used to make trade-offs transparent and to document all assumptions and priorities clearly.

5.7. Conclusion

SRQ 3: How can a multi-layered framework be developed to systematically structure and quantify the relationships between circular strategies, upfront embodied carbon, and financial feasibility?

This chapter focused on the development of the CCF, transitioning from the contextual groundwork laid in earlier chapters to a fully structured and operational model. Drawing from both literature and expert input, the chapter translated the theoretical and practical foundations into a decision-support tool that aims for early-stage evaluation of circular strategies in regards to carbon and cost.

It began with the creation of a Program of Requirements, which was derived from the objectives of the CCF and the needs identified during interviews with DT members. Once these requirements were established, the actual construction of the model was undertaken.

The CCF is structured into four layers: Input Parameters, Comparison Model, Decision Dashboards, and Sources. The Input Parameters layer maps all project information and sets the carbon, cost, and circularity budgets that act as reference values. The Comparison Model forms the technical core of the framework, where different circular strategies are evaluated by computing alternative material compositions. The third layer, the Decision Dashboards, interprets the outputs from the Comparison Model. It consists of three dashboards: total performance for carbon, cost, and circularity; normalized outcomes per square meter; and a tailored Carbon Efficiency Ratio, which measures carbon emissions per euro invested. The final layer, Sources, contains the datasets that underpin the model, including EPDs for carbon and circularity data, as well as material cost references.

This chapter further elaborated on the logic and parameterization of both the Comparison Model and the Decision Dashboards, ensuring that all input data and underlying assumptions are transparent and well-motivated. It also examined the reliability of the input data and discussed key assumptions and boundaries. For carbon, the main challenge was the use and interpretation of EPDs in relation to the NMD database. For cost, the volatility of market prices and the dependence on purchase volumes posed limitations. For circularity, the unstructured nature of EPD data made it difficult to consistently map materials to the four circular indicators of the CCF. These data challenges defined the model's limitations and system boundaries.

The expert panel feedback confirmed that the CCF is a promising tool for practical application, but it also highlighted areas requiring further refinement. The architect, cost advisor, project developer, and environmental consultant each provided unique insights: the need for more intuitive high-level material comparisons, improved technical rigor in aligning NMD and EPD data, and simplified cost structures.

Finally, the implementation section outlined how the CCF could be integrated into design processes. It was proposed that the cost advisor should take responsibility for managing the CCF, given their expertise with budgets. However, full collaboration between all DT members is essential for the model to reach its full potential.

6

Case Study

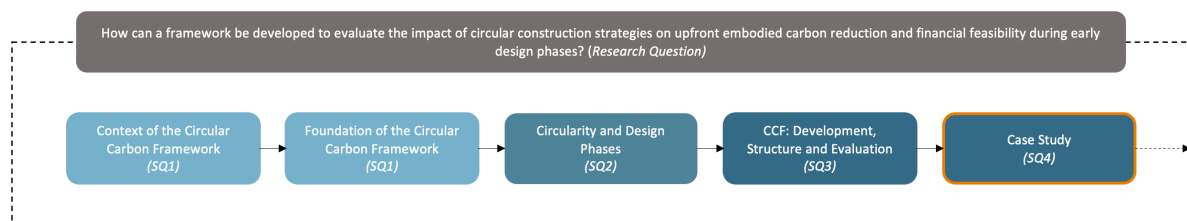


Figure 6.1: Chapter 6 roadmap. Own illustration.

6.1. Introduction

After the understanding of the design variables, their attributes, and the configuration of the CCF as a whole, the final stage of the Value-Driven Design framework takes place: Evaluation (Figure 2.2). The evaluation is necessary to determine whether the initial intentions behind the system align with the objectives that the design teams (DTs) seek to achieve.

A case study is conducted using an office building under construction from EDGE. Known for its strong environmental ambitions, EDGE provides a suitable context to assess how well the CCF aligns with real project conditions. The ex post approach allows for critical reflection on how the framework would have performed if applied during the design phase, using data and outcomes from the completed project.

The evaluation is structured along the three layers of the CCF. First, the project's key characteristics are introduced (Layer 1), establishing its scope and sustainability ambitions. Second, the available project data is compared to the CCF input requirements (Layer 2), leading to a gap analysis that categorizes missing or incomplete data. Finally, the CCF is demonstrated using the available data (Layer 3), and the resulting outputs are analyzed in terms of interpretability and decision-support potential.

The chapter concludes by reflecting on the CCF's limitations, practical usability, and alignment with industry practice, offering recommendations for future development and implementation.

6.2. Case-study Description

Approach

To assess the practical value of the CCF, this chapter applies it to a real-world development project by EDGE. A case study approach is chosen for its ability to provide in-depth and context-specific insights, which are particularly valuable in exploratory research (McCombes, 2019). By engaging directly with a real project, the study allows for a grounded evaluation of how well the CCF performs when confronted with actual data constraints, decision-making dynamics, and trade-offs between the carbon, cost, and circularity. This approach not only tests the framework's technical logic but also reflects how DTs experience and interact with it in practice, thereby supporting its intended use as a decision-support tool (Marrelli, 2007; Patton, 2002). Although the specificity of a single case limits the generalizability of findings and introduces the risk of researcher bias, the method remains effective for revealing whether the CCF offers actionable value in realistic conditions (Pelto & Pelto, 1978). Through this application, the case study strengthens the evaluation by linking theoretical model design with project-based implementation.

Selection Procedure

The quality and relevance of a case study are directly influenced by the appropriateness of the selected case. As with any analytical framework, the validity of the output is directly dependent on the quality of the input data. Therefore, to ensure that the CCF is tested against a meaningful and data-rich project context, a set of clear and methodologically sound selection criteria was defined. These criteria are designed to secure the analytical depth, practical relevance, and technical feasibility required for a robust demonstration of the CCF.

The following conditions were applied during the case selection process:

1. **Portfolio Relevance**

The project must be part of EDGE's real estate development portfolio. This ensures alignment with the research context and facilitates access to internal project knowledge and reliable documentation.

2. **Project Maturity**

The project must be situated in either the development, realization, or operational phase. These phases allow for ex post reflection on design intent and performance, making it possible to assess the alignment between initial ambitions and actual outcomes.

3. **Sustainability Commitments**

The project must include explicit goals concerning UEC and circularity. At minimum, this includes a commitment to Paris Proof performance standards and the application of circular strategies that aim to contribute to UEC reduction.

4. **Circular Potential in Primary Layers**

The project must offer opportunities to reduce UEC through circular interventions within the structural and envelope layers of the building, as defined by Brand (1994). These layers typically represent the largest carbon impact and are therefore essential for a meaningful CCF application.

5. **Data Availability and Quality**

Verifiable data on UEC, cost, and circularity must be available and accessible. All data must be traceable to established calculation methods and produced or validated by certified experts.

6. **Stakeholder Willingness**

Key stakeholders involved in the project, such as architects, sustainability consultants, or developers, must be willing to participate in interviews or provide clarification regarding data sources, assumptions, and decision-making processes.

By applying these selection criteria, the case ensures a high-quality basis for testing the CCF against real-world project conditions. It supports both technical validation and strategic reflection, thereby strengthening the internal validity of the study while preserving relevance for future application.

Description

The selected case for this study is an office development by EDGE, located in the city center of Rotterdam (Figure 6.2 and 6.3). EDGE Coolsingel comprises approximately 24,110 square metres (GFA) and is currently in the construction phase. The projected delivery date is set for September 2026. This project exemplifies EDGE's core development approach: a complex, sustainability-focused, office-led building within an urban setting. While it represents a smaller project within EDGE's active portfolio, the clearly defined building specifications and efficient floor-plans make it highly suitable for evaluating the applicability of the CCF. (DGBC, 2024; Edge, 2024)

The building consists of 16,000 square metres of office space, 5,000 square meters of co-working areas, and 1,000 square metres allocated to retail. Together, these functions amount to 21,500 square meters of lettable floor area (LFA), distributed across eleven floors. The architectural design emphasizes openness and transparency, integrating indoor and outdoor spaces to create an inviting and dynamic work environment. (DGBC, 2024; Edge, 2024)

The project sets clear environmental ambitions, with the Paris Proof target serving as a central benchmark for EC and OC reduction. Because the building permit was granted before 2023, the applicable threshold for UEC has been set at 250 kg CO₂-eq. per m² GFA. To reach this target, the DT has incorporated a combination of circular and low-carbon strategies. A key focus lies in the use and retention of bio-based materials, aimed at significantly lowering the carbon footprint of the structure. The building employs a hybrid construction system that combines wooden columns and CLT floors with a concrete core. Timber is also used extensively in the interior design, contributing not only to the project's carbon performance but also to the creation of a comfortable and natural indoor environment that supports user well being and productivity. For the façade, the composite panels from the first seven floors of the original building were carefully disassembled and reused in the new design. (DGBC, 2024; Edge, 2024)

In addition to meeting the Paris Proof target, the project aims to obtain a BREEAM-NL New Construction (2020) design certificate with an Excellent rating, as well as a WELL Platinum certification focused on health and user comfort. (DGBC, 2024; Edge, 2024)

The governance of the project's sustainability objectives is managed by EDGE's internal innovation and ESG-team, in collaboration with two environmental advisors, one representing EDGE and the other representing the contractor, De Vries en Verburg. This structured configuration of internal and external expertise is intended to ensure objectivity and traceability in the assessment of EC and circularity targets. (DGBC, 2024; Edge, 2024)

The case was selected based on its strong alignment with the predefined selection criteria. In particular, the presence of measurable sustainability objectives, a collaborative governance structure, and access to detailed design documentation made it a suitable candidate for demonstrating the use of the CCF in analyzing material strategies and their resulting trade-offs in carbon, cost, and circular performance.



Figure 6.2: Architectural render of the Coolsingel 75 project (Exterior). Adapted from EDGE.



Figure 6.3: Architectural render of the Coolsingel 75 project (Interior). Adapted from EDGE.

6.3. Data Assessment & Gap Analysis

1. Purpose and Approach

This subsection investigates the applicability of the CCF within a practical project environment by analyzing the availability and suitability of design data from the Coolsingel project. The primary objective is to assess whether the CCF can be meaningfully implemented using real-world project information. A secondary aim is to evaluate the extent to which the structure and skin data of the project meet the framework’s input requirements. This analysis provides insights into the compatibility between theoretical models and the data conditions typically encountered in professional design contexts.

1. Data Mapping

The input variables required by the CCF, carbon, cost, and circularity, are compared with the available documentation from the Coolsingel project. The outcome is summarized in a data mapping table, which provides a clear overview of the alignment between theoretical requirements and available project data.

2. Gap Analysis

A gap analysis is performed to identify and categorize missing or insufficient data. These data gaps are evaluated based on their maturity level, which is classified as market ready, near ready, or latent. Each gap is further analyzed to determine its underlying cause, which may be technical, contractual, or procedural.

Where significant data gaps are observed, potential mitigation strategies are proposed. These may include the use of expert assumptions provided by the DT or the use of alternative data sources. This step serves to determine whether a full or partial implementation of the CCF is feasible within the context of the Coolsingel project.

Ultimately, this analysis supports a critical reflection on the data readiness of real-world projects and the conditions under which integrated circular carbon assessments can be meaningfully applied.

2. Mapping of Project Data vs CCF Input Requirements

This section will examine the extent to which the available project data aligns with the input requirements of the CCF. In chapter 5, the data requirements of the CCF are explained in detail. The following analysis evaluates each variable based on the data provided for the Coolsingel project.

Carbon

The Coolsingel project includes three forms of carbon-related data: the MilieuPrestatieGebouwen (MPG), the Paris Proof Indicator (PPI), and the Global Warming Potential (GWP). Each serves a different purpose and originates from different stakeholders. Their relevance to the CCF varies, as outlined below (Figure 6.4).

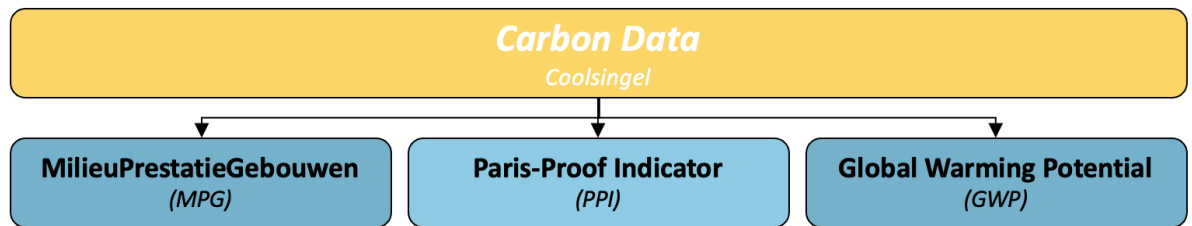


Figure 6.4: Available carbon-related data for the Coolsingel case study. Own illustration.

MilieuPrestatieGebouwen (MPG)

The MPG is the primary environmental performance metric in the Coolsingel case, as it is mandatory under Dutch building regulations. The MPG expresses the environmental ‘shadow price’ (schaduwprijs) in euros per square meter gross floor area per year (€/m² GFA/year). It reflects the total environmental impact costs (Milieu Kosten Indicator) of building materials over the entire building life cycle, not lim-

ited to carbon emissions. The MPG integrates multiple impact categories, including: GHG-emissions, Human toxicity, Fossil resource depletion, Acidification, Eutrophication and Water pollution.

In the Netherlands, the MPG is the legally required environmental assessment for buildings and is widely used in project practice. It relies on data from the NMD, which is built on standardized EPDs derived from LCAs. Because the NMD covers a broad range of environmental impact categories, the MPG is less focused on carbon-specific indicators such as those required for the CCF.

Paris Proof Indicator (PPI)

The PPI was developed by the project's environmental advisor and are based on EPDs. It quantifies embodied carbon emissions during the production and construction stages, expressed in kg CO₂-eq per functional unit. In the context of the CCF, this corresponds to the 'carbon factor' and is the most critical dataset.

The PPI in the Coolsingel case includes:

- Modules A1–A5: from raw material extraction to construction completion.

In contrast, the CCF focuses primarily on Modules A1–A3, as it operates in early design stages where downstream construction data (A4–A5) is not yet available. However, in this case, since the data was collected ex-post (after construction planning), A4–A5 are included and cannot be separated. For this reason, the entire A1–A5 value is used as a proxy in the case study. As this approximation is applied consistently across all materials, it is assumed that relative differences between materials remain valid, and thus, the comparison retains practical value for evaluating carbon intensity.

Global Warming Potential (GWP)

The GWP is reported as kg CO₂-eq / m² LFA per year. It includes only the material-related CO₂ emissions and is calculated over a fixed building lifespan of 50 years, in alignment with EU Taxonomy reporting.

Although informative, the GWP is not directly relevant for the CCF for the following reasons:

- It is aggregated at the building level, not per material
- It is designed for reporting EU compliance rather than decision support
- It overlaps functionally with the PPI, which already provides carbon data

As such, the GWP is acknowledged in the dataset but is not used as a functional input to the CCF.

Cost

The second variable analyzed in this case study is cost, which is an essential input to the CCF. In practice, cost data is derived from cost estimates (kostenramingen) that are produced during the design and procurement stages of a project.

During the design phases, the cost advisor prepares a cost estimate based on the evolving design developed by the DT. These estimates help the project developer and building owner to understand the expected material costs and to make informed financial decisions as the design progresses. As the design moves from concept to final design (DO), the cost estimates are updated to reflect increasing detail and accuracy.

After the final design is completed, the project enters the procurement phase. At this stage, one or more contractors submit their own cost estimates. These are based on their internal calculations, current market prices, and project-specific risk assessments. The project developer selects a preferred contractor and conducts final negotiations based on the submitted cost estimates. Once an agreement is reached, the parties formalize the arrangement through an engineering and build contract.

In practice, the CCF relies on the cost estimate prepared by the cost advisor, since this is the only cost information available during the design phases when the model is intended to be used. The contractor's

estimate becomes available only after the final design is completed, and is therefore not suitable for design-phase modeling (Figure 6.5).

In this case study, the available cost data is derived from the estimate provided by the contractor. However, because this estimate includes rounding of material costs and considers only the major material used in large quantities, the resulting dataset still approximates the level of detail and structure typically found in a cost estimate prepared by a cost advisor. As such, the data remains appropriate for the purpose of early design-phase modeling within the CCF framework.

However, since this case study is conducted ex post, the contractor’s cost estimate is used. This estimate reflects the final, project-specific material costs and thereby increases the reliability and accuracy of the case study results.

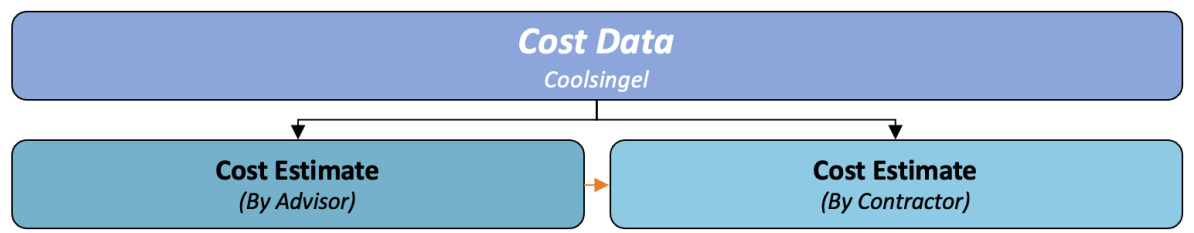


Figure 6.5: Available cost-related data for the Coolsingel case study. Own illustration.

Circularity

The final and arguably most critical variable to consider is circularity. As outlined throughout this research, while financial and carbon-related metrics have become well-established in the built environment, the same cannot yet be said for circularity-related data. Although project developers often possess an intuitive sense of which circular strategies may be applicable, the structured implementation and evaluation of these strategies remain largely underdeveloped (Bellini et al., 2024).

This deficiency is also evident in the Coolsingel case study. Circular concepts such as the use of bio-based materials, the application of reused and recycled components, and design for disassembly have been incorporated into the project. However, the systematic mapping of these strategies, along with their quantification and assessment in relation to UEC and material cost, remains absent. For ex post evaluations of circular performance, material passports, such as the BCI and Madaster, offer valuable insight. Nevertheless, such tools are mostly applied following project completion, at which point design decisions can no longer be altered and improved.

By contrast, an ex ante approach is more desirable, particularly in the early design stages when key decisions are still being made. Currently, no integrated platform exists that enables systematic mapping of circularity strategies alongside carbon and cost metrics during these critical phases. This gap is illustrated in figure 6.6, which outlines the fragmented nature of circular data in the Coolsingel project.

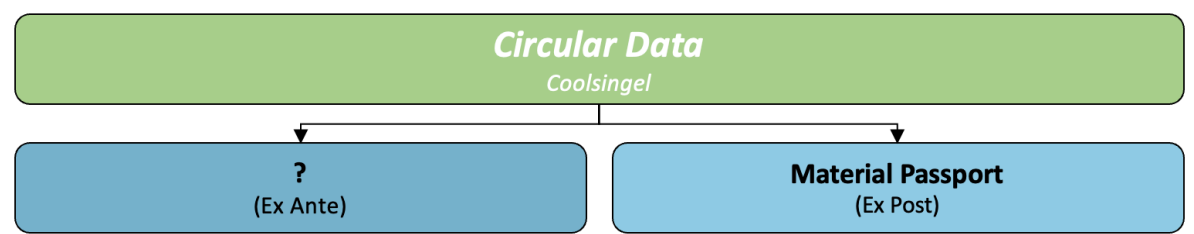


Figure 6.6: Overview of available circularity-related data for the Coolsingel case study. Own illustration.

To further elucidate this issue, figure 6.7 demonstrates the lack of integration between circularity data and the design process. This misalignment occurs precisely during the phases in which DT members

possess the greatest agency to influence material choices and long-term sustainability outcomes. The CCF seeks to address this shortcoming by supporting the structured identification, analysis, and application of circular strategies in parallel with carbon and cost considerations.

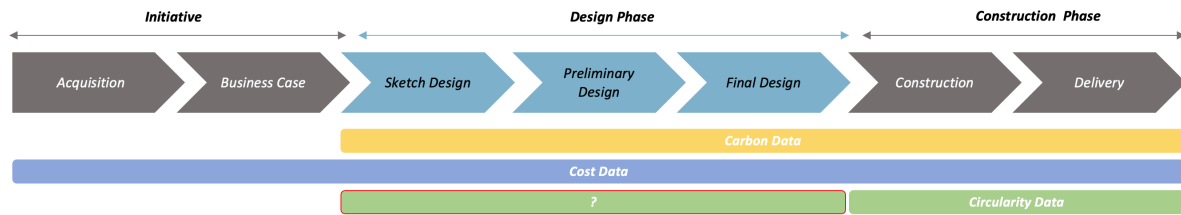


Figure 6.7: Availability of key data streams across project phases. Own illustration.

Although the Coolsingel project can be considered a front-runner in terms of circular construction, the precise impact of its circular strategies on UEC and cost remains uncertain. Moreover, it is possible that alternative decisions, better aligned with carbon and cost objectives, could have emerged had the CCF been applied during the early design stages. This underscores the significance of the case study as a central component of this research.

To conclude, table 6.1 presents the data mapping table, which summarizes which data from the Coolsingel project is directly available for use within the CCF. The table distinguishes between attributes that are:

- Directly available (indicated with: ✓),
- Not directly available but retrievable (indicated with: ⚠),
- Unavailable (indicated with: ✗).

This mapping provides a structured overview of the model's input feasibility based on existing project documentation.

Table 6.1: Comparison of available data in the Coolsingel project and the input requirements of the CCF. Own illustration.

Variable	Attribute	Available	Data Source	Comments
Parameter	Layer and Type	✓	Design documentation	N/A
Parameter	Measurement unit	✓	Cost estimates	N/A
Parameter	Quantity	✓	Cost estimates	N/A
Carbon	Carbon Factor (PPI)	⚠	Environmental consultant report	Indirect, see Section Carbon
Carbon	Total Carbon	✓	MPG Calculation	N/A
Cost	Unit Cost	✓	Cost estimates	N/A
Cost	Total Cost	✓	Cost estimates	N/A
Circularity	RBM	⚠	Cost estimates	Indirect, partially available
Circularity	BBR	⚠	Cost estimates	Indirect available
Circularity	RBC	✗	Not available	Module C and D not available
Circularity	DFD	⚠	Supplier data	Applied, not mapped

To understand why certain data is not directly available, only partially retrievable, or entirely unavailable, these limitations are examined in more detail in the following gap analysis.

3. Gap Analysis and Data Maturity Classification

Following the data mapping in table 6.1, which assessed the availability of each input attribute for the CCF, it becomes evident that several critical data inputs are either not directly available or entirely missing. Therefore, a structured gap analysis is necessary to gain deeper insights into the nature and implications of these data limitations.

This analysis is relevant for two key reasons. First, it reveals that even in projects aiming for low-carbon and high-circularity outcomes, the data infrastructure is not always in place to quantify performance reliably. The absence or partial availability of certain data attributes prevents a robust and complete application of circular-carbon metrics. Understanding these limitations allows for the identification of systemic barriers and informs the development of improved data strategies or project practices.

Second, given that this study is based on a case project, it is essential to assess the overall quality and readiness of the available project data. For inputs that are partially or not available, the gap analysis identifies the current maturity of the data, the root causes of their absence, and the responsible stakeholders who can potentially provide the required information. This provides practical insights for implementing the CCF in similar projects, highlighting where data acquisition efforts should be focused and which advisors or actors should be engaged.

Table 6.2: Gap analysis of missing or incomplete input data for key attributes in the Circular-Carbon Framework. Own illustration.

Missing Input		Gap Type	Data Maturity	Root Cause	Workaround
Carbon (PPI)	Factor	Inaccessible data	Near-ready	Procedural	Environmental advisor
RBM		Partial data	Near-ready	Procedural	Environmental- and Cost advisor
BBR		Partial data	Market-ready	Technical	Cost advisor
RBC		Absent data	Market-ready	Procedural	Direct use of EPDs instead of NMD
DFD		Unmapped data	Near-ready	Technical	Request mapping support from advisors

The **Carbon Factor** is not directly accessible in the project data. As explained in the previous section, environmental performance in Dutch building projects is primarily assessed using the MPG, which relies on NMD data. This assessment expresses environmental impact in terms of euros and covers a broad range of categories, making it less focused on specific carbon-related metrics. Consequently, the carbon factor, central to the Paris Proof methodology and the CCF, is often not explicitly reported, but it is embedded in the same dataset. Environmental advisors track these carbon factors for materials in projects targeting Paris Proof performance, but the data remains secondary and not directly visible. It is therefore classified as near ready, with the root cause being procedural. Ideally, the carbon factor would be more clearly available, but in practice, an environmental advisor performs this extraction.

The **Recycled Building Material (RBM)** data, related to Module A1 to A5, is partially available. Some cost estimates include percentages of recycled content for selected materials, but this is not consistent across the entire dataset. Moreover, the NMD, which is the standard reference for MPG calculations, does not specify recycled content. While EPDs do provide this information, they are not available for all materials and are not the primary source in Dutch assessments. This results in recycled content being underrepresented, despite its availability. The data is considered near ready and the gap is procedural in nature. Collaboration with an environmental or cost advisor can help clarify and enhance the visibility of recycled content within the CCF.

Regarding **Bio-Based Resources (BBR)**, also for Module A1 to A5, the total quantity of timber and other biobased materials is clearly documented in the cost estimates. However, the current structure and categorisation of the estimates do not allow for an easy extraction or breakdown of bio-based

content. As a result, the data is near ready, but the root cause is technical due to the format and level of detail in the estimations. Mapping the quantities with support from a cost advisor can resolve this issue and align the data with the CCF input requirements.

The data on **Reused or Recycled Building Components (RBC)**, relevant for Module C and D, is mostly absent. Although some EPDs include this data, its translation into the NMD is unclear. It relies on end-of-life scenarios, but the exact methodology is not transparent. A clearer and more consistent translation is needed. Nonetheless, the data is considered market ready and could be included through the use of EPDs. The root cause is procedural, and a practical workaround is to use EPDs internally to support circular design decisions in line with the CCF.

Lastly, the **Design for Disassembly (DfD)** information is incorporated in the Coolsingel project, but its quantified contribution to the total project remains unknown. While it is theoretically possible to map this data using material passports or related tools, it is not a standard practice during the design phase. Therefore, the data is considered near ready but unmapped. The root cause is procedural, as there is currently no structured method or platform for processing disassembly-related data during early design stages. Advisors within the DT can support the developer by mapping and structuring this information to allow for future integration into the CCF.

5. Mitigation Strategies

For each identified data gap, a corresponding mitigation strategy is proposed. Since a central component of this case study is a demonstration run of the CCF, it is essential to justify how missing or incomplete data will be addressed. The table below outlines the proposed strategies to ensure that the model can be applied effectively despite current data limitations.

Table 6.3: Mitigation strategies for missing or incomplete input data for the case study. Own illustration.

Missing Input	Mitigation Strategy
Carbon Factor (PPI)	The Coolsingel project includes an environmental advisor who provides reliable carbon factor data for construction materials. This information is of high quality and can be directly used in the CCF analysis.
Recycled Building Material (RBM)	For materials in the cost estimation that include clear and traceable recycled content, this data will be incorporated into the CCF. If recycled content is not convincingly documented, the material will be excluded from the analysis.
Bio-Based Resources (BBR)	The amount of CLT used in the structure will be calculated in advance, based on the quantities provided in the cost estimation. This allows for a quantitative assessment of bio-based material use.
Recycled Building Components (RBC)	EPDs will be consulted to determine the end-of-life recycling potential of materials. If no suitable EPD is available or the data is not sufficiently specific, the data will be excluded from the CCF.
Design for Disassembly (DfD)	Material suppliers involved in disassemble elements, such as steel components, will be contacted. Based on their input, an estimation will be made regarding the proportion of the building designed for disassembly.

6.4. Results

The data analyzed in paragraph 6.3 is implemented into the CCF, and the resulting outputs are discussed in this chapter. Carbon, cost, and circularity are assessed using a base case and four circular strategies as alternative. Evaluating these strategies and understanding how their performance dynamics are captured within the CCF is essential for guiding sustainable design decisions in the early stages of a construction project.

This chapter focuses on **Layer 3** of the model, the *Decision Dashboards*, which are intended to support DT members in evaluating and comparing circular strategies. As introduced in Chapter 5, these dashboards assess each strategy from three perspectives:

1. **Total values**, directly derived from Layer 2 (e.g., total upfront embodied carbon and total cost),
2. **Normalized values per m²**, to allow for more easy comparison, and
3. **Carbon Efficiency Ratio**, which quantifies the environmental return (in grams of CO₂ saved) per euro invested.

By interpreting the results from the Decision Dashboards, a final synthesis will be made to distinguish between high- and low-performing strategies. The analysis will also reflect on whether a single strategy emerges as the optimal choice, or if a combination of strategies may offer the best overall balance between carbon reduction, cost-effectiveness, and circularity.

For a visual reference of the Layer 2 results and the specific materials considered, please refer to Appendix F or the Excel model.

6.4.1. Case Study Strategies

Because the CCF is specifically developed for application in the early design phases, it was decided to 'go back in time' and evaluate the project before material decisions were finalized by the DT. This approach ensures that the model operates as intended, objectively guiding design during the design phases. Using this setup, the model evaluates the initial building concept and, based on the principles of the CCF, determines which circular strategy, or combination of strategies, should be pursued.

Strategy Selection

The base case functions as a reference within the sketch design phase and reflects the original, un-influenced design, without targeted interventions regarding circularity or embodied carbon reduction. To explore the potential for improvement, four circular strategies are introduced: Hybrid, Bio-Based, Promote Recycling, and Smart Circular Strategy.

All selected configurations, except for the base case, are based on circular design principles. The strategy selection was deliberately set up to represent both a variety of design approaches and a range of performance outcomes. The process was reverse-engineered to include the most distinct and informative configurations, allowing for a comprehensive evaluation of how circular interventions affect UEC, cost, and circularity.

The first three circular strategies primarily focus on the *structural configuration*:

- A **concrete** structure representing the base case,
- A **hybrid** structure combining concrete and timber (as built), and
- A **fully bio-based** structure using timber throughout.

These variants were selected to evaluate the structural design space in terms of material choice and to assess how these choices impact the circular indicators, based on circular design principles from literature (Çetin et al., 2021; Eberhardt et al., 2022). Based on the results of these three, the most feasible and balanced structural approach was identified and is further discussed in the results section.

Subsequently, two additional strategies were developed that extend beyond structural interventions and also include modifications to the *building skin*:

- **Promote Recycling**, derived directly from literature (Eberhardt et al., 2022), investigates how increasing the share of recycled content influences circularity and feasibility.
- **Smart Circular**, a *project-specific addition* created within this thesis, explores whether a tailored, material-by-material balancing of carbon, cost, and circularity could outperform standard strategies.

This selection method ensures that the case study captures a *diverse set of circular strategies*, ranging from conventional applications of literature-based approaches to a more integrative, context-specific strategy designed to optimize project outcomes.

The performance outcomes of each strategy are discussed in the following section. To ensure transparency and traceability, every strategy is explicitly linked to the corresponding circular framework in Table 4.2, clarifying which strategies are literature-based and which were developed specifically for this project. The remainder of this section presents a detailed explanation of how each strategy was implemented within the case study, outlining its configuration, scope, and contribution to the comparative analysis.

Strategy Application

Base Case - Concrete

In the base case, the building is modeled as a fully concrete structure. This means that the current hybrid configuration (concrete and CLT) is replaced entirely by concrete. No timber is used in the load-bearing structure, which reflects a traditional construction approach commonly applied today. The skin of the building is included in the model based on the as-build scenario. The focus is on the primary load-bearing structure. This should not be regarded as a circular strategy, but rather as a comparative reference value used to evaluate the performance of the actual circular strategies

Strategy 1 – Hybrid (As Built)

Source: Table 4.2, Strategy BMM (Bio-Based Materials)

The hybrid strategy reflects the actual built scenario. In this configuration, the core and floor slabs remain concrete, while the rest of the primary load-bearing structure is replaced with CLT. The building skin is again modeled based on the assigned function, but the primary focus remains on the structure. Although it is known that this strategy was implemented in practice, it is valuable to evaluate whether this was a good decision. For this strategy, reliable data on UEC, cost, and circularity was available through project reports and assessments.

Strategy 2 - Bio-Based

Source: Table 4.2, Strategy BMM (Bio-Based Materials)

This strategy proposes a fully bio-based load-bearing structure. All concrete, including the structural core and floor slabs, is replaced by timber solutions. As a result, this configuration achieves high circularity and low UEC performance, as will be shown in the analysis.

Strategy 3 - Promote Recycling

Source: Table 4.2, Strategy PRC (Promote Recycling)

While Strategies 1 and 2 only modify the structure, this strategy takes a more integrated design approach. The Promote Recycling strategy maximizes the percentage of recycled content across both the structure and the façade. (Table 4.2)

In this scenario, the materials used in the as-built structure are retained in type, but replaced by variants with the highest available recycled content. For example, the same type of concrete is used but substituted with a mix that includes recycled content. The same logic applies to the steel reinforcement,

which is replaced by an identical grade with higher post-consumer recycled content.

For the building skin, changes are made to the type of glazing and cladding, replacing standard components with those having the highest available recycled content. This strategy does not consider carbon or cost impact but focuses solely on maximizing recycled material use.

Strategy 4 - Smart Circular

Source: Table 4.2, Strategy PSA (Project-Specific Addition)

The Smart Circular strategy is a tailored, project-specific approach that falls outside the standardized strategies listed in table 4.2. This strategy considers both the structure and the skin, and evaluates each material based on a balance of UEC, cost, and circularity.

A detailed material-by-material assessment was carried out to evaluate the trade-offs between circularity and UEC for each material application. For instance, concrete C30/37 was not replaced by a more circular alternative, as such alternatives would have introduced significantly higher UEC emissions. In this case, the increase in emissions outweighed the potential circularity benefits, and thus, substitution was not considered justifiable.

In contrast, both steel reinforcement and structural steel were assessed for more efficient and circular alternatives included in the CCF, as these offered meaningful environmental gains without disproportionate carbon or cost increases. Regarding the façade system, a new glazing type with a higher recycled content was selected. This choice improved circularity performance while remaining within acceptable carbon and financial limits.

Unlike earlier strategies that focus on specific elements or criteria, this strategy evaluates materials in context, considering their total quantity and impact on UEC, cost, and circularity. This makes it the most refined and integrative approach in the analysis.

In conclusion, the five case study strategies differ not only in material type but also in the scope of their application. The Base Case, Strategy 1 (Hybrid), and Strategy 2 (Bio-Based) focus exclusively on the load-bearing structure, with an identical façade across all three. This allows for a controlled comparison of structural interventions. In contrast, Strategy 3 (Promote Recycling) and Strategy 4 (Smart Circular) build upon the Hybrid structure of Strategy 1 but also include modifications to the building skin. These strategies therefore consider both structure and façade, representing a more integrated approach to circular design. This distinction is essential for interpreting the outcomes of the CCF, as the extent of material intervention influences both environmental and financial performance.

6.4.2. Layer 1: Input Parameters

Before applying the different circular strategies through Layer 2 of the model, the input parameters of the case study must be defined (Appendix F). These parameters form the backbone of Layer 3 and serve as the reference framework for evaluating carbon, cost, and circularity outcomes (Figure 6.8).

Input Parameter Sheet

Fill in all applicable project details below. Use default values as reference where applicable.

Category	Parameter	Description	Value	Unit
General	Project Name	<i>Coolsingel</i>	-	-
	Project Location	<i>Rotterdam</i>	-	-
	Project Phase	<i>Sketch Design</i>	-	-
	Gross Floor Area (GFA)	<i>24110</i>	-	m ²
	Building Type	<i>Commercial</i>	-	-
	Number of Floors	<i>11</i>	-	-
	Year of Permits Issuance	<i>2023</i>	-	-
	Year of Completion	<i>2026</i>	-	-
	Structural System	<i>Hybrid</i>	-	-
	Façade System	<i>Aluminium / Glass</i>	-	-
Design Strategy	Circular Strategy	<i>Smart Circular</i>	-	-
Carbon Indicator	CO ₂ Boundary (Life Cycle Stages)	<i>A1-A3</i>	-	-
	EPD Database	<i>Nationale Milieu Database / EPD International</i>	-	-
	Functional Unit	<i>Used functional Unit</i>	-	kg CO ₂ -eq/m ²
	Paris-Proof Embodied Carbon Threshold	<i>Used Paris-Proof Threshold Value</i>	250	kg CO ₂ -eq/m ² GFA (A1–A3)
	Carbon Budget (Structure and Skin)	<i>Carbon budget for Structure and Skin</i>	185	
	Carbon Budget (Structure, 60%)	<i>Carbon budget for Structure</i>	160	kg CO ₂ -eq/m ² GFA (A1–A3)
	Carbon Budget (Skin, 10%)	<i>Carbon budget for Skin</i>	25	kg CO ₂ -eq/m ² GFA (A1–A3)
Cost Indicator	Unit Cost Basis	<i>Snapshot (Not time adjusted)</i>	-	-
	Currency	<i>Euro (€)</i>	-	€
	Total Budget	<i>Total cost budget</i>	€ 51,200,000	€
	Total Budget (Structure and Skin)	<i>Total cost budget Structure and Skin</i>	€ 28,160,000	
	Cost Budget (Structure, 40%)	<i>Cost budget for Structure</i>	€ 20,480,000	€
	Cost Budget (Skin, 15%)	<i>Cost budget for Skin</i>	€ 7,680,000	€
	Conversion Factor	<i>Materials vs Labour</i>	0.5	-
	Material Cost Budget (Structure and Skin)	<i>Material budget for Structure and Skin</i>	€ 14,080,000	€
	Material Cost Budget (Structure, 40%)	<i>Material budget for Structure</i>	€ 10,240,000	€
	Material Cost Budget (Skin, 15%)	<i>Material budget for Skin</i>	€ 3,840,000	€
Circularity Indicator	Circularity Framework	<i>Circular Index Meter (CIM-Score)</i>	-	%
	CIM Score	<i>0-100</i>	Own entry	%
	CIM Total Score	<i>0-100</i>	30%	%
	CIM Structure	<i>Circular Index for Structure</i>	15%	%
	CIM Skin	<i>Circular Index for Skin</i>	15%	%

Figure 6.8: Overview of the input parameters in Layer 1 of the case-study (screenshot). Own illustration.

Figure 6.8 displays the completed input parameter sheet used in Layer 3 of the CCF, corresponding to the Coolsingel case study in Rotterdam. This input sheet defines the project-specific boundary conditions and reference values against which circular strategies are evaluated in terms of UEC, material cost, and circularity performance.

The project concerns a commercial building in the sketch design phase, located in Rotterdam. It consists of 11 floors with a gross floor area of 24,110 m². The year of permit issuance is 2023, with expected project completion in 2026. Following the guidelines from the DGBC, the Paris-Proof UEC threshold is set at 250 kg CO₂-eq/m² (A1–A3), which is used as the reference benchmark for carbon performance in this case.

The threshold is split into project-specific budgets: 160 kg CO₂-eq/m² for the structure and 25 kg CO₂-eq/m² for the skin, summing to a total carbon budget of 185 kg CO₂-eq/m². These targets are applied in Layer 3 to assess whether the circular strategies meet carbon performance goals.

The environmental data used in this case study is a combination of sources: project-specific additions are based on the NMD, while EPDs are used for all other standard material inputs.

The total project budget is €51.2 million. Of this, €28.16 million is allocated to structure and skin (materials and labor). A conversion factor of 0.5 is applied to reflect that 50% of construction costs are attributed to materials, which is regular in the Dutch context due to high labor costs (based on cost

estimate). This results in material cost budgets of €10.24 million for the structure and €3.84 million for the skin, yielding a total material reference budget of €14.08 million. These material cost thresholds are used in the evaluation dashboards of Layer 3.

The project aims for a total CIM-score of 30%, divided equally between the structure and the skin, each set at 15%. These values serve as the circularity targets used to evaluate whether a circular strategy meets minimum project ambitions.

6.4.3. Layer 3: Decision Dashboards

Decision Dashboard 1 - Aggregate Performance

Figure 6.9 presents the first decision dashboard developed in Layer 3 of the CCF. This dashboard displays the *total values* for UEC, total material cost, and the CIM across the base case and four alternative circular strategies. The dashboard results are based on the output from the comparison layer (Layer 2), where all materials were modeled and assessed per scenario.

The layout of the dashboard is subdivided by indicator and component (structure and skin), which facilitates a clear comparison between strategies. For each indicator, the dashboard also includes reference budget values, allowing immediate identification of scenarios that exceed or comply with project targets.

In terms of **total cost**, the dashboard shows that Strategies 2 and 3 (Bio-Based and Promote Recycling) exceed the maximum budget of €14.08 million. Conversely, the Smart Circular strategy remains within the budget limits, as well as the As-Built strategy and the Base Case.

Regarding **circularity**, the CIM scores reveal that Strategies 2, 3, and 4 all exceed the required 30% project target. Specifically, the Bio-Based strategy achieves a CIM of 53%, significantly outperforming the Base-case (25%) and the As-Built scenario (28%).

However, for **UEC**, interpreting the total values is more complex due to the large scale of the project. While the table provides absolute values in kg CO₂, these are not directly comparable to the project's carbon budget, which is expressed in kg CO₂/m². Therefore, a second dashboard is developed (Decision Dashboard 2), in which all values are normalized per square meter (GFA). This approach aligns with industry practice in both carbon and cost analysis, as normalized figures improve interpretability and comparability across circular strategies.

Input							
Gross Floor Area (m²)	24110						
Conversion Factor (Kg / Gram)	1000						

Decision Dashboard 1								Budget
Totals								
Parameter	Unit	Base Case (Concrete)	1. Hybrid (As-Built)	2. Bio-Based	3. Promote Recycling	4. Smart Circular		
Upfront Embodied Carbon	kg CO₂	8750270	3559249	2413889	3998046	3384881	4460350	
UEC (Structure)		8410317	3219296	2073936	3389006	3068202	3857600	
UEC (Skin)		339953	339953	339953	609041	316679	602750	
Total cost	€	€ 10,369,951	€ 14,070,961	€ 17,436,466	€ 14,128,401	€ 13,750,636	€ 14,080,000	
TC (Structure)	€	€ 5,805,435	€ 9,506,445	€ 12,871,950	€ 9,051,435	€ 9,333,420	€ 10,240,000	
TC (Skin)	€	€ 4,564,516	€ 4,564,516	€ 4,564,516	€ 5,076,966	€ 4,417,216	€ 3,840,000	
Circularity Index Meter		25%	28%	53%	43%	37%	30%	
CIM (skin)		17%	19%	45%	27%	25%	15%	
CIM (Structure)		8%	8%	8%	17%	12%	15%	

Figure 6.9: Overview of the Decision Dashboard 1 in Layer 3 of the case-study (screenshot). Own illustration.

Decision Dashboard 2 - Normalized Performance

Figure 6.10 presents Decision Dashboard 2, which builds upon the total outcomes from Dashboard 1 by expressing all values relative to the GFA of the building. This normalization results in indicators expressed per square meter ($\text{kg CO}_2/\text{m}^2$ for UEC and $\text{€}/\text{m}^2$ for cost), which aligns with common industry practice and is essential for interpreting results against fixed benchmarks, namely, the Paris-Proof threshold of $185 \text{ kg CO}_2/\text{m}^2$ and the cost ceiling of $\text{€}584/\text{m}^2$.

The dashboard is divided into two parts. The first is the **Regular Dashboard**, which presents the normalized figures per m^2 for each of the five strategies (Base Case, Hybrid, Bio-Based, Promote Recycling, and Smart Circular). The second is the **Color-Coded Dashboard**, which provides the same data but highlights whether a strategy complies with the respective budget. Values that fall within the predefined budgets are shown in green, while those that exceed the thresholds are marked in red. This color logic enhances readability and allows decision-makers to quickly grasp which strategies are viable within the constraints of carbon, cost, and circularity.

Decision Dashboard 2 (Regular)							Budget
Per m²							
Parameter	Unit	Base Case (Concrete)	1. Hybrid (As-Built)	2. Bio-Based	3. Promote Recycling	4. Smart Circular	
Upfront Embodied Carbon	kg CO ₂ / m² (GFA)	363	148	100	166	140	185
UEC (Structure)		349	134	86	141	127	160
UEC (Skin)		14	14	14	25	13	25
Total cost	€ / m² (GFA)	€ 430	€ 584	€ 723	€ 586	€ 570	€ 584
TC (Structure)		€ 241	€ 394	€ 534	€ 375	€ 387	€ 425
TC (Skin)		€ 189	€ 189	€ 189	€ 211	€ 183	€ 159
Circularity Index Meter	-	25%	28%	53%	43%	37%	30%
CIM (structure)		17%	19%	45%	27%	25%	15%
CIM (skin)		8%	8%	8%	17%	12%	15%

Decision Dashboard 2 (Color coded)							Budget
Per m²							
Parameter	Unit	Base Case (Concrete)	1. Hybrid (As-Built)	2. Bio-Based	3. Promote Recycling	4. Smart Circular	
Upfront Embodied Carbon	kg CO ₂ / m² (GFA)	363	148	100	166	140	185
UEC (Structure)		349	134	86	141	127	160
UEC (Skin)		14	14	14	25	13	25
Total cost	€ / m² (GFA)	€ 430	€ 584	€ 723	€ 586	€ 570	€ 584
TC (Structure)		€ 241	€ 394	€ 534	€ 375	€ 387	€ 425
TC (Skin)		€ 189	€ 189	€ 189	€ 211	€ 183	€ 159
Circularity Index Meter	-	25%	28%	53%	43%	37%	30%
CIM (structure)		17%	19%	45%	27%	25%	15%
CIM (skin)		8%	8%	8%	17%	12%	15%

Figure 6.10: Overview of the Decision Dashboard 2 in Layer 3 of the case-study (screenshot). Own illustration.

Base Case (All-Concrete)

For the Base Case, it is immediately clear that the UEC significantly exceeds the carbon budget (363 vs. $185 \text{ kg CO}_2/\text{m}^2$). This is expected given the full use of concrete in the structural system. Although the skin component performs within the carbon limit, the structure has a far greater impact on total emissions and dominates the outcome. On the other hand, the Base Case is the most cost-efficient strategy ($\text{€}430/\text{m}^2$), staying well below the cost budget. The CIM is 25%, slightly below the 30% target. Interestingly, the structure contributes a relatively high portion of the circularity score (17%), mainly because concrete has a high recyclability rate at end-of-life. Despite this, the excessive UEC makes the Base Case unfeasible under the Paris Proof framework and would not be eligible for a building to call it Paris Proof.

Strategy 1: Hybrid Structure (As-Built)

Strategy 1 replaces a portion of the concrete with bio-based materials, resulting in a substantial drop in UEC to $148 \text{ kg CO}_2/\text{m}^2$, comfortably within the budget. Both structure and skin comply individually with their respective carbon thresholds. From a cost perspective, the strategy scores exactly at the budget limit ($\text{€}584/\text{m}^2$), indicating that it is technically feasible, but with little margin for further cost increases. The circularity score of 28% is close to the 30% target and is therefore considered acceptable. Given its compliance with both UEC and cost benchmarks and near-compliance with circularity, Strategy 1 is considered feasible and is retained for further consideration.

Strategy 2: Bio-Based Structure

Strategy 2 represents the most radical shift, using a fully bio-based structure and eliminating concrete and steel reinforcement entirely. This results in an exceptionally low UEC of 100 kg CO₂/m², far below the benchmark. However, this gain in environmental performance comes with a significant trade-off: total cost rises to €723/m², exceeding the budget by more than 20%. On the other hand, circularity reaches its peak at 53%, making it the best performer on this metric. Despite its strong performance in carbon and circularity, the excessive cost renders this strategy financially unfeasible in the current context.

A comparison between the Base Case, Strategy 1 (Hybrid), and Strategy 2 (Bio-Based) shows how changes in structural composition affect the outcomes. The Base Case (full concrete) fails on carbon, the bio-Based strategy fails on cost, and only the Hybrid design manages to strike a viable balance, meeting both the carbon and cost criteria, while nearly achieving the circularity target.

Strategy 3: Promote Recycling

Therefore, Strategy 3 takes Strategy 1 as a baseline but enhances the circularity of both structure and skin by selecting materials with higher recycled content. As a result, circularity improves to 43%, well above the 30% target. However, interestingly, UEC also increases slightly from 148 to 166 kg CO₂/m². Although counterintuitive, this reflects a known phenomenon observed in early literature, where increasing recycled content in materials (e.g. concrete or steel) does not always reduce carbon due to energy-intensive processing or transport emissions. This was also specifically noted by Dodoo et al. (2009) and confirmed by Interviewee 2.

Although UEC remains within the budget, total cost increases slightly to €586/m², marginally exceeding the cost ceiling. This small overrun might be acceptable in some projects, but in this model it places Strategy 3 just outside the feasible range. As a result, despite its excellent circularity score, this strategy cannot be considered feasible without further optimization.

Strategy 4: Smart Circular

Strategy 4 takes a selective and integrated approach by optimizing for all three criteria: carbon, cost, and circularity. It builds upon the hybrid base (Strategy 1), but instead of maximizing recycled content (Strategy 3), it focuses on intelligent trade-offs. For example, in the structure, both the steel reinforcement and structural steel were replaced by more circular alternatives. In contrast, for the façade, the triple glazing with the highest recycled content (as applied in Strategy 3) was substituted with a slightly less circular option that performed significantly better in terms of cost and UEC. Although this reduced the circularity score of the façade component, the overall environmental and financial impact was more favorable.

As a result, total UEC drops to 140 kg CO₂/m², cost decreases to €570/m² (well below budget), and the CIM remains strong at 37%, comfortably above the target. The major cost reduction comes from the skin component (from €211/m² to €183/m²), confirming the impact of strategic material selection. It can be concluded that, in this strategy, circularity primarily served as a means to reduce UEC and material cost, aligning precisely with the main objective of this research.

Conclusion

Based on this analysis, Strategy 1 (Hybrid) and Strategy 4 (Smart Circular) emerge as the most balanced and feasible options. Both strategies remain within the carbon and cost budgets while achieving or approaching the desired circularity score. Strategy 4 in particular demonstrates how targeted circular interventions can yield better overall outcomes than a singular focus on one criterion. The next section will further evaluate the effectiveness of these strategies using the Carbon Efficiency Ratio.

Decision Dashboard 3 – Carbon Efficiency Ratio

It is important to recognize that circularity, while actively promoted by the European Union and the Dutch government, is not yet a primary objective within existing policy frameworks. In this research, circularity is positioned as a means to reduce UEC while remaining within financial constraints. However, in practice, project developers often prioritize a lower carbon footprint, for example, to obtain sustainability certification, or a higher net return over achieving a highly circular design.

In this context, the third decision dashboard introduces the carbon efficiency ratio, expressed as the number of grams of CO₂ emitted per euro invested. This metric offers developers and investors a clearer understanding of carbon performance in financial terms and supports the comparison of alternative strategies on a cost-adjusted basis.

Decision Dashboard 3						
Parameter	Unit	Base Case (Concrete)	1. Hybrid (As-Built)	2. Bio-Based	3. Promote Recycling	4. Smart Circular
Carbon Efficiency Ratio	Gr CO ₂ /€ invested	844	253	138	283	246

Figure 6.11: Overview of the Decision Dashboard 3 in Layer 3 of the case study (screenshot). Own illustration.

The base case, consisting of a fully concrete structure, provides a useful benchmark. It generates the highest level of UEC emissions and is also the least expensive design option. This combination results in a carbon efficiency ratio of 844 grams of CO₂ per euro invested, making it the least carbon-efficient alternative in the analysis.

At the opposite end of the spectrum, Strategy 2 (Bio-Based) achieves a much lower carbon efficiency ratio of 138 grams of CO₂ per euro, driven by its low emissions and relatively high cost. However, as shown in Decision Dashboard 2, this strategy exceeds the predefined budget and is therefore not financially feasible. While it remains included in the analysis for completeness, its result holds no practical value for final decision-making since it cannot be selected.

The same conclusion applies to Strategy 3 (Promote Recycling), which also exceeds the financial threshold. Regardless of its carbon efficiency ratio, 283 grams of CO₂ per euro, it does not meet the cost criteria and cannot be considered a viable alternative.

This narrows the focus to the two strategies that are both feasible in carbon and cost: Strategy 1 (Hybrid As-Built) and Strategy 4 (Smart Circular). Strategy 1 results in a carbon efficiency ratio of 253 grams of CO₂ per euro, while Strategy 4 performs slightly better at 246 grams per euro. Although the difference is relatively small, it indicates that per euro invested, Strategy 4 avoids approximately 7 grams more CO₂ emissions than Strategy 1.

An important observation can be drawn when comparing the results of this dashboard with those from Decision Dashboard 1. In the earlier analysis, both Strategy 3 and Strategy 4 achieved higher CIM-score than Strategy 1. However, this does not consistently translate into better carbon efficiency. Strategy 3 performs worse than Strategy 1 (283 vs. 253 g CO₂/€), while Strategy 4 performs slightly better (246 g CO₂/€).

These findings suggest that, within the context of this case study, the relationship between circularity and carbon efficiency is not necessarily linear. Both the CIM-score and the carbon efficiency ratio appear to be influenced by specific material compositions and their associated environmental impacts. As such, while circular strategies may support carbon reduction, this cannot be assumed without detailed material-level analysis.

This final distinction reinforces what the previous dashboards have already indicated: Strategy 4 (Smart Circular) consistently offers the most balanced performance across the three key dimensions of carbon, cost, and circularity, even when evaluated through the lens of carbon efficiency. The analysis confirms that, under the conditions of this case study, circularity can function as an effective instrument to reduce UEC. However, this does not necessarily have to be the case, as the effectiveness of circular strategies depends strongly on material-specific choices and their carbon implications.

6.4.4. Summary of Findings

The comparative analysis of the four circular strategies (Base Case, Hybrid, Bio-Based, Promote Recycling, and Smart Circular) reveals key insights into the interrelationship between UEC, cost and circularity within the early design stages. By operationalizing these strategies through the CCF, it becomes evident that performance across sustainability metrics is highly dependent on how circular principles are implemented at the material level.

The results show that most strategies involve trade-offs between carbon, cost, and circularity, only Strategy 4 (Smart Circular) manages to excel across all three dimensions. For instance, the Bio-Based strategy achieves the lowest UEC and highest circularity score but significantly exceeds the material cost budget, thereby limiting its feasibility. In contrast, the Base Case, while financially attractive but fails dramatically in terms of UEC.

The Hybrid strategy (Strategy 1) emerges as a practical baseline, offering compliance with both carbon and cost targets while approaching the minimum circularity threshold.

The Promote Recycling strategy (Strategy 3) demonstrates that circular interventions, particularly those focused solely on increasing recycled content, do not always result in lower UEC or financial improvements. Despite achieving a high circularity score (43%), this strategy incurs a slight cost overrun and, paradoxically, increases UEC relative to the Hybrid strategy. This counterintuitive outcome aligns with established literature indicating that higher recycled content can lead to increased emissions, owing to energy-intensive reprocessing or long-distance transport. As such, although Strategy 3 scores well in terms of circularity, it fails to meet carbon and budget, highlighting the risks of applying circular principles without thought-out performance assessment.

In contrast, the Smart Circular strategy (Strategy 4) consistently delivers the most balanced performance. Also building upon the Hybrid strategy, it employs a selective and context-sensitive approach to material substitution, optimizing for UEC, cost, and circularity simultaneously. Rather than pursuing maximum circularity, it focuses on trade-offs that yield the most favorable overall outcomes. As a result, Strategy 4 achieves the lowest carbon emission and efficiency ratio (246 g CO₂/€) among feasible options. It slightly outperforms the Hybrid case, while staying comfortably within both carbon and cost budgets.

In conclusion, this analysis demonstrates that circular interventions can lead to both lower carbon emissions and cost (as seen in Strategy 4), but this outcome is not guaranteed (as demonstrated by Strategy 3). The variability in outcomes underscores the need for a structured and transparent platform, like the CCF, through which different strategies can be compared, customized, and optimized. The CCF enables stakeholders to evaluate circularity not in isolation, but in conjunction with UEC and cost, thereby supporting more informed and balanced decision-making. Ultimately, it highlights the importance of improving material-level implementation, rather than merely increasing the level of circular ambition.

6.5. Limitations

While chapter 5.4.3 discussed the methodological limitations of the CCF itself, this section focuses on limitations specific to the case study. Considering the aims of transparency and reproducibility, it is important to critically reflect on the boundaries and assumptions embedded in the case-based research approach.

Firstly, due to time constraints, this research included only a single case study. This inherently limits the generalisability of the findings. As with any single-case design, the outcomes are closely tied to the specific characteristics of the selected project. Variations in project type, scale, stakeholder composition, or procurement strategy could lead to different conclusions in other contexts. Therefore, while the case provides valuable insight into the application of the CCF, caution must be taken when extrapolating these findings to the broader construction sector (Pelto & Pelto, 1978).

Secondly, the interpretation and assessment of case data may be subject to researcher bias. To mitigate this, interviews were conducted with a broad range of DT members, not only the project developer but also the architect, structural engineer, cost consultant, and sustainability advisor. In addition, objective project data were used when constructing the 'as-built' strategy within the CCF, to ensure that modeling was grounded in verifiable inputs.

A further limitation concerns the level of simplification applied to the circular strategies in the case study. In order to enable a structured comparison across all decision dashboards, the scenarios (e.g., hybrid, full concrete, full bio-based) were developed in a stylised manner. Although expert input was obtained from a cost consultant to translate the hybrid structure into the alternative variants, this process necessarily involved assumptions and simplifications. These modeling decisions may have influenced the outcomes, even though professional advice was used to limit inaccuracies.

Lastly, discrepancies in material data sources present another constraint. While the project-specific quantities and material data were derived from the NMD, the generic material assumptions used in the base CCF model were based on EPDs. Due to paywall restrictions, direct access to the NMD database was not available during the development of the generic model. This mismatch between data sources may have introduced inconsistencies in UEC values across the circular strategies.

6.6. Conclusion

SRQ 4: How can the Circular-Carbon Framework be applied to support design teams in selecting circular strategies that aim for Paris Proof building performance while maintaining financial feasibility?

This final chapter focused on the application of the CCF in a real-world design context. By selecting the EDGE Coolsingel project as a case study, the chapter aimed to test the functionality and decision-making potential of the CCF using project-specific data. A comprehensive data assessment and gap analysis were conducted to determine which inputs required by the CCF were available in real-world project documentation. This step clarified the limitations of existing data, particularly regarding carbon factors and circularity indicators. It also justified the mitigation strategies applied, such as including only verified project data or excluding unavailable inputs.

Using this case study, the base case and four circular strategies: Hybrid, Bio-Based, Promote Recycling, and Smart Circular, were simulated within the CCF. The results showed that circular strategies can indeed lead to both lower upfront embodied carbon and cost, particularly when materials are analyzed in sufficient detail. The Smart Circular strategy demonstrated that a tailored approach can yield high performance across all metrics. However, the Promote Recycling strategy revealed that circular interventions do not always guarantee reductions in emissions or cost. This illustrates that circularity must be treated as a design variable requiring nuanced evaluation, rather than assumed to be beneficial in every case.

Answering the sub-question of how the CCF can be applied in selecting circular strategies that align with Paris Proof ambitions while maintaining financial feasibility, the framework provides a method to balance carbon, cost, and circularity at the material level. By applying this framework in the early design phases, DTs retain the flexibility to make trade-offs between different circular strategies, thereby enhancing opportunities for more impact full circular and low-carbon design choices. The application of the CCF to the Coolsingel Rotterdam case demonstrates its potential to support real-world decision-making and to guide DTs towards strategies that are both environmentally and financially sustainable.

With this, the sub-research question is effectively concluded. The case study confirms that the CCF can support DTs in selecting circular strategies that align with both Paris Proof carbon goals and financial feasibility. Its application illustrated that such strategies can indeed reduce emissions and costs, provided material choices are evaluated with sufficient detail and project-specific insight. At the same time, the results show that circularity alone does not guarantee improved outcomes. Each strategy must be assessed within its unique design context. While based on a single case study, the findings affirm the value of the CCF as a practical, structured, and transparent tool for early-stage decision-making.

7

Conclusion

The aim of this chapter is to present the final conclusions and key insights derived from this research. This is achieved by first revisiting the sub-research questions and summarizing their main findings. Subsequently, these insights are integrated to formulate an answer to the main research question:

How can circular strategies influence the minimization of upfront embodied carbon during the design phases to align with Paris Proof carbon goals while maintaining financial feasibility?

Research sub-question 1

Question: What are the contextual foundations necessary to develop a framework that integrates carbon, cost, and circularity?

Goal: Identify and refine the basic elements required to define and structure the Circular-Carbon Framework.

To understand how circular strategies can reduce Upfront Embodied Carbon (UEC) while maintaining financial feasibility, it is first necessary to examine the contextual environment in which such a framework operates. Chapters 2 and 3 addressed this question by defining both the external and internal foundations of the Circular-Carbon Framework (CCF). The external foundations comprise the theoretical backbone of the model, the regulatory environment, and the existing models. The internal foundations focus on defining carbon, identifying carbon-intensive materials with circular potential, and establishing the cost variable.

Chapter 2 explored the external context, beginning with a review of theoretical and methodological foundations. A structured design methodology is essential to ensure that the framework operates in a systematic and balanced manner. For this reason, Value-Driven Design (VDD) was adopted as the methodological backbone. Originally developed in the aeronautical industry, VDD offers a structured yet flexible approach to decision-making by translating diverse stakeholder values into quantifiable objectives. VDD supports the integration of the three key variables: carbon, cost, and circularity, along with their corresponding attributes required for structuring the CCF.

The regulatory context was then examined in detail. It was shown that the Paris Proof threshold values, introduced by the Dutch Green Building Council, are a central driver of UEC reduction in the Dutch built environment. These targets are embedded in the broader European Green Deal and the Circular Economy Action Plan, which aim to close material loops and support climate neutrality. At the national level, these ambitions are operationalized through the MilieuPrestatie Gebouwen (MPG) requirement. The MPG, calculated using data from the Nationale Milieu Database (NMD), is required for obtaining

an environmental permit. The Paris Proof threshold value also exists within this regulatory environment and sets the maximum allowable CO₂ impact per square meter. It is integrated into the in with MPG calculation but is specifically needed to obtain certifications like BREEAM-NL.

A key challenge lies in how the DGBC communicates Paris Proof threshold values, which are currently provided only at ten-year intervals, such as 2020, 2030, and 2040. Since the applicable threshold value is determined by the year in which the environmental permit is granted, this creates uncertainty for projects initiated in between the released years. To address this, the research applied a linear interpolation method to estimate threshold values for the intermediate years, thereby providing a more consistent and usable reference. Nonetheless, the responsibility for issuing clear and continuous target guidance remains with the DGBC.

The chapter also reviewed several tools operating within the current policy and regulatory context. While Building Information Modelling (BIM) is widely used for design coordination, it does not directly support assessment of carbon, cost, or circularity. The Building Circularity Indicator (BCI) covers circularity and carbon but lacks cost integration. Material passports, such as Madaster, include carbon, cost, and circular data but are primarily applied post-construction, limiting their value in early design. Carbon trackers, like those from LEVS, do integrate all three dimensions but face challenges in openness, accessibility, and multi-user support. These limitations, also raised during expert interviews, underline the need for a framework that is integrated, accessible, and tailored to the design phase.

Building upon this external foundation, chapter 3 defined the internal scope of the framework by focusing on the variables carbon and cost, as well as the material component. The carbon scope was limited to UEC, corresponding to lifecycle stages A1 to A3, which include raw material extraction, manufacturing, and transport (Figure 1.2). These emissions are fixed before a building becomes operational and represent a critical window for intervention. Operational carbon refers to emissions generated during the use phase of a building. It was excluded from the framework because it is only marginally influenced by material selection, which is the primary focus of this study.

The material scope of the CCF was narrowed to the structure and skin layers of buildings, which together account for approximately 75 % of total UEC. In the structural layer, the most carbon-intensive materials are concrete, steel reinforcement, and architectural steel, with engineered timber products such as CLT, GLT, and LVL identified as lower-carbon alternatives. For the skin, aluminum, glazing, and steel are the primary contributors to carbon impact. Interviews with material suppliers provided valuable insights into the technical specifications, circular potential, and real-world application of these materials, thereby enhancing the quality of the framework's material input data.

The material interviews revealed several important insights into the implementation of circular and low-carbon strategies. Material suppliers expressed a strong interest in joining the design team (DT) earlier in the process to better align their products with specific sustainability goals. However, this was met with resistance from developers and contractors who are concerned that early involvement could create a lock-in effect, preventing optimal pricing through competition. Additionally, although material reuse is one of the most circular strategies available, its practical application remains limited due to regulatory, technical, and supply-chain barriers. These include challenges such as complex disassembly processes, strict certification requirements, and the need for adapted logistics. Consequently, recycling is currently the most feasible circular strategy in practice. Furthermore, while low-carbon recycled materials are available, they are often more expensive than conventional options. This makes the metric of carbon reduction per euro spent increasingly relevant. However, the comparison of material suppliers in terms of both carbon performance and cost is still highly non-transparent. This highlights an urgent need for improved data accessibility and benchmarking tools to support informed decision-making in the early design stages.

Finally, the cost scope was defined in terms of capital expenditures, focusing specifically on the material costs associated with the structure and skin layers. These costs are directly linked to the carbon-intensive materials assessed and serve to evaluate the financial feasibility of different circular strategies. This integration ensures that the CCF can support real-world design choices by balancing environmental and financial performance.

Together, these external and internal contextual foundations form the necessary basis for the CCF. They ensure the framework is not only theoretically grounded and policy-aligned, but also practically usable by DTs aiming to make carbon- and cost-conscious decisions in the early phases of building projects.

Research sub-question 2

Question: What circular construction strategies can be categorized and applied across different design phases to support early-stage decision-making?

Goal: Identify and define applicable circular strategies and indicators that can be assessed quantitatively and integrated into the Circular-Carbon Framework.

This research question examines the third variable, circularity. Since circularity is intended to serve as a tool for reducing UEC, it was essential to analyze this variable in detail. To answer the question, the perspectives of DT members on circularity were explored through interviews, after which the concept of circularity was defined and structured for the CCF.

Understanding the role of the DT in circular decision-making was a key first step. Thirteen interviews were conducted with architects, project developers, structural engineers, environmental consultants, circularity consultants, and cost consultants. These interviews provided insights into how carbon, cost, and circularity are discussed within DTs, and whether circularity is regarded as an effective means of reducing UEC without compromising financial feasibility. The results revealed a wide range of interpretations of circularity, highlighting its ambiguous status. Unlike UEC, circularity is not consistently quantified or systematically assessed, which results in unclear prioritization during design processes.

The cross-interview analysis demonstrated that DTs experience conflicting priorities when integrating circular strategies. While there is broad agreement on the importance of reducing UEC, circularity remains less clearly defined and is often treated as secondary. Environmental and circular advisors tend to push for early integration of circular strategies, but their influence is often outweighed by the risk-averse perspectives of developers and cost advisors, who emphasize financial certainty and feasibility. This dynamic often leads to early material and structural decisions that limit the potential for circular solutions later in the process. To address this challenge, one interviewee proposed adding an extra design phase called VO+. This phase would create a specific moment to keep design options adjustable, allowing circular strategies to be further integrated and existing material inventories to be reconsidered before final decisions are made.

A significant barrier is the lack of flexibility within traditional design processes. Material choices are frequently locked in before the environmental implications of circular alternatives can be fully evaluated. Moreover, while some internal tools used by DT members offer flexibility and customization, they often lack transparency and openness, which hinders collaboration and cross-disciplinary validation. Nevertheless, there is consensus among DT members on the need for transparent and integrative tools that can compare carbon, cost, and circularity from the earliest design phases. The CCF addresses this need by offering an accessible and comparative platform that supports more coordinated and adaptive design workflows. From the interviews, it became clear that DTs seek specific guidance in such a framework: open-source accessibility, clear and measurable KPIs, ease of use, and flexibility across all design phases.

Having established these needs, circularity within the CCF was conceptualized through two distinct but interrelated components: circular strategies and circular indicators.

Circular strategies refer to the design interventions that can be applied to reduce upfront embodied carbon (UEC) and potentially lower material costs. They represent the means by which circularity is pursued in practice. These strategies were derived from a combination of academic literature and input from material suppliers, resulting in a structured 'menu' of possible interventions that can be selected and adapted by design teams based on project-specific needs (Figure 4.2). Example strategies include the use of bio-based materials, promoting recycling, and minimizing material use. While the thesis identifies a limited number of representative strategies for demonstration purposes, it is recognized that in practice, the range of possible strategies is virtually limitless and highly context-dependent. Within the CCF, these strategies serve as the basis for comparison and are evaluated for their impact on carbon, cost, and circularity.

Circular indicators, in contrast, are the metrics used to quantify the circular potential of a chosen strategy or design option. Given the CCF's focus on early-stage, data-driven decision-making, only indicators that are measurable in practice were included. These comprise the share of reused components, recycled content, bio-based material input, and design-for-disassembly potential, all of which can be extracted from EPDs. While these four indicators do not encompass the full range of circularity dimensions, they align with the quantifiable parameters used in established tools such as Madaster, BCI, and Het Nieuwe Normaal. This narrowed focus is considered appropriate for early-phase design decisions, where data availability and model simplicity are essential. Within the CCF, these indicators are collectively visualized and assessed through the Circular Index Meter (CIM), which forms the basis for evaluating the circular performance of each strategy.

Importantly, the outcomes of these strategies are reflected through the circular indicators. In other words, for a strategy to be considered effective within the CCF, it must influence one or more of the four defined indicators. This linkage ensures that strategies do not remain abstract concepts but are translated into quantifiable performance metrics within the model.

Finally, to address the main research question as a whole, the applicability of circular strategies across different design phases was examined. The analysis confirms that load-bearing elements are typically finalized early, during the sketch or preliminary design phase, limiting the opportunity for late-stage changes. By contrast, skin components can often be adjusted later, even in the final design phase, particularly when projects risk exceeding Paris Proof threshold values and low-carbon alternatives must still be introduced.

Research sub-question 3

Question: How can a multi-layered framework be developed to systematically structure and quantify the relationships between circular strategies, upfront embodied carbon, and financial feasibility?

Goal: Translate the variables of carbon, cost, and circularity into a structured, quantifiable framework that supports transparent trade-offs in early-stage design

Figure 7.1 presents an overview of the variables and attributes used in the Value-Driven Design. Carbon, cost, and circularity, the three core variables within this research, have been introduced, defined, and analyzed through the first two sub-research questions. This third research question focused on converting these qualitative insights into a working model. The objective was to build the basic structure of the CCF by assigning measurable attributes to each variable, enabling parameterization and quantitative assessment.

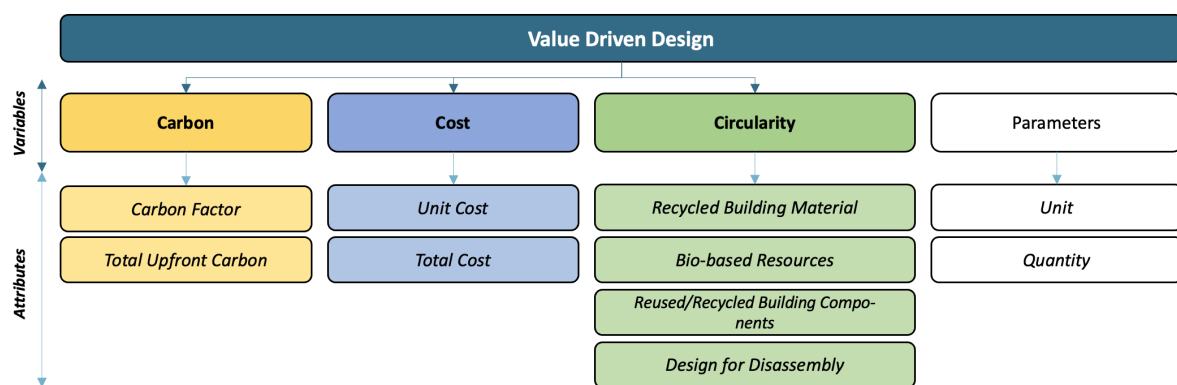


Figure 7.1: Overview of the variables and attributes of the value driven design model as adapted for the CCF. Own illustration.

To create a quantifiable model, a program of requirements was first established to verify and validate whether the framework delivers the intended outputs. These requirements exist in two forms. General requirements define functional, technical, and contextual conditions under which the model should operate. Model-specific requirements identify the attributes necessary to make carbon, cost, and circularity assessable and useful in practice.

The architecture of the framework is organized into four layers. Layer 1, the input layer, requires project-specific data including project name, gross floor area, and the year the environmental permit is issued. It also collects project-specific carbon, cost, and circularity targets. These inputs reflect the unique conditions of each design project.

Layer 2 contains the comparison model. In this layer, various circular strategies are assessed and compared based on their material composition. Each strategy is evaluated for its carbon impact, material cost, and circularity score, allowing the DT to consider trade-offs across the three dimensions.

Layer 3 is the decision dashboard. This layer presents the outputs from the comparison model in a visual format that enables quick interpretation and informed decision-making. The first dashboard shows the total results for carbon, cost, and circularity. The second dashboard presents the same data normalized per square meter of gross floor area, making the values more interpretable. Both dashboards include benchmarks that function as thresholds. For cost, this is the maximum available budget. For carbon, it is the Paris Proof threshold. For circularity, the DT determines a minimum target score based on project ambitions. A third dashboard, the carbon efficiency ratio, shows how many grams of CO₂ are emitted per euro spent. This indicator enables financial steering for carbon performance, which is relevant since cost and carbon are both regulated, unlike circularity.

Layer 4 contains the data sources used in the framework. For carbon and circularity, the model uses Environmental Product Declarations (EPDs). For cost, material prices are gathered from various platforms. However, access to reliable and open pricing data remains limited, which complicates consistent cost estimation.

The implementation section proposed that the cost consultant should be responsible for filling in the CCF, using input provided by the rest of the DT. Since the cost consultant is already familiar with working with budget estimates, this role can be extended to estimating values for carbon and circularity as well.

Key findings from this research question concerns the misalignment between EPDs and the NMD, which is used for MPG assessments. Although NMD profiles are based on EPDs, not all EPDs are accepted. This is due to additional methodological and verification requirements set by the NMD and relevant standards. As a result, many EPDs cannot be used, forcing designers to rely on sector-wide material averages (category 2) or unchecked generic data (category 3), which are less accurate. This discourages transparency among material producers. EPDs are often only submitted to the NMD when a product scores well. If performance is poor, producers may prefer to rely on generic category 2 or 3 data, which can mask true impact and avoid competitive disadvantage. As a result under performing products remain hidden behind industry averages. This may slow market-driven improvements and undermines fair comparison.

To illustrate this even further, the analysis reveals that circularity assessments thru the MPG are based on generic NMD profiles, particularly category 2 and 3, are inconsistent. These profiles often include end-of-life benefits without verifying their applicability to specific projects, leading to unreliable circularity scores. To address this, the CCF uses EPDs directly, as they provide detailed and project-relevant data on key circular indicators such as recycled content, bio-based materials, reuse potential, and disassembly for disassembly. This approach ensures a more transparent and accurate assessment of circular performance in the early design phase.

Finally, the expert panel provided a valuable validation step and directly informed the refinement of the CCF. The feedback confirmed that the CCF addresses a clear gap in early-stage design processes and supports the decision-making logic of various expert roles. At the same time, several limitations were identified. The Excel-based interface was seen as too complex for first-time users, and the definitions of circularity indicators required further clarification. Additionally, the current cost outputs were considered too limited, as they do not yet capture labor, construction logistics, or time-related implications. Despite these limitations, the experts agreed on the framework's value in facilitating structured, data-informed discussions across disciplines. The panel helped strengthen the framework's practical relevance and confirmed its potential as a strategic decision-support tool in integrated design settings.

Research sub-question 4

Question: How can the Circular-Carbon Framework be applied to support design teams in selecting circular strategies that aim for Paris Proof building performance while maintaining financial feasibility?

Goal: Demonstrate and evaluate the applicability of the CCF in a real-world project context to assess how it supports integrated decision-making on carbon, cost and circularity.

To determine whether the CCF is applicable in real-world design contexts and can meaningfully support circular decision-making aimed at UEC, a case study was conducted. The selected case is EDGE Coolsingel, a 24,110 m² office development in central Rotterdam, currently under construction and scheduled for delivery in 2026. The project was selected for its strong Paris Proof ambition, demonstrated through its hybrid timber-concrete structure and partial reuse of façade elements. Its well-documented design process made it suitable for evaluating the usability and relevance of the CCF.

The analysis began by verifying whether the necessary data for using the CCF were available and structured in a compatible format. Carbon, cost, and circularity data were collected and assessed through a dedicated data mapping process (Table 6.1). An interesting finding was that the Paris Proof carbon factor was not directly available. This is because Dutch environmental assessments are based on the MPG methodology, which evaluates environmental performance through the Milieukostenindicator (MKI), rather than only carbon emission values. However, due to the project's sustainability ambitions, the Paris Proof emission factors were retrieved from the environmental consultant's internal documentation.

Circularity data proved more difficult to obtain. This was expected given the previously identified misalignment between data contained in EPDs and the information used in the NMD. To resolve this, only validated internal circularity data from the environmental consultant sheets or verified supplier sources were used in the case study. In the absence of reliable data, specific indicators were excluded to preserve the validity of results.

With the data validated, four circular strategies were developed and compared to a base case. The base case represented a full-concrete structure. The four strategies included: a Hybrid structure (CLT and concrete structure, as-built scenario), a Bio-Based structure (full CLT), a Promote Recycling strategy (hybrid with maximized recycled content), and a Smart Circular strategy (hybrid with a targeted, material-based selection process). After the strategies were developed, they were uploaded into the CCF to enable structured comparison and initiate the case study.

The case study results demonstrate that the impact of circular strategies on UEC, cost, and circularity is highly dependent on how circular principles are implemented at the material level. While the full-concrete base case performed well in terms of cost, it failed significantly on carbon performance.

The Hybrid strategy established a more balanced baseline, achieving compliance with both the Paris Proof carbon budget and the cost budget, while nearing the minimum circularity requirement. The Bio-Based strategy achieved the lowest UEC and highest circularity score, but far exceeded the material cost boundary, limiting its practical feasibility.

Building on the Hybrid approach, both the Promote Recycling and Smart Circular strategies explored more targeted circular interventions. The Promote Recycling strategy focused on maximizing recycled content, which raised its circularity score to 43%, but paradoxically led to an increase in UEC and a slight cost overrun compared to the Hybrid strategy. These results reflect that high recycled content can sometimes increase environmental impact due to reprocessing energy and logistics. This phenomenon was previously raised in interviews and is now quantitatively confirmed through the CCF results.

In contrast, the Smart Circular strategy applied a more selective and context-sensitive substitution approach. It improved circularity beyond the Hybrid strategy while also reducing UEC and material cost, thereby achieving the lowest carbon-efficiency ratio among the feasible options.

These dynamics reveal that the success of circular design lies not in the ambition to maximize circularity but in the ability to evaluate trade-offs across multiple performance dimensions. This requires DTs to move beyond intuition or isolated sustainability targets and instead focus on material-level decisions that influence carbon, cost, and circularity simultaneously. While circularity can serve as a valuable tool to reduce UEC while maintaining financial feasibility, this is not guaranteed. The effectiveness of circular strategies depends entirely on how they are implemented at the material level and whether they align with both carbon performance and cost constraints.

Currently, no early-phase design tool supports this level of integrated assessment. The CCF addresses this gap. It offers the first platform that enables DTs to compare and customize circular strategies based on quantifiable outcomes. By making trade-offs transparent and grounded in real data, the CCF helps teams navigate the complexity of circular design and supports better-informed, project-specific decisions.

The case study offers meaningful insight into the practical application of the CCF, but several limitations should be acknowledged. As the analysis was based on a single project, the findings are not broadly generalizable and should be interpreted within the context of the specific case. The design scenarios were simplified to allow structured comparison, requiring assumptions that may have influenced the accuracy of outcomes. In addition, discrepancies between EPD data and the NMD introduced limitations in the consistency of carbon assessments. Nonetheless, the case confirms the framework's relevance and potential in early-stage decision-making.

Main Research Question

Question: How can a framework be developed to evaluate the impact of circular construction strategies on upfront embodied carbon reduction and financial feasibility during early design phases?

Goal: To determine how circular construction strategies can be systematically assessed, compared, and applied during early-stage design to reduce UEC in alignment with Paris Proof targets, while maintaining financial feasible.

This thesis set out to investigate how a framework can be developed to evaluate the impact of circular construction strategies on UEC and material cost during the early design phases of commercial construction projects. The increasingly stringent Paris Proof carbon thresholds are pushing the construction sector to adopt more innovative approaches to carbon reduction. In response, the objective of this research was to explore how circularity could be operationalized as a strategic design tool to help align projects with these thresholds. This required the development of a framework that enhances data utilization and supports informed, collaborative decision-making among design team members.

The literature review revealed that existing academic methods and industry tools are not yet capable of meeting this goal. Challenges such as unreliable data, fragmented databases, and incompatibilities between tools, for example between the MPG method and EPD data, hinder effective assessment. These issues are particularly urgent due to stricter carbon regulations and increasing material costs, which place additional pressure on the feasibility of sustainable design ambitions.

The early design phase is especially critical, as it determines the long-term trajectory and environmental impact of a project. Yet, this phase is often characterized by a lack of reliable data. This dilemma, referred to in this thesis as the *early-decision paradox*, highlights the need for better data structuring and sharing from the start. However, the current lack of open, transparent, and user-friendly tools remains a key limitation. This research addresses that limitation by proposing a framework that enables improved data integration and collaboration within DTs, thereby supporting more strategic decision-making related to circularity.

The CCF developed in this study is grounded in both academic literature and practical insights. The Value-Driven Design method, originally developed in the aeronautical industry, was used as the foundation for structuring the framework. It provides a balance between three core variables: UEC, material cost, and circularity. Each of these dimensions was investigated in detail using both theoretical models and practical frameworks. Literature frameworks such as the R-ladder and CSF were analyzed alongside practical tools such as Madaster, BCI, and the HNN method. In addition, interviews and an expert feedback panel were conducted to deepen understanding of how these concepts can be applied effectively in a real-world context.

Several key findings emerged from this research. From a carbon perspective, approximately 75% of the UEC in commercial buildings is related to the structure and skin. As a result, the scope of the CCF was narrowed to focus specifically on these two building layers. The highest-emitting materials within these layers were identified and included in the model to enable comparison between different circular strategies. From a cost perspective, these materials were classified as capital expenditures and integrated accordingly. Although the concept of residual value is gaining attention in circular construction, both literature and industry experts indicate that it is not yet influential in investment decisions. Therefore, residual value was excluded from the CCF at this stage.

From a circularity perspective, two key concepts emerged: circular strategies and circular indicators. Circular strategies are the design decisions that DTs need to compare in order to reduce UEC. This thesis outlines what circular strategies are according to literature and provides a 'menu' of strategies that can be selected. At the same time, the framework allows DTs to incorporate their own strategies, depending on the project context.

The circular strategies in this research were selected to target both structural and skin-related changes. This reflects the dynamic nature of the model and helped identify the non-linear relationship between upfront carbon emissions, material cost and circularity.

These circular strategies are evaluated in the CCF through four circularity indicators: reuse, recycled content, bio-based material, and design-for-disassembly. The combined score of these indicators is expressed through the Circularity Index Meter (CIM). Together with total UEC and total material cost, the CIM score enables DTs to assess and compare the performance of different circular strategies in a structured and transparent way.

To validate the CCF, a case study was conducted. Its purpose was to demonstrate the functionality of the CCF and assess whether circularity can be used to reduce both embodied carbon and material cost while aligning with the Paris Proof carbon thresholds. The findings show that circular strategies can indeed support both goals, but only when applied strategically. Circularity alone does not guarantee carbon or cost savings. The effectiveness of any strategy depends on careful alignment between material selection, carbon targets, and cost constraints. This highlights the need for more detailed material analysis early in the design process and for tools that allow DTs to assess all relevant data, on carbon, cost, and circularity, collectively.

The case study showed that different strategies affect carbon and cost in different ways. For instance, while the Promote Recycling strategy increased the circularity score, it also led to higher emissions and costs. In contrast, strategies such as Hybrid and Smart Circular resulted in carbon and cost reductions. These outcomes highlight the need for a decision-support platform where such trade-offs can be evaluated transparently, instead of relying on intuition or on tools that are not designed for integrated assessment.

When placed in the context of existing literature, this thesis provides a novel contribution. While recent studies focus on the qualitative relationships between circularity and carbon reduction, this research goes further by integrating cost as a third dimension. This reflects real-world trade-offs more accurately and acknowledges the specific, project-based nature of building design. Furthermore, this thesis is among the first to quantify the relationships between circularity, carbon, and cost in a unified framework.

For circularity to be used effectively as a tool for reducing UEC and cost, several enabling conditions must be addressed. From a regulatory perspective, inconsistencies between the MPG method, its underlying NMD database, and wider EPD sources must be resolved to create more objective and consistent environmental assessments. From the perspective of material suppliers, earlier involvement in the design process is essential. Their expertise could significantly influence sustainable outcomes, but engagement is often delayed due to fears of financial lock-in. Overcoming this is crucial.

From the DT perspective, the research revealed that circularity is frequently poorly defined and overshadowed by carbon and cost concerns. This lack of clarity leads to missed opportunities, particularly when circular ambitions are not backed by measurable performance data. A shared understanding of circularity across disciplines is necessary. Increasing design flexibility, for example by introducing a VO+ phase, could provide the space needed to integrate circular strategies effectively. Additionally, a dedicated decision-support tool is needed to align DT members, facilitate open discussions, and ensure transparent strategy selection. The CCF was developed to address precisely this gap. Moreover, the findings indicate that although material reuse is one of the most impactful strategies, it is rarely implemented due to regulatory, technical, and supply chain barriers that must be addressed.

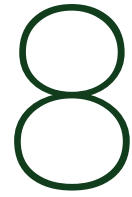
Expert panel feedback confirmed the relevance and potential of the CCF but also noted that its usability and technical setup require further development before it can be applied at scale in industry practice.

In conclusion, this thesis presents a structured and transparent methodology, the CCF, that supports early-stage design decisions in which carbon, cost, and circularity must be balanced. The framework enables DTs to assess circular strategies based on quantifiable outcomes, making it easier to identify solutions that are both sustainable and financially feasible. Whereas most research and tools address these variables in isolation or in pairs, this research treats them as an interconnected system. It also

challenges the assumption that circularity automatically leads to carbon reduction, showing instead that strategic application is required.

To achieve the national circularity target of 50% by 2030, it is essential that carbon, cost, and circularity are evaluated together. If even one of these elements is misaligned, overall project feasibility may be at risk. However, as shown in this research, when aligned properly, they can reinforce each other and lead to better outcomes.

As Paris Proof targets become increasingly demanding, circularity must evolve from an abstract design philosophy into a measurable and operational tool. What has been lacking is a way to identify which circular interventions are needed, when they should be applied, and at what cost. The CCF provides this missing link. It transforms circularity from a vague ambition into a strategic approach that enables DTs to act, adapt, and align from the earliest stages of design with both carbon and financial performance goals.



Discussion

This chapter discusses the main findings of the research by placing them in theoretical and practical context. It reflects on how the results relate to existing literature and real-world design processes. Finally, it identifies key limitations that influence how the findings should be interpreted.

Interpretation of Key Findings

Evaluating carbon, cost, and circularity in parallel has proven to be a critical lens for assessing the feasibility of contemporary construction projects. Embodied carbon (EC) is already regulated through the Dutch MPG framework, and compliance is required to obtain environmental permits. Cost, as always, is a decisive factor in project feasibility, particularly for commercial developments. Circularity, by contrast, has become a major policy goal at the European level, aiming to reduce dependency on virgin materials, cut energy use, and minimize waste. However, it has not yet been structurally integrated into national regulatory systems such as the MPG.

As the construction industry is one of the largest contributors to GHG-emissions, balancing these three performance areas is increasingly important. Yet because circularity is not mandatory, it often remains underdeveloped in project decision-making. The central hypothesis in this study was that circularity could serve as a tool to reduce upfront embodied carbon (UEC) while maintaining financial feasibility.

The findings indicate that circularity has the potential to support carbon reduction, but that this relationship is not guaranteed. The assumption that increasing circularity will automatically result in lower emissions and costs does not hold in every case. Circularity must be treated not as an abstract ambition, but as a variable with complex, context-specific impacts. Its effectiveness is largely determined by how it is implemented at the material level, meaning that individual design decisions and material compositions play a crucial role in determining outcomes.

To address this challenge, this research introduced the Circular-Carbon Framework (CCF) as a way to evaluate and balance carbon, cost and circularity during the early design phase. The framework was developed to assist design teams (DTs) in navigating trade-offs between performance goals when only limited data is available. By enabling the analysis of different circular strategies, the CCF helps clarify when and how circularity can contribute meaningfully to project feasibility and environmental performance. The framework offers a structured and transparent decision-support tool that responds to a critical gap in current design processes.

Comparison with Literature, Practice, and Policy

This research contributes to both academic literature and professional practice by addressing a critical gap in the integration of carbon, cost and circularity during early design stages. Existing literature consistently identifies the lack of structured, interoperable data as a major barrier to implementing circular principles in construction projects (Charef, 2024; Marchi et al., 2024; Santos et al., 2025; Tirado

et al., 2022). However, few studies present concrete frameworks to systematically structure and apply such data in practice. This thesis responds to that need by developing the CCF, a quantifiable and structured approach for guiding design-phase decision-making.

Literature frequently explores the potential synergies between circularity and carbon reduction but rarely offers methods to quantify this relationship at the building level (Dodoo et al., 2009; Mikulėnas & Še-duikytė, 2025; Wang et al., 2024). This gap is problematic because building projects are highly context-specific, with distinct material choices, performance requirements, and DT preferences. By integrating carbon, cost and circularity into a single model, the CCF supports comparative assessments across strategies and fills an important methodological gap. It strengthens the operational relevance of circularity theory by translating it into measurable and project-specific outcomes.

Furthermore, literature often assumes that circularity inherently leads to carbon reduction. While this relationship is supported in some cases, the findings of this research reveal that it is not always straightforward (Wang et al., 2024). In practice, increasing circularity can reduce UEC but may also introduce financial barriers. For example, the Bio-Based strategy performed well in terms of carbon and circularity but exceeded the cost threshold, making it unfeasible. This highlights the need to consider financial feasibility alongside carbon performance. The Smart Circular strategy showed that carefully aligning material-level decisions across all three performance dimensions yields more balanced and feasible outcomes. These insights extend current literature by demonstrating that the impact of circularity must be assessed critically and holistically.

From a practical perspective, the CCF offers a novel contribution to early-stage design processes. Most existing tools fail to integrate carbon, cost, and circularity or to support collaboration across the full design team. BIM is widely used for spatial coordination and 4D modeling, while tools like Madaster and the Building Circularity Index (BCI) are generally applied post-design and do not influence early material selection. Some tools, such as LEVS' Carbon Tracker, offer carbon assessments during design phases, but these are often managed by a single actor, such as the architect, and do not promote multi-disciplinary engagement.

The interviews conducted for this research confirmed these shortcomings. DT members expressed a clear need for tools that are shared, open-source, and user-friendly across disciplines. They also emphasized the importance of having clearly defined key performance indicators that assess all three dimensions simultaneously. The CCF directly addresses these needs by offering a structured, collaborative platform that facilitates the evaluation of circular strategies during the earliest design phases.

This research also highlights the importance of more active and collaborative roles within DTs. The early-decision paradox, in which the most impactful decisions are made at a stage where the least data is available, remains a significant challenge. As the Paris Proof requirements become stricter, DTs must better utilize the expertise and data available across disciplines. Shared metrics, such as those provided by the CCF, can enable earlier and more informed discussions around material selection and sustainability goals. By aligning performance goals at the material level, the CCF fosters deeper collaboration and aims to improve project outcomes.

Finally, this research offers critical insight into regulatory gaps. The Dutch MPG assessment method currently limits a big part of circularity data from its evaluation criteria. This omission prevents the integration of valuable circularity data already present in Environmental Product Declarations (EPDs), leading to a loss of information between material producers and regulatory frameworks. As a result, DTs are unable to objectively reflect circular performance in their MPG scores, which may hinder the adoption of more circular strategies.

This regulatory misalignment sits at the intersection of literature and practice. While academic work emphasize the importance of circular indicators, policy frameworks have not yet adapted (Benachio et al., 2020; Çetin et al., 2021; Eberhardt et al., 2022; Kanters, 2020). There is a need for policymakers to establish methodologies that incorporate circularity into national assessment schemes such as the MPG. The CCF contributes to this objective by proposing a standardized method for quantifying circularity through the Circularity Index Meter (CIM). The indicators selected for the CIM were based

on literature relevance, their presence in EPDs, and their practical feasibility for data collection and analysis. The CIM operationalizes circularity in a way that is measurable and consistent.

Limitations

Methodological limitations

Several methodological limitations were previously identified in the research design, including challenges related to literature access, interview subjectivity, expert panel dynamics, and case study generalizability. These limitations not only shaped the setup of the study but also became apparent during its execution and analysis.

The literature review was instrumental in identifying theoretical gaps and setting the foundation of the CCF, but its effectiveness was constrained by limited access to peer-reviewed databases. As a result, some relevant international publications may have been overlooked, which could have enriched the theoretical foundation. Additionally, the selection of reviewed studies may have introduced bias, particularly where publication trends favored positive results, especially in terms of gaining attention for circularity research.

The semi-structured interviews provided valuable practical insights. They focused on understanding the dynamics within DTs as well as the requirements they expected from the CCF. Yet their interpretive nature introduced a level of subjectivity. Interviewees may have presented filtered views based on personal or organizational perspectives. Despite efforts to triangulate responses across disciplines, the findings were inevitably shaped by what was prioritized during the sessions. Also, since I interviewed front-runner companies, there may be a bias toward overstating the ambitions in circularity.

The expert panel played a crucial role in validating the CCF, but the limited number of participants affects its generalizability. While the expert feedback led to important clarifications and refinements, the composition of the panel, though diverse, may not fully represent the breadth of viewpoints across the construction industry.

Finally, the use of a single case study limited the external validity of the findings. Although the case was carefully selected for its relevance and transparency, conclusions drawn from one project cannot be directly generalized to the wider construction sector, especially not to other types of real estate. Material compositions and regulations differ per building type. Nevertheless, the case offered strong practical grounding and confirmed the operational feasibility of the CCF within a real-world design context.

Model Limitations

From a modeling perspective, the CCF represents a necessary simplification of the complex realities found in construction practice. A key limitation lies in the availability and consistency of data across the three core variables. While relatively robust datasets exist for UEC and material cost, reliable and standardized circularity data remains underdeveloped. Although EPDs provide a useful starting point, they are not always available. Some manufacturers choose not to publish EPDs if performance is poor, or they may lack the resources to produce them at all. This limits transparency and reduces the quality of circularity assessments within the framework.

Another important constraint relates to the quantification of circularity itself. The CIM translates circular indicators into numerical values. However, some circular strategies are inherently qualitative and cannot be easily measured. As a result, the CCF captures only a portion of a design's true circular potential.

The cost component of the model is also sensitive to market volatility. Construction material prices have shown unpredictable fluctuations, especially due to recent geopolitical developments. Because design phases can span several months or even years, early-stage cost estimates may quickly become outdated. Although the model uses best-available data at the time of analysis, its financial outputs are not guaranteed to remain accurate under rapidly changing conditions.

A further limitation arises from the way in which circular strategies were modeled. To enable clear and structured comparison between scenarios, simplified representations such as hybrid, full concrete,

and fully bio-based were used. These scenarios were developed with support from expert input, but they inevitably required assumptions about materials, quantities, and construction methods. These assumptions may have influenced the comparative outcomes.

Finally, there were inconsistencies in the data sources used across the different modules of the model. While the project-specific material data was obtained through the NMD, the base model relied on EPDs. This was due to restricted access to the NMD during earlier development stages. The use of different data sources may have introduced small inconsistencies in UEC calculations across the circular strategies.

Despite these limitations, the CCF has shown that it is both practical and insightful in supporting early-phase decision-making. These findings reinforce the need for continued development of integrated tools, improved data accessibility, and better alignment between circularity, cost, and carbon assessment practices.

Practical Implications

The results show that the CCF can support DTs in early-phase decision-making by enabling quantitative evaluation of circular strategies based on carbon, cost, and circularity. While the project developer and owner benefit from better project outcomes, consultants should also use the tool to provide added value. Cost consultants, together with environmental and circularity advisors, can jointly assess both carbon and material budgets. This enhances collaboration and contributes to project feasibility now and in the future.

The framework enables trade-offs between carbon, cost, and circularity and addresses a clear gap in existing tools. Although it has only been tested on a single case, its generic structure makes it applicable to other commercial real estate developments, with material compositions adjustable to suit different building types. Expert panel feedback further suggested incorporating BIM or AI functionality into the system, enabling the simulation of multiple strategies and producing a more complete material composition.

However, broader adoption is not yet feasible. The model still requires alignment between EPD and NMD data, expansion of material options, and validation through additional cases. Despite these limitations, the model shows clear potential and provides a solid foundation for future use.

Recommendation

This chapter contains recommendations for further research, as well as for the practical implementation and advancements.

Scientific Recommendations

1. **Advance circularity quantification methods.**

Future research should focus on developing robust methods to quantify circularity indicators. Although various circular frameworks are available in literature, substantial challenges remain in translating these into measurable and standardized formats. It is the responsibility of the science to formalize such indicators into applicable frameworks, which may serve as the basis for future policy integration. Reliable quantification is essential for enabling data-driven decision-making in early-stage design processes.

2. **Expand empirical testing across diverse building types.**

The current study applied the Circular-Carbon Framework (CCF) to a single commercial office development. To improve the generalizability of the model, future research should test the CCF across a broader range of real estate typologies, including residential, public, and educational buildings. Applying the model in varied contexts would allow for a more comprehensive evaluation of how circular strategies influence UEC. This may help identify material-specific interventions that consistently support both environmental and financial performance goals.

Practical Recommendations

1. **Test the CCF in integrated design workflows.**

Project developers aiming to enhance environmental performance through circular strategies are encouraged to pilot the CCF within actual design workflows. Integrating the CCF during early-phase design allows design teams (DTs) to assess its practical usability and gain familiarity with evaluating trade-offs between carbon, cost, and circularity. Such testing will not only support learning within DTs but also contribute to iterative improvements of the framework itself.

2. **Strengthen cross-disciplinary collaboration.**

Regardless of the specific tool employed, DTs should intensify collaboration across disciplines, particularly at the material level, if future buildings are to meet increasingly stringent Paris Proof requirements. Using a shared platform such as the CCF can facilitate this process by providing a common reference point and structured indicators to guide decision-making. Early-phase cooperation between architects, cost consultants, and sustainability advisors is essential for ensuring feasible outcomes.

Policy Recommendations

1. **Integrate circularity into environmental assessment frameworks.**

To realistically achieve the national goals of 50% circularity by 2030 and full circularity by 2050, existing policy instruments such as the MPG must be revised. Circularity indicators should be incorporated into the MPG framework through both quantitative and qualitative metrics. Otherwise an alternative regulation could be developed alongside MPG and BENG, specifically focused on circularity. Without such integration, current policies risk falling short of their stated targets because they can't measure them.

2. **Align national databases with environmental declarations.**

Currently, EPDs contain valuable circularity data, but some of this information is not utilized in MPG assessments due to structural limitations in the NMD. This misalignment results in the exclusion of relevant data, reducing the accuracy and transparency of environmental assessments. Policy efforts should focus on aligning the NMD with EPD content to ensure a more complete and consistent evaluation of material performance and to support effective progress toward circularity goals.

10

Reflection

Introduction

Understanding the positioning of this thesis is essential before evaluating the research process and its personal impact. This study aims to explore how circularity can be used as a tool to reduce upfront embodied carbon in buildings, while simultaneously maintaining financial feasibility. As such, the topic is inherently embedded in the ongoing sustainability transition in the construction industry, a development that has gained momentum over the past decade and continues to evolve through various initiatives aiming to reform construction practices.

My academic journey has significantly influenced the way this thesis was approached. During my bachelor's degree in Systems Engineering, Policy Analysis and Management, I was trained to tackle complex societal challenges through a technical and systemic lens. Central to this approach is the use of technology not as an end, but as a means to serve broader community needs, ensuring practical applicability and responsible implementation.

The transition into my master's program in Construction Management and Engineering allowed me to focus this systems perspective on a more specific domain: the construction sector. The curriculum, rooted in legal and financial classes, collaborative design, and project management optimization, provided exactly the foundation necessary to undertake a thesis like this. The alignment between the program's core learning objectives and this thesis topic was both natural and strategic.

This thesis, therefore, reflects a convergence of my academic background: it leverages technical tools to enhance the design process while addressing real-world constraints, such as policy boundaries and cost limitations. The initial chapters focused on understanding the context: defining key concepts, identifying system boundaries, and clarifying the constraints within which circular strategies must operate. This foundation enabled the development of the Circular-Carbon Framework (CCF), which was then tested through a case study to explore its applicability in early-stage design decisions.

In conducting this research, I fully applied the skills, tools, and methodologies developed throughout my studies. The work contributes to addressing pressing challenges in the built environment: enabling more sustainable design decisions, improving environmental performance, and facilitating more data-informed implementation of circularity in construction.

From a personal standpoint, this thesis represents the integration of my academic interests, accumulated knowledge, and long-term motivation to contribute to a more sustainable society. It marks the pinnacle of years of education, and illustrates how a carefully designed engineering approach can provide tangible solutions to complex environmental problems.

Research Method

This thesis employed a mixed-methods approach combining qualitative and quantitative techniques to develop and evaluate the CCF. In reflection, the use of complementary methods proved essential for addressing the complexity of the research question, which required balancing UEC, material cost, and circularity during early design phases.

The literature study served as the theoretical foundation, shaping both the conceptual model and the framework's performance indicators. Although the study followed a systematic approach, its scope was limited by restricted access to peer-reviewed sources and a selective focus on materials with clear circular and low-carbon potential. This constrained the diversity of materials represented in the model and may limit generalizability across different building types.

Semi-structured interviews with design team (DT) members and material suppliers provided valuable practical insights that directly informed the development of the framework. However, most participants were affiliated with companies already engaged in sustainability leadership. This may have introduced a bias toward optimistic assessments of circular strategies and their feasibility in real-world projects.

The expert panel validation improved the model's usability and interpretability, though the limited number of participants and the absence of key roles such as cost advisors restricted the breadth of validation. Similarly, the case study demonstrated the framework's operational potential, but its single-project scope means findings cannot be generalized without further empirical testing.

Overall, the chosen methods aligned well with the research aim. However, future work would benefit from more diverse stakeholder inclusion, broader material coverage, and multi-case validation to improve robustness and applicability.

Research Process

The journey of writing this master thesis often felt like a rollercoaster, a continuous cycle of highs and lows with no option to step off. Despite the pressure, I genuinely found joy and fulfillment in the process. Much of this came from knowing the research addressed a real-world problem. To my knowledge, no existing tool or model currently analyzes carbon, cost, and circularity in the integrated way that my framework does.

Throughout the research period, the encouragement I received from interview participants, both during the exploratory and writing phase, was a major source of motivation. Their interest and engagement gave me confidence that my work was not only relevant in science but also contributed to practical knowledge gaps and the broader goal of a more sustainable built environment. Since I aim to become a project developer, the topic also allowed me to gain expertise in an increasingly important area of development practice. As a result, the thesis became both an academic journey and a personal investment.

At the same time, the process was demanding and at times stressful. When working on the research proposal, I already had a clear idea of what I wanted to investigate. I had been speaking with DT members to discuss the concept and define a research gap. I was highly motivated by the novelty of the topic and its potential impact. However, once the proposal was approved and the balance between scientific rigor and practical relevance was set, the real challenge began: writing the actual content.

Soon after starting the project in March, I began to worry about whether I would be able to access the necessary amount and quality of data. At the same time, the contextual understanding required for the thesis started to feel overwhelming. Theoretical frameworks, policy regulations, material performance, cost structures, carbon accounting, circularity strategies, and model design each demanded a certain level of background knowledge. I found it difficult to determine what needed to be included or excluded, and how to present the content with just the right level of detail. My supervision team guided me through this phase with critical insights and constructive feedback, which was incredibly valuable.

The mid-term review at the end of June marked a pivotal moment. Feedback from the research committee was collected and shared with me. Although I was proud of what I had accomplished by then, I

received extensive comments on the early chapters. I was eager to begin building the computational model for the framework, but it became clear that the written content needed to be revised first. This meant adding context, improving visuals, and restructuring the chapters. In my view, this required rewriting almost everything. While that was disappointing at first, the process significantly improved the quality of the thesis. After spending two full weeks on revisions and falling behind schedule, I finally began to see the structure and direction of the thesis take form.

Once the revisions were completed, I resumed developing the computational model. I quickly encountered challenges in gathering and integrating data on carbon, cost, and circularity into a generic model. Eventually, I made the decision to simplify the model and shift the focus toward the dynamics of the outcomes. This strategic choice helped me regain momentum. Soon after, I faced a new obstacle: processing the case study data within the model. This stage became highly iterative and at times felt never-ending. However, once the model was finalized and the results were generated, I finally saw a clear path to completion.

I consider myself fortunate to have had a strong supervision team at TU Delft. The combination of academic expertise and practical insight, along with a genuine commitment to support me, was crucial throughout the process. During our progress meetings and through regular updates, I always received the guidance I needed to keep moving forward.

The support I received from EDGE was also instrumental. My colleagues were eager to contribute and offered thoughtful perspectives throughout the process. During the case study phase in particular, I relied heavily on their input regarding project information, contacts within the DT, and practical knowledge about real-world decision-making. My company supervisor, as executive director of the development team, played a central role in facilitating this. His familiarity with my academic supervisors, and their familiarity with him, created a very collaborative and comfortable atmosphere during the meetings with the research committee, which I appreciated greatly.

Personal Learning

Writing this thesis has been the most valuable learning experiences of my academic journey. Taking full responsibility for the project's direction, without fixed deadlines or predefined tasks, challenged me to stay focused and motivated. There were moments of doubt when progress stalled, but also a strong sense of achievement when things came together. Along the way, I developed a broad set of skills: applying research methods, analyzing literature, building a model, and working closely with experts and stakeholders. The thesis required both critical thinking and practical coordination, and taught me to work independently and adapt to uncertainty, something I had not experienced in the same way during my bachelor and master studies.

I am grateful for the lessons I have learned during this journey. In many ways, it shaped me academically and personally. I would like to sincerely thank everyone who supported me throughout the process. One of the most valuable insights I gained is that even when you give your full effort, outcomes do not always follow expectations. You must remain adaptable, resilient, and open to change at all times. These lessons are not only embedded in the pages of this thesis but will stay with me for life.

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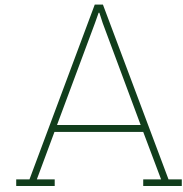
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Glossary

Table A.1: Glossary of abbreviations used throughout the thesis (Alphabetical order)

Abbr.	Term	Explanation	Source
BCI	Building Circularity Index	A metric that quantifies circularity performance across material, product, system, and building levels by integrating disassembly potential and various circularity indicators into a single composite score.	(van der Zwaag et al., 2023)
BENG	Bijna Energie Neutraal	Dutch standard for Nearly Energy Neutral Buildings, requiring low energy demand, renewable energy use, and limited fossil energy consumption in accordance with EU directives.	(Rijksdienst voor On- dernemend Nederland, 2017)
BIM	Building Information Modeling	Integrated software for generating and managing project data within a three-dimensional digital environment.	(Autodesk, 2024)
CC	Circular Construction	Construction approach aimed at minimizing resource use, waste, and environmental impact by prioritizing reuse, recycling, adaptability, and material longevity across a building's life cycle.	(Potting et al., 2017)
CCF	Circular-Carbon Framework	A design-phase decision-support tool that helps design team members transparently evaluate and discuss material choices by linking circular construction strategies to reductions in UEC, while simultaneously tracking their financial implications. The framework enables informed, balanced decisions that align environmental and budgetary objectives during early design stages.	N/A
CE	Circular Economy	"The circular economy is a regenerative economic system which necessitates a paradigm shift to re-place the 'end of life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities".	(Kirchherr et al., 2017)

Abbr.	Term	Explanation	Source
CIM	Circular Index Meter	A scoring tool within the CCF that evaluates the circular potential of selected strategies in relation to UEC, offering a structured and comparable index to inform material selection decisions.	N/A
CLT	Cross-Laminated Timber	Engineered wood product consisting of multiple layers of timber boards arranged crosswise and bonded with structural adhesives, resulting in a highly stable panel suitable for walls, floors, and roofs.	N/A
DT	Design Team	A multidisciplinary group responsible for the design of a construction project.	N/A
EC	Embodied Carbon	All carbon emissions from life cycle stages A1–A5 + B1–B5 + C1–C4 (excluding operational and energy-related emissions).	EN 15978:2011
EoL	End of Life	Refers to the stage when a structure or its components are deconstructed or demolished, after which materials may be reused, recycled, recovered, or disposed of.	N/A
EPD	Environmental Product Declaration	A document that provides quantified information on the environmental impact associated with a specific building material throughout its life cycle.	N/A
GFA	Gross Floor Area	Total floor area inside the building envelope.	(IPCC, 2025)
GHG	Greenhouse Gas	Gases that trap heat in the atmosphere, contributing to climate change.	
GLT	Glue-Laminated Timber	Engineered wood product made by bonding multiple layers of timber boards with structural adhesives to create strong, dimensionally stable load-bearing elements.	N/A
HNN	Het Nieuwe Normaal	Practical framework that defines and measures circular construction through clear indicators across three themes: environmental impact, material use, and value retention.	(HNN, 2025)
LVL	Laminated Veneer Lumber	Engineered wood product made by bonding thin wood veneers in a parallel orientation to form a high-strength, dimensionally stable material commonly used for beams, headers, and structural framing.	N/A
NMD	Nationale Milieu Database	Central database containing environmental profiles of construction materials, products, and installations used in the Netherlands.	N/A
NZCB	Net-Zero Carbon Buildings	A building or asset that first minimises energy demand through energy efficiency measures, meets the remaining energy needs using on-site and/or off-site renewable energy sources, and offsets any residual emissions arising from embodied carbon and operational fossil fuel use.	(WGBC, n.d.)
OC	Operational Carbon	All carbon emissions from stage B6-B7 (building use phase: energy for heating, cooling, lighting, water etc.).	EN 15978:2011
PoR	Program of Requirements	A formal document that translates stakeholder needs into concrete design and performance criteria.	N/A
UEC	Upfront Embodied Carbon	All carbon emissions through project stages A1–A5 (product and construction stages).	EN 15978:2011
WWR	Window-to-Wall Ratio	Ratio of window area to total exterior wall area.	(Troup et al., 2019)



Informed Consent

Delft University of Technology

Human Research Ethics
Informed Consent

Research Period: March - September

Research Team:

Principal Researcher:

Ezra (S.) de Jong

Supervisors:

Dr. ir. E. (Erwin) Heurkens

Dr. ir. R. (Ruben) Vrijhoef

Dr. ir. S. (Sultan) Çetin

Research Objective:

The objective of this research is to develop a dashboard that enables the tracking and evaluation of CO₂ emissions across the early design phases of construction projects, specifically the Sketch Design (SO), Preliminary Design (VO), and Final Design stages (DO). The tool aims to establish a CO₂ baseline per phase and assess both the environmental (CO₂) and financial impacts of applying various circular strategies. This will be achieved through a literature review and expert interviews.

Opening Statement

You are being invited to participate in a research study titled *From Data to Paris Proof*. This study is being done by E.S. (Ezra) de Jong from the TU Delft and Edge Technologies.

The purpose of this research study is to develop a dashboard that tracks circular strategies and their impact on CO₂ emissions and the corresponding building cost. It will take you approximately [X] minutes to complete. The data will be used for understanding circular strategies and their impact, answering the research question from a professional perspective, and publishing findings in an anonymized format. I will be asking you to discuss circular strategy implementations and their impact on CO₂ emissions, as well as your understanding and experience with certain platforms used for sustainability assessment.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by storing all data on secured servers, deleting all personal data after the research is completed, and ensuring that no information traceable to interviewees will be published. Any critical information that needs to be included will be fully anonymized.

Your participation in this study is entirely voluntary, and you can withdraw at any time. You are free to omit any questions. If you choose to withdraw, any collected data can be removed upon request, provided this request is made before data analysis begins. Once the data has been anonymized and integrated into the research findings, removal may also be possible after consulting.

Options	YES	NO
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A: General Agreement – Research Goals, Participant Tasks and Voluntary Participation

1. I have read and understood the study information dated [DD/MM/YYYY], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: - Interviews will be either audio-recorded or video-recorded, depending on whether they are conducted online or in person. - The recordings will be transcribed and summarized for analysis. The content will be used anonymously in the thesis, with no reference to personal names or identifiable details. - All audio and video recordings will be permanently deleted upon completion of the research project.	☐	☐
4. I understand that the study will end either when the interviewer indicates that the interview is complete or earlier if I choose to stop at any time.	☐	☐

B: Potential Risks of Participating (Including Data Protection)

5. I understand that taking part in the study involves the following risks a potential feeling of discomfort when answering certain questions, or a sense of obligation to participate due to the researcher's academic position. I understand that these will be mitigated by my right to decline any question, stop the interview at any time without consequences, and the assurance that participation is entirely voluntary and confidential.	☐	☐
6. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [such as name, role, and professional background] and associated personally identifiable research data (PIRD) such as specific project experiences or opinions that may be linked to my professional identity with the potential risk of my identity being revealed through indirect identification based on unique roles or affiliations within the construction sector	☐	☐
7. I understand that none of this PIRD is considered as sensitive data within GDPR legislation	☐	☐
8. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach All interviews will be transcribed and anonymized, with any identifying details removed or pseudonymized. Audio or video recordings will be securely stored on TU Delft-approved storage systems with restricted access and will be permanently deleted after transcription. Only the researcher and academic supervisor will have access to the data. Any quotations used in the thesis will be anonymized to prevent traceability	☐	☐
9. I understand that personal information collected about me that can identify me, such as name, company and function, will not be shared beyond the study team	☐	☐
10. I understand that the (identifiable) personal data I provide will be destroyed at the end of the research period	☐	☐

C: Research Publication, Dissemination and Application

11. I understand that after the research study the de-identified information I provide will be used for the purpose of completing a master's thesis, which will be published in the TU Delft repository. The results may also be used in academic reports or publications related to CO ₂ tracking and circular strategies in construction projects. All shared data will be fully anonymized, and no recognizable images, names, or direct quotations that could reveal my identity will be included without explicit prior consent. No secondary use beyond academic dissemination is currently planned.	☐	☐
12. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐

D: (Longterm) Data Storage, Access and Reuse

13. I give permission for the de-identified until the research period that I provide to be archived in the TU Delft repository so it can be used for future research and learning.	☐	☐
14. I understand that access to this repository is open, meaning the final thesis will be publicly accessible. However, the underlying data will not be deposited in the repository. Only fully anonymised summaries or findings may be included in the thesis text itself.	☐	☐

Signatures

I, as researcher, have accurately read the information sheet to the participant and, to the best of my ability, ensured that they understand to what they are freely consenting.

Researcher	Participant
Name: Ezra (S.) de Jong	Name:
Signature:	Signature:



Interview Summaries

Table C.1: Overview of all conducted interviews material related (Alphabetical order)

No.	Organization	Role	Date
1	Concrete Manufacturer	Technical Manager	May 8, 2025
2	Glass Manufacturer	Project Manager	April 24, 2025
3	Steel and Aluminum Distributor	Data-analyst	April 29, 2025
4	Steel Manufacturer	Managing Director	May 16, 2025

Table C.2: Overview of all conducted interviews design team related (Alphabetical order)

No.	Organization	Role	Date
5	Architect 1	Partner Architect	May 19, 2025
6	Architect 2	Partner Architect	May 21, 2025
7	Circular Advisor	Managing Director	May 19, 2025
8	Cost Advisor	Cost Advisor	May 22, 2025
9	Environmental Advisor 1	Senior Advisor	May 12, 2025
10	Environmental Advisor 2	A: Sustainability Advisor B: Partner	May 15, 2025
11	Project Developer 1	Development Manager	May 20, 2025
12	Project Developer 2	Partner	May 20, 2025
13	Structural Engineer	Managing Director and Engineer	May 16, 2025

Material Related Interviews

1. Concrete Manufacturer

Company:	Concrete Manufacturer
Interviewee Function:	Technical Manager
Date:	May 8 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To explore the role of concrete in structural design with a specific focus on circularity, embodied carbon and cost.

Summary

Interview Context

The interviewee is the technical-commercial manager of a Dutch ready-mix concrete supplier with eight batching plants. The company delivers concrete to both real estate and infrastructural projects and is actively engaged in strategies to EC and enhance circularity in its product offerings.

Main Themes and Insights:

The company has developed a structured sustainability framework, focusing on five pillars: binder composition, raw materials, logistics, production efficiency, and innovation. The key strategy for EC reduction lies in minimizing clinker content, the main CO₂ emitter in cement, by substituting it with ground granulated blast furnace slag (GGBS). Dutch practice favors CEM III/B cement, which contains 70–75% GGBS, contrasting with global reliance on CEM I (pure Portland cement). This results in a substantially lower EC profile for Dutch concrete mixes.

Concrete mix design is highly case-specific and project-dependent. Common strength classes such as C30/37 and C35/45 dominate the Dutch market, while higher classes like C45/55 are reserved for foundations or aggressive environments. These strength classes are combined with various exposure classes (milieuklassen) tailored to environmental conditions. Despite the high variability, the interviewee advised design teams to maintain simplicity by focusing on a core set of typical mixes with clear EC benchmarks, rather than overcomplicating specifications.

In terms of circularity, approximately 30–40% of natural aggregates in their mixes are replaced with certified recycled concrete granulate (RCG), sourced through strategic partnerships with demolition contractors. Though full recycling of concrete binder is not yet applied, the use of RCG significantly contributes to circular material flows.

The company is also piloting the use of geopolymers concrete at one of their plants, with the first tests scheduled for summer 2025. These binders eliminate clinker entirely, replacing it with alkali-activated materials such as sodium silicate and sodium hydroxide. While promising in terms of EC performance, geopolymer mixes are currently around twice as expensive as standard concrete (€250–260/m³ versus €120–160/m³), and require extensive safety and process modifications, limiting scalability. They are mainly applied in public-sector projects where sustainability targets outweigh cost constraints.

An important insight concerns the under utilization of supplier expertise in early project phases. In roughly 90% of cases, the company is only contacted after concrete specifications are finalized in the tender. The interviewee emphasized that earlier engagement, during the sketch design or preliminary design phase, could enable more sustainable design choices, including delayed-strength formulations. Designing for strength at 56 or 92 days, instead of the conventional 28 days, permits reductions in cement content and cost, without sacrificing performance. These strategies are feasible under Dutch regulations but rarely adopted due to inertia, scheduling concerns, or rigid design workflows.

Challenges and Contradictions:

- Geopolymer concrete is ecologically beneficial but economically and operationally viable only for niche applications.
- Late-stage engagement limits the potential for mix optimization and EC reduction.
- Although delayed-strength concrete reduces EC and cost, it is often dismissed due to perceived schedule impacts or lack of design flexibility.

Relevance to Research:

This interview supports the thesis focus on the importance of early-stage decision-making for EC and circularity. It reveals how tailored binder selection, aggregate substitution, and performance planning can yield substantial EC reductions, while also identifying systemic and procedural barriers in current design practice. It underscores the supplier's role as a strategic partner in carbon-sensitive design processes.

Key Takeaways

- Dutch concrete commonly uses strength classes C30/37 and C35/45, with design choices driven by exposure class and structural needs.
- The Netherlands reduces EC through widespread use of GGBS-rich CEM III/B cement instead of traditional Portland cement.
- Concrete mix design is highly specific but should remain simple at the design stage to avoid unnecessary complexity.
- Early supplier involvement and use of delayed-strength mixes offer significant opportunities for EC reduction and cost savings.

2. Glass Manufacturer

Company: Glass Manufacturer
Interviewee Function: Project Manager
Date: April 24 2025
Format: Online interview conducted via Microsoft Teams
Duration: +/- 30 minutes

Goal

To explore the role of glass in façade design with a specific focus on circularity, EC and cost.

Summary

Interview Context

The interviewee is a professional specializing in the technical and operational aspects of commercial glazing systems, particularly for large-scale projects in London. He represents a major flat glass manufacturer involved in both primary production and circular strategies for end-of-life (EoL) glass recovery.

Main Themes and Insights:

The interview centered on circularity, EC, and financial considerations within the commercial glazing sector. The company has implemented an expansive program for recovering EoL commercial glass, having completed approximately 50 projects and assessed over 180 sites in London. While circular recovery efforts for domestic glazing are progressing well, commercial glass presents complex challenges due to technical, logistical, and economic factors.

Circular strategies are tailored to three waste streams: internal production waste, pre-consumer waste from customers, and post-consumer waste split between domestic and commercial. Internally recycled and pre-consumer glass is effectively reintegrated, while commercial post-consumer recovery remains constrained by system design, deterioration (especially of seals), and lack of standards for reused glass.

The company's circular approach is founded on four principles: recycling over reuse, scalability, simplicity, and cost-time balance. Reuse of façade glass is largely impractical under current conditions due to design limitations, seal degradation, and regulatory constraints (e.g., lack of CE marking for reused panels). Instead, the focus is on scalable recycling initiatives and incentivizing clients to return large volumes of glass for reuse in new production.

Regarding EC, the company participates in the Carbon Disclosure Project and provides Environmental Product Declarations (EPDs) that quantify EC based on recycled content. Their low-carbon glass product contains up to 64% recycled (mainly pre-consumer) content. Despite a typical cost premium of 15–20%, the company offers this product at near-standard prices when clients commit to returning old glass, promoting circular flows.

The trade-off between EC and operational carbon in façade design was also examined. The interviewee expressed a preference for prioritizing EC reduction, citing rapid decarbonization of energy grids and the urgent need to reduce material throughput as emphasized by the Ellen MacArthur Foundation. High EC systems like double-skin façades, often justified by operational efficiency, are viewed critically.

Innovations identified as promising include the development of longer-lasting sealants for insulating glass units, which would extend product lifespan and improve circular potential. However, market pressures such as the aesthetic obsolescence of façades often lead to premature replacements, undermining circular objectives.

Challenges and Contradictions:

- Design for disassembly is widely promoted in literature but deemed irrelevant for current buildings due to retroactive alterations and site complexities.
- Market behavior (e.g., façade replacement to avoid stranded assets) often conflicts with sustainability goals.
- Reuse is technically and logistically infeasible for commercial façades, despite theoretical circularity benefits.

Relevance to Research:

This interview provides critical insights into the real-world limitations of circular façade systems, especially regarding reuse feasibility and EC implications. It reinforces the need for scalable, economically viable recycling strategies and offers tangible metrics (e.g., recycled content, cost differentials, EPDs) relevant to evaluating circular

strategies in the design phase.

Key Takeaways

- Reuse of commercial façade glass is not currently viable; recycling is the primary circular strategy.
- High recycled content can significantly reduce EC but may entail cost premiums unless incentivized.
- Practical barriers such as seal degradation and economic drivers (e.g., façade renewal for rent optimization) impede long-term circularity.

3. Steel and Aluminum Distributor

Company:	Steel and Aluminum Distributor
Interviewee Function:	CO ₂ Data-analyst
Date:	April 29 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To explore the role of steel and aluminum in structural design with a specific focus on circularity, EC and cost.

Summary

Interview Context

The interviewee is a business development specialist at a major metal distribution company operating across the Netherlands, Belgium, Germany, Luxembourg, and Northern France. The company supplies a wide range of structural and façade-grade metals and has implemented internal systems to track product carbon footprints (PCFs) using EPDs, supplier data, and in-house processing and transport emissions. The interview focused on supply-side circularity, EC quantification, and financial trade-offs associated with low-carbon procurement.

Main Themes and Insights:

The interview covered circularity in procurement and internal operations, the variability of EC across suppliers, and the economic implications of sourcing low-carbon metals. The company calculates emission which factors varied significantly, from 0.52 to 3.6 tCO₂/t steel, depending on production methods and recycled content.

Recycling is the main circular strategy; the company does not directly handle reclaimed construction materials. However, closed-loop practices are applied internally, such as compressing aluminum scrap from production into recyclable blocks. Direct reuse is uncommon in the construction sector and mostly limited to niche applications.

Low-carbon metals generally incur a 10–20% cost premium. Procurement is optimized tactically to maximize CO₂ savings per euro spent. Most low-carbon steel and aluminum is sourced from European suppliers using electric arc furnaces or hydrogen steel making. Although there is increasing client demand for materials with traceable EC and recycled content—driven by sustainability regulations, there is no unified market database to compare materials by carbon impact and cost.

Challenges and Contradictions:

- Direct reuse of structural or façade-grade metals is not widely practiced due to logistical and regulatory constraints.
- There is substantial variation in EC performance across global suppliers, especially between Europe and Asia.
- Low-carbon materials are more expensive, creating trade-offs between EC reduction and budget constraints.
- The production of EPDs is costly and not standardized across all suppliers, complicating consistent data collection.
- Global steel decarbonization is uneven, limiting the wider impact of regional progress.

Relevance to Research:

This interview provides applied insights into the EC impacts and circular potential of metals used in commercial construction. It supports the development of design-phase decision tools by offering a practical understanding of procurement choices, EC tracking, and financial implications. It highlights the importance of tactical sourcing and supply chain transparency in achieving circular and carbon-efficient construction outcomes.

Key Takeaways

- Recycling is the dominant circular strategy for steel and aluminum; reuse remains rare in the construction sector.
- EC varies widely between suppliers, ranging from 0.52 to 3.6 tCO₂/t steel.
- Green steel and aluminum typically cost 10–20% more than conventional alternatives.
- EPDs are increasingly used for procurement but remain costly and inconsistently available.
- Regional sourcing from European producers generally supports lower EC profiles but may limit flexibility.

4. Steel Manufacturer

Company:	Steel Manufacturer
Interviewee Function:	Director
Date:	May 16, 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To assess the role of steel in office construction, focusing on circular strategies, EC performance, and economic implications.

Summary

Interview Context

The interviewee is the director of one of the biggest Dutch steel construction company specialized in sustainable steel solutions for the built environment. With operational oversight of multiple entities, the interviewee emphasized her company's leadership in embedding circularity within steel design and procurement strategies.

Main Themes and Insights:

The company sources 90–100% of its structural steel from European factories utilizing 100% recycled input and powered by renewable energy. This strategy minimizes EC, reducing emissions from 2.5 kg CO₂/kg for conventional virgin steel to as low as 0.3 kg CO₂/kg for low-carbon alternatives.

Key structural elements include I- and H-beams, tubes, and box profiles, typically used in high-end office developments. While lightweight plate-based components are sometimes selected for cost reasons, these generally have higher EC and limited reuse potential compared to heavier beam-based systems.

The firm actively promotes design for disassembly (DfD), supported by a proprietary demonstrator project in 2020 where all elements were mechanically joined and fully demountable. Although DfD proved cost-neutral when implemented early, its adoption remains limited by the lack of supplier involvement in early design stages. The interviewee stressed the need for earlier collaboration with structural engineers to ensure reusability, disassembly potential, and low-carbon procurement are integrated from the VO (preliminary design) phase.

Urban mining and the reuse of steel components are technically feasible but face certification, contamination, and logistical barriers. As a result, the company prioritizes high-quality recycling and circular procurement of low-carbon steel over direct reuse.

Financial feasibility emerged as a key point: the interviewee revealed that even with premium low-carbon steel, the additional cost is marginal, estimated at under 1% of total contract value. For example, a €25,000 premium on a €3.5 million contract still allowed for profit. Despite this, contractors often default to cheaper virgin options due to short-term cost considerations and traditional procurement practices.

The company contributes CO₂ data through updated EPDs and BCI assessments. Although internal tools are simple, they support client-side life cycle assessments and carbon accounting.

Challenges and Contradictions:

- Structural steel reuse is limited by legacy design, lack of certification, and contamination risks.
- Design teams rarely consult steel suppliers in early phases, hindering DfD and low-EC strategies.
- Modular designs face resistance in office projects due to architectural variability, despite circular benefits.

Relevance to Research:

This interview reinforces the importance of early-stage collaboration with material suppliers to enable circular and low-carbon steel design. It illustrates how strategic sourcing, DfD, and knowledge sharing can drive down EC without compromising cost. Moreover, it exemplifies the potential of high-performance recycled materials within the framework of Paris Proof construction targets.

Key Takeaways

- The company procures low-carbon steel with 90–100% recycled content and green energy input.

- Design for disassembly can be cost-neutral if integrated from early project phases.
- Despite common misconceptions, low-carbon steel premiums are negligible in total project budgets.
- Early supplier involvement is critical to achieving circularity and EC reduction in structural steel design.

Design Team Related Interviews

1. Architect

Company:	Architect
Interviewee Function:	Partner
Date:	May 19 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To explore the architect's role in embedding circularity, carbon-conscious design, and financial considerations throughout the design process, and to understand their perspective on material-related decision-making within the multidisciplinary design team.

Summary

Interview Context

The interviewee is a partner architect with extensive experience in complex urban and architectural developments, particularly at the intersection of design, stakeholder management, and concept development. Their firm is vertically integrated, covering the full project lifecycle, from early development and feasibility phases through to technical detailing and delivery—across urban planning, architecture, and engineering.

Main Themes and Insights:

Circularity and EC are structurally embedded in the architectural practice's internal discourse, particularly during the VO and DO phases where materiality is concretely defined. The interviewee emphasized that major decisions affecting carbon impact, such as building typologies, densities, and infrastructure layout, are determined during early area development, while material-level decisions emerge later in detailed design phases.

Circular strategies are considered throughout the process, but actual implementation often depends on client willingness to accept risk or additional procurement complexity. The architect highlighted a key contradiction: while theoretical strategies (e.g., reuse, disassembly) are feasible on paper, they frequently encounter practical obstacles on the construction site—particularly due to uncertainties around timelines, warranties, and execution guarantees.

The relationship between the architect and sustainability advisors is described as collaborative but differentiated. Environmental consultants often focus on theoretical potential, whereas the architect must translate ambitions into buildable, budget-compatible outcomes. Embodied carbon is increasingly referenced (e.g., through façade reuse or timber design alternatives), but few clients explicitly demand or reward carbon metrics such as kg CO₂/m².

The interviewee acknowledged that real influence on material selection and sustainability is frequently deferred until the execution phase, when contractors and suppliers make final procurement decisions. Architects often advocate for sustainable materials in early design, but client preferences for traditional procurement and tendering methods reduce the chance of early, circular-aligned commitments.

Challenges and Contradictions:

- Circular and reused materials face systemic barriers in availability, standardization, and insurance acceptance.
- Lack of EC targets in client briefs and PVEs prevents meaningful accountability.
- Tendering mechanisms discourage early procurement of sustainable or reused materials, reinforcing linear practices.

Relevance to Research:

This interview validates the thesis focus on the design phase as a critical window for steering EC and circularity. It highlights the architect's influential yet constrained position in the design team, balancing design intent, regulatory obligations, and cost feasibility. The need for tools that enable comparative material decision-making—linking carbon, circularity, and cost—is strongly supported by the architect's feedback.

Key Takeaways

- Circular ambitions are often sidelined due to procurement risk and client hesitancy.
- Architects play a crucial intermediary role in translating sustainability concepts into buildable and insurable designs.
- Decision-support tools enabling early material impact comparison can enhance circularity adoption within design teams.

2. Architect

Company:	Superuse
Interviewee Function:	Architect and Circular Material Specialist
Date:	May 21, 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 15 minutes
Disclaimer:	Company name used with explicit permission from the interviewee

Goal

To understand how Superuse integrates circularity, EC, and financial feasibility in architectural design practice and material selection processes.

Summary

Interview Context

The interviewee is a leading architect at Superuse, an architecture firm with a unique dual role: acting as both designers and material scouts. Their projects focus exclusively on circular strategies and the use of secondary materials, often participating either as full design leads or as consultants providing material reuse solutions.

Main Themes and Insights:

Superuse is typically involved from the early design stages (concept to final delivery) in projects with circular ambitions. The architect emphasized that their most impactful input occurs during the VO to VO+ phase, where material choices, construction systems, and spatial layouts are still adaptable. In projects where they act as consultants, involvement often starts late, at the definitive design phase, making integration of circular materials more difficult.

To safeguard circular ambitions through execution, Superuse employs a “dynamic definitive design” (CDO) approach that allows updates to material specifications in later phases. Their internal framework combines open methodologies like “Het Nieuwe Normaal” with custom tools for ambition tracking and material selection. Systemic analyses are also used in concept phases to link design interventions to contextual regenerative value.

Environmental and financial KPIs are central. The firm prioritizes material reuse based on weight percentages and environmental impact per kilogram, while also conducting MPG, MKI, and Circularity Index calculations where required. Although financial modeling is not their primary domain, they recognize cost and labor-related barriers and support increased transparency and open budgeting from contractors to enable well-informed decisions.

Material sourcing focuses heavily on secondary markets, including urban mining and industrial by-products from non-construction sectors. Superuse maintains its own internal material liaison function to bridge design and supplier domains, ensuring unbiased material selection. In contrast to conventional suppliers (e.g., steel or concrete), their partnerships prioritize circular readiness over vested material interests.

Challenges and Contradictions:

- Economic structures do not yet reward circular design efforts; architects are often paid by square meter, not by circular performance.
- Labor costs and lack of incentives across the chain limit circular implementation, despite technical feasibility.
- Open contractor budgets are rare, limiting transparency needed for effective decision-support tools.

Relevance to Research:

The interview strongly supports the thesis premise that circularity and EC considerations must be integrated early and transparently. It validates the need for a decision-support tool that merges circular, carbon, and financial data, and highlights gaps such a tool could address, especially around budget transparency and shared ambition tracking.

Key Takeaways

- VO–VO+ phases are key for implementing impactful circular strategies and material choices.
- Superuse uses internal frameworks and tools to link material reuse to project ambitions and environmental metrics.

- A lack of systemic economic incentives and transparency in construction budgets remains a core barrier to circular adoption.

3. Circular Advisor

Company:	Circular Advisor
Interviewee Function:	Owner
Date:	May 19 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To explore the circular advisor's role within the design team, focusing on the integration of circularity, EC, and financial feasibility from early design phases onwards.

Summary

Interview Context

The interviewee serves as a senior advisor on circular construction strategies, advising clients from the initial program of requirements through to the start of construction. Their consultancy focuses exclusively on material-related sustainability, including EC, material circularity, and financial implications.

Main Themes and Insights:

The circular advisor stressed the importance of early involvement—ideally from the program of requirements (PoR) and SO/VO phases, when major decisions on structure, installations, and materials are still flexible. They advocate for system-level assessments comparing structural concepts (e.g., steel vs. timber vs. concrete) based not only on cost and aesthetics, but also EC, circular potential, and material origin.

A strong emphasis was placed on prioritizing higher-order circular strategies such as reuse and avoiding unnecessary new production. Design for disassembly was acknowledged but framed as less relevant unless a building has a short intended lifespan. Tools like the Building Circularity Index (BCI) and product-specific circularity metrics are used to quantify and compare scenarios, including reuse, recycling, and downcycling.

Financial feasibility is a key pillar of their advisory approach. Although the firm no longer performs cost consultancy, it collaborates closely with external cost advisors to align carbon and circularity metrics with real project budgets. Metrics such as CO₂ per invested euro, financial residual value, and biobased or non-virgin content percentages are integrated into early design decision-making. Circularity is further tied to financial models through parameters such as demountability, which correlates with residual asset value and influences financing conditions.

The interviewee highlighted the increasing importance of institutional investors and public clients introducing EC thresholds. This shift is seen as a critical driver for mainstreaming circular strategies. Tools developed by their firm are widely used in the market and are open to other consultancies, promoting standardization and benchmarking across projects.

Challenges and Contradictions:

- Tension between short-term cost optimization and long-term value creation remains a major barrier to implementing circular strategies.
- Lack of standardization and integration between BIM models and material databases hinders reliable circularity assessments.
- Suppliers with vested material interests (e.g., traditional steel or concrete producers) may seek early involvement to secure specifications, risking biased decision-making.

Relevance to Research:

The interview confirms the thesis premise that circularity and EC reduction must be addressed from the earliest stages of design to be effective. It provides evidence that circular design must align with financial models, and that the use of quantifiable KPIs can support informed decision-making. The insights also validate the development of a decision-support tool that helps steer design teams based on EC and financial performance trade-offs.

Key Takeaways

- Early-phase decision-making (PoR to VO) is critical for impactful circular and carbon strategies.
- Financial KPIs like CO₂ per euro and residual value enable circularity to be aligned with real estate investment logic.

- Circular success depends on transparency, data access, and maintaining independent, unbiased decision-making within the design team.

4. Cost Advisor

Company:	Cost Advisor
Interviewee Function:	Cost Advisor
Date:	May 22 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To examine how financial feasibility, EC, and circularity are integrated into the early design stages from a cost management perspective.

Summary

Interview Context

The interviewee serves as a senior cost advisor, providing strategic financial guidance throughout the building process, from concept phase through design development and contractor negotiation. The firm integrates material-based sustainability considerations, including EC and circularity, directly into its cost estimations.

Main Themes and Insights:

The interview emphasized the significance of early-phase engagement, particularly during the sketch and preliminary design phases. According to the interviewee, these stages offer the greatest opportunity to influence material efficiency, spatial design, and environmental performance. Key decisions regarding form factor, grid dimensions, and structural concept can dramatically affect both cost and carbon outcomes.

The advisor employs a dynamic feedback loop where real project data continuously informs early-stage cost models. This allows for timely quantification of EC and cost implications linked to different structural and material scenarios (e.g., timber versus concrete). The firm utilizes internal tools supported by the National Environmental Database (NMD) to compare options and calculate environmental impacts. They also incorporate key performance indicators such as CO₂ per euro invested and restwaarde index (residual value index).

While carbon metrics currently dominate decision-making, especially due to Paris Proof benchmarks, circularity is increasingly considered through reuse strategies, component demountability, and design-for-reuse. However, circularity is often embedded qualitatively rather than through direct quantification.

Early supplier involvement was discussed as a double-edged strategy: while it can stimulate innovation and enable lifecycle-based Environmental Product Declarations (EPDs), it may also undermine cost competitiveness if tendering is restricted. Nonetheless, it offers long-term benefits like material-specific carbon reductions and design alignment.

Challenges and Contradictions:

- Circular design is hindered by unfamiliarity, technical constraints (e.g., fire ratings), and limited financial justification under current models.
- Cost increases for sustainable materials, especially timber, are not always absorbed within standard development budgets.
- There is a disconnect in responsibility within the design team, where circular ambitions are not consistently aligned between developers, architects, and engineers.

Relevance to Research:

The interview confirms the necessity of integrating EC and cost metrics during early design phases to achieve feasible circular strategies. It supports the thesis assumption that quantifiable KPIs, such as CO₂ per euro, can bridge sustainability and economic performance. The findings also highlight the potential value of decision-support tools for design teams, especially those incorporating material choice guidance, cost forecasts, and environmental trade-offs.

Key Takeaways

- Sketch and preliminary design phases are critical for effective circular and carbon-based decision-making.
- EC and circularity strategies must be financially substantiated to be adopted at scale.
- Supplier involvement can trigger market innovation, but should be managed carefully to avoid cost inflation.

5. Environmental Advisor

Company:	Environmental Advisor
Interviewee Function:	Senior Advisor
Date:	May 12 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To explore the role of the environmental advisor within the design team, with a specific focus on their influence on circularity, EC, and early-stage decision-making.

Summary

Interview Context The company as an environmental advisor within design teams, focusing on health, energy, and sustainability aspects throughout construction projects. The interviewees role spans from early conceptual stages to project delivery, assisting in setting and verifying sustainability ambitions, including circularity and EC considerations.

Main Themes and Insights: The environmental advisor emphasized the importance of early involvement in projects, preferably starting at the program of requirements (PoR) phase, where sustainability ambitions can be effectively embedded. The highest influence on circularity and EC is exerted during the PoR and preliminary design (VO) phases, where fundamental material and construction system choices are made.

Circular strategies such as reuse and design for disassembly were discussed. The interviewee highlighted that while these strategies are important, particularly reuse should be prioritized higher on the circularity ladder. Design for disassembly is often seen as superficial unless a building is explicitly intended for a short lifespan. In general, the goal remains to construct buildings with long, durable life cycles.

The incorporation of circularity within projects is heavily dependent on client demands. If circular ambitions are not embedded in the project requirements, the ability of advisors to promote circular strategies is limited. Among design team members, the structural engineer is considered the most impactful in initiating circular decisions due to their influence on material mass.

Regarding tools and data, the advisor expressed skepticism toward the multitude of existing instruments, noting that fundamental circular and EC decisions should be driven by common sense rather than overreliance on imperfect or inconsistent tools. A major issue is the lack of accessible data on available reused materials, hindering practical circular design choices.

The use of KPIs such as MKI (Milieu Kosten Indicator) and Building Circularity Index (BCI) was acknowledged, but their application often involves subjective interpretations. True success lies in ensuring that ambitions are maintained throughout the design and execution phases, not just in calculations.

Challenges and Contradictions:

- A lack of consistent definitions and understanding of key terms like circularity and EC among stakeholders leads to confusion.
- Supply chain limitations and the absence of reliable reused material inventories complicate circular implementation.
- Early-stage choices are often locked in without broad evaluation of alternative circular strategies.

Relevance to Research:

The interview reinforces the thesis focus on the critical importance of early-phase decision-making in maximizing EC reduction and implementing circular strategies. It highlights systemic issues such as inconsistent definitions, data gaps, and the need for client-driven sustainability ambitions. It also supports the development of decision-making tools that are simple yet sufficiently robust to guide early strategic choices without overcomplicating the design process.

Key Takeaways

- Maximum impact on circularity and EC is achieved through early-stage involvement, particularly at the PoR

and VO phases.

- Reuse strategies have higher priority over design for disassembly unless short building lifespans are planned.
- There is a need for better data availability on reusable materials and more consistent use of sustainability definitions across projects.

6. Environmental Advisor

Company:	Environmental Advisor
Interviewee Function:	Senior Sustainability Consultant and Partner
Date:	May 15 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 35 minutes

Goal

To explore the role of the environmental advisor within the design team, focusing on their influence on circularity, EC, and financial feasibility in early-stage design decision-making.

Summary

Interview Context

The interviewee operates as a senior sustainability consultant for large-scale construction projects, supporting clients and design teams from the earliest project stages. Their role centers on establishing sustainability ambitions—including circularity, EC, and energy objectives, and integrating these goals into the architectural and technical designs across all disciplines.

Main Themes and Insights:

The environmental advisor stressed the importance of being involved even before formal design phases, during feasibility studies and site acquisition, to maximize influence on sustainability outcomes. Early decisions, including location selection and reuse potential, heavily impact the achievable ambitions for circularity and carbon reduction.

Throughout the design phases (from SO to VO), sustainability targets are continuously monitored and enforced across all disciplines. Material choices must align with EC targets, with each discipline, especially structural engineering, tasked to design within specific EC limits. A "Carbon bank" management approach is applied, balancing carbon budgets across disciplines when deviations occur.

Circularity and EC are seen as interlinked yet distinct concepts: while circular strategies help reduce carbon emissions, circularity encompasses broader resource efficiency and design for long lifespans. Early integration of flexibility in layouts to avoid future demolition is a key design strategy.

Financial feasibility is assessed in parallel with sustainability goals. The cost consultant, an external party, evaluates material options alongside carbon performance to ensure economically viable solutions. The advisor highlighted the emergence of low-carbon products that are now competitively priced, aiding in achieving both carbon and financial goals.

Internal carbon tools, such as the "carbon sketcher" and other early-stage design configurators, were developed to quantify real-time carbon impacts of design choices. These tools facilitate transparent, dynamic decision-making without needing to wait for lengthy calculation periods.

Challenges and Contradictions:

- The slow development and approval of product-specific EC data in the National Environmental Database hampers the adoption of innovative materials.
- Circular material reuse from existing buildings (urban mining) faces major practical and financial obstacles, particularly regarding certification, reprocessing, and cost competitiveness.
- Early-phase flexibility is critical; however, definitive material and system decisions are required by the VO phase to maintain carbon targets, causing tension within design teams.

Relevance to Research:

The interview reinforces the thesis emphasis on the need for early strategic integration of circular and low-carbon ambitions to achieve Paris Proof standards. It highlights that systemic barriers, especially data gaps and supply chain immaturity, must be addressed. The findings also underline the potential of internal tools to support better early-stage decision-making, aligning with the dashboard development goals.

Key Takeaways

- Maximum impact on circularity and EC is achieved by influencing decisions from site acquisition through the

early SO and VO design stages.

- Material reuse remains complex and costly, requiring new supply chain innovations to become truly feasible.
- Successful integration of sustainability requires aligning carbon targets, circular strategies, and financial viability from the project's outset.

7. Project Developer

Company:	Project Development Firm
Interviewee Function:	Development Manager
Date:	May 20 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 25 minutes

Goal

To understand the project developer's influence on circularity, EC, and financial decision-making throughout the design and procurement process of commercial developments.

Summary

Interview Context

The interviewee is a development manager involved in high-profile commercial building projects, overseeing the process from acquisition and design through execution and post-delivery phases. They coordinate design, procurement, and financial oversight, acting as the linking role between client ambitions, design teams, and contractors.

Main Themes and Insights:

The developer emphasized their continued influence across all project phases, with significant impact during both the early acquisition/design stage and the contractor procurement phase. While key material decisions—such as adopting timber or preserving existing structures, must occur early, many circular choices (e.g., insulation, floor reuse) remain negotiable well into the execution phase.

Circularity strategies vary strongly by project. In reuse-focused renovations, the developer emphasized facade reuse and structural preservation, guided by both architectural and client ambitions. In other cases, like new-build mixed-use developments, circularity was less central. The architect plays a leading role in proposing reuse or circular alternatives, while the developer evaluates these proposals based on feasibility and cost implications.

Carbon and circularity are often considered as separate concepts, despite their overlap. Large EC reductions stem from early design decisions (e.g., structural reuse), while smaller circular interventions (e.g., reused raised floors) contribute more symbolically. Carbon metrics like MPG and EC are tracked in design documentation and variation forms, but financial cost and client willingness remain decisive. The presence of a committed end-user, was noted as a critical enabler for ambitious circular goals.

The developer acknowledged that current circularity practices often conflict with conventional processes and stakeholder expectations. Challenges include higher upfront costs, lack of guarantees for reused elements, and resistance from institutional investors expecting “new” quality standards. Tools such as the R-ladder and MPG calculators are integrated into workflows, but decision-making still largely relies on traditional cost-risk assessments.

Challenges and Contradictions:

- High costs and logistical complexity of reclaiming and storing reused materials limit practical circular implementation.
- Lack of warranties and investor conservatism around reused components hinder adoption.
- Supply chain timing mismatches obstruct cross-project reuse; urban mining coordination remains underdeveloped.

Relevance to Research:

This interview illustrates how circular and carbon-related ambitions are shaped by developer decision-making frameworks. It reinforces the importance of early-phase material decisions, the value of client commitment, and the need for integrated carbon-cost-circularity tools to inform trade-offs. The feedback directly supports the relevance of a dashboard to align early-stage design strategy with EC and financial feasibility.

Key Takeaways

- Developers play a key gatekeeping role in balancing carbon, circularity, and financial risk across phases.
- Circular strategies are most impactful and viable when supported by end-user commitment and early planning.

- Practical implementation is hampered by cost premiums, logistical hurdles, and lack of systemic reuse coordination.

8. Project Developer

Company:	Project Development Firm
Interviewee Function:	Partner
Date:	May 20 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 30 minutes

Goal

To examine the project developer's approach to integrating circularity, EC, and financial feasibility across various project stages, and to explore how these sustainability ambitions are reflected in design and procurement decisions.

Summary

Interview Context

The interviewee is a partner and technical director at a real estate development firm, overseeing the internal technical team and managing the design, procurement, and realization of both delegated and risk-bearing development projects. Their responsibilities span from early SO phases to post-completion, focusing on design coordination, budget control, and project delivery.

Main Themes and Insights:

The developer highlighted that circularity and EC considerations are most effectively integrated during the early VO and DO phases. Structural and spatial concepts defined in these stages heavily influence the design's carbon performance and cost flexibility. While structural decisions are typically finalized by DO, minor adjustments (e.g., façade detailing) may still occur during execution.

The organization has recently formalized an internal sustainability policy, requiring all projects to follow a standardized stepwise framework prioritizing reuse, biobased materials, and demountable construction. This policy is operationalized through project phase documents, which now include a dedicated sustainability section outlining circular strategies and EC targets.

Design teams are increasingly incorporating carbon and circularity into early-stage budget and planning discussions. Architects play a key role in proposing material strategies, while cost consultants are embedding EC metrics into their estimates (e.g., MPG and CO₂ equivalents). The developer noted that institutional clients, particularly pension funds, are the strongest external drivers of EC targets and circular KPIs, often linked to Paris Proof benchmarks or green financing requirements.

Financial feasibility remains the dominant constraint. Circular solutions often face cost premiums, logistical complexity, and limited material guarantees. These challenges are particularly acute in residential developments with affordability targets. Nevertheless, performance-based financial incentives (e.g., interest discounts) and rising investor awareness are encouraging more projects to pursue sustainability upgrades.

Challenges and Contradictions:

- EC and circularity targets from institutional investors are often unrealistically strict, deterring implementation.
- Reused and alternative materials face acceptance issues due to insurance, warranty, and procurement limitations.
- Market fragmentation and lack of unified standards complicate integration of sustainability goals into design briefs.

Relevance to Research:

This interview supports the thesis argument that circularity and EC must be addressed early and holistically. It confirms that project developers, when equipped with robust frameworks and client alignment, can steer design teams toward sustainable outcomes. The conversation also reinforces the demand for decision-support tools that balance EC reduction with financial constraints, particularly in early-phase trade-off analysis.

Key Takeaways

- Early design stages (SO–DO) are critical for embedding impactful circular strategies and EC targets.

- Financial feasibility is the dominant filter for circular decision-making, despite growing external sustainability pressure.
- Developers need clearer and more realistic EC benchmarks and tools to steer decisions across disciplines.

9. Structural Engineer

Company:	Structural Engineering
Interviewee Function:	Structural Engineer and Company Owner
Date:	May 16, 2025
Format:	Online interview conducted via Microsoft Teams
Duration:	+/- 25 minutes

Goal

To understand the structural engineer's role in steering circularity and EC reduction in early design phases, with attention to material reuse, design strategies, and cost feasibility.

Summary

Interview Context

The interviewee is a senior structural engineer working on complex building projects, including public, residential, and commercial developments. Their involvement spans from early feasibility studies through technical detailing, focusing on structural integrity, buildability, and sustainability goals, including carbon and circularity considerations.

Main Themes and Insights:

The interview emphasized that early structural choices, especially regarding the load-bearing system, significantly influence the project's total EC. While concrete remains dominant in Dutch construction, there is growing interest in alternative systems like timber and hybrid constructions, though these are still niche and often project-dependent.

Circular design strategies such as adaptability, demountability, and standardization were noted as essential principles. The interviewee described the practical application of these strategies by favoring bolted connections, modular grid layouts, and predictable spans that facilitate future reuse or transformation. However, the actual reuse of structural elements remains rare, primarily due to certification challenges, lack of supply chain readiness, and the bespoke nature of structural solutions.

From a carbon perspective, the engineer highlighted the increasing use of Environmental Product Declarations (EPDs) and carbon budgeting across design disciplines. Structural engineers are increasingly expected to deliver low-carbon solutions within predefined EC targets, requiring iterative design loops and close collaboration with sustainability advisors. Internal calculation tools (e.g., carbon calculators) are used early on to compare material options and structural systems in terms of EC impact.

Regarding financial feasibility, the interviewee noted that many circular or low-carbon strategies are viable when integrated from the outset, but retrofitting these intentions later in the process tends to escalate costs. Industrially prefabricated systems and biobased materials (like CLT or laminated timber) were seen as promising from both a performance and cost standpoint, especially as market familiarity and supply chains mature.

Challenges and Contradictions:

- Certification and documentation requirements hinder structural element reuse from existing buildings.
- Biobased systems often face skepticism due to limited long-term performance data and higher perceived risk.
- Circular ambitions can be difficult to reconcile with static project requirements such as fire safety and acoustic demands.

Relevance to Research:

This interview reinforces the thesis focus on structural systems as a major lever for reducing EC. It highlights the need for early-phase carbon-informed decision-making and showcases how circular design strategies can be structurally embedded, provided systemic and regulatory barriers are addressed. It also affirms the need for tools that support early-stage carbon and cost evaluation, aligning with the circular-carbon dashboard development.

Key Takeaways

- Structural design decisions are critical to achieving EC reduction goals.
- Design for adaptability and standardization are feasible circular strategies when implemented early.
- Reuse of structural elements is limited by certification, logistics, and bespoke design constraints.

D

Reader: Expert Panel

July, 2025

Feedback Reader
CIRCULAR CARBON FRAMEWORK

Dear,

First of all, thank you for your willingness to participate in this feedback round. Your professional experience is of great value to ensure that the Circular-Carbon Framework (CCF) is both practically relevant and well aligned with real-world decision-making in construction projects.

This reader serves two main purposes:

1. To briefly introduce the CCF, including its objectives, structure, and intended use in the early design phase of buildings.
2. To collect targeted feedback on the clarity, practical applicability, and added value of the framework from your professional perspective.

Your input will be used to refine and improve the CCF so it can better support design teams in making circular and carbon-conscious choices during the early stages of building design.

Please feel free to send your responses to the same email address from which you received this document. If you prefer, you may provide your feedback as a brief email message or by filling out the questions in a separate document (Word or PDF).

Should you have any questions, or if you would like to schedule a short follow-up conversation, do not hesitate to get in touch.

Kind regards,

Ezra de Jong

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What is the Circular-Carbon Framework?

The **Circular-Carbon Framework (CCF)** is a decision-support tool designed to assist design teams in selecting circular strategies that contribute meaningfully to the reduction of **embodied carbon (EC)** during the early design phases of a building project (Conceptual Design, Preliminary Design, and Final Design – SO, VO, DO).

Key principles of the framework:

1. The framework allows for a structured comparison of circular design strategies based on three core pillars:
 - **Carbon** – the potential for reducing embodied carbon,
 - **Cost** – the financial implications of each strategy, and
 - **Circularity** – the contribution to material and systemic circularity.
2. The tool is intended to be accessible and user-friendly, offering insight into how specific design choices impact each of the three pillars. It aims to facilitate transparent and integrated decision-making.
3. The CCF promotes interdisciplinary collaboration by offering a shared platform for all design team members to collectively assess and weigh circular strategies against carbon and cost objectives.

Intended users:

- **For content input:** All members of the design team (e.g., architect, structural engineer, sustainability consultant, cost advisor).
- **For strategic use:** All stakeholders involved in early-phase decision-making, including project developers, owners, and clients.

Objective within projects:

The CCF supports early-phase decision-making by enabling a shared understanding of circular strategies and their tangible impact on embodied carbon. It provides a structured basis for dialogue among team members and stakeholders about the environmental and economic consequences of design choices.

For a more detailed description, please refer to page 4.

Feedback and Questions:

A. Clarity and Structure

- Is the purpose of the framework clear to you?
- Is the structure logical and understandable (e.g., levels of scale, strategy categorization, linkage to embodied carbon)?

Please answer here

B. Practical Applicability

- Do you see opportunities to apply the framework within your professional context?
- Which components do you consider directly usable, and which are less relevant or unclear?
- Are there any strategies or elements that you feel are missing?

Please answer here

C. Value for Decision-Making

- Does the framework help to support better-informed decision-making in the early design phase?
- Could it contribute to improved alignment and communication within design teams?

Please answer here

D. General Feedback

- Do you have any suggestions for improvement of the framework?
- Would you be willing to contribute further to its development or future applications?

Please answer here

For a more detailed description, please refer to page 4.

Detailed Description of the Circular-Carbon Framework

Layer 1 – Project Input

This layer captures the basic project characteristics and design context. It forms the starting point of the framework and sets the stage for material selection and strategy evaluation. Typical inputs include project type, scope, floor area, and relevant baseline assumptions. These parameters ensure that the subsequent comparisons are grounded in realistic project data.

Layer 2 – Comparison Model

The Comparison Model forms the analytical core of the framework. It enables design teams to evaluate material options and circular strategies at the product and material level. This includes both a conventional base case (typically aligned with the initial design concept) and one or more circular alternatives.

The model is structured per material category and includes key input parameters:

- **Embodied Carbon** – expressed in kg CO₂-equivalent per unit of material;
- **Cost** – estimated unit costs or cost ranges;
- **Circularity Indicators**, including:
 - RBM (Recycled Building Material),
 - BBR (Bio-Based Resources),
 - RBC (Reused/Recycled Building Components),
 - DfD (Design for Disassembly).

Based on these inputs, the model calculates:

- Total upfront embodied carbon,
- Total cost implications,
- A Circularity Index Score (CIM), which reflects the circular potential of the design.

The goal is to help design teams explore the trade-offs between carbon reduction, cost efficiency, and circularity. Some strategies may significantly reduce embodied carbon but increase costs, while others offer financial benefits with limited environmental gain. The Comparison Model facilitates both quantitative insight and qualitative dialogue among stakeholders.

Layer 3 – Decision Dashboard

The Decision Dashboard translates the technical outputs of the Comparison Model into accessible and actionable information for decision-makers such as project developers, clients, or investors, individuals who may not be directly involved in material specification.

The dashboard consists of three components:

1. Totals Overview Presents absolute project-wide values for:

- Total upfront embodied carbon (kg CO₂),
- Total cost (€),
- Total circularity score.

2. Per m² Metrics Displays normalized values per square meter of Gross Floor Area (GFA):

- Embodied carbon per m² (kg CO₂/m²),
- Cost per m² (€/m²),
- Circularity index.

This component includes a benchmark for Paris Proof compliance, allowing for direct evaluation against climate targets.

3. Efficiency Ratio Introduces a combined indicator that links carbon to cost:

- Embodied carbon per euro invested (kg CO₂/€).

This metric helps assess which strategies deliver the most environmental benefit per unit of investment.

Together, the three dashboard components enable transparent comparison of alternative design options and help stakeholders align on circular and carbon-conscious strategies.

Closing

Thank you once again for taking the time to review the Circular-Carbon Framework (CCF). Your feedback is essential to ensure that the framework becomes a valuable and practical tool for design teams and stakeholders involved in sustainable construction.

Should you have any questions, or if you would like to schedule a short follow-up conversation, do not hesitate to get in touch.

Kind regards,

Ezra de Jong

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Feedback: Expert Panel

Table E.1: Overview of all conducted Experts Feedback Sessions (Alphabetical order)

No.	Organization	Role	Date
1	Architect	Technical Manager	May 8, 2025
2	Cost Advisor	Project Manager	April 24, 2025
3	Environmental Advisor	Data-analyst	April 29, 2025
4	Project Developer	Managing Director	May 16, 2025

1. Architect

Company: Project Development Firm
Interviewee Function: Concept Developer
Date: July 4 2025
Format: Feedback reader

A. Clarity and Structure

The expert noted that the overall purpose and structure of the framework are clear. However, the accompanying Excel file can feel overwhelming for first-time users. A short voice-over explanation or the addition of a written user manual within the tool itself was recommended to improve accessibility and initial understanding.

B. Practical Applicability

The expert was positively surprised that a tool like this had not yet been developed. They expressed strong belief in its practical applicability, particularly in early-phase design. From their perspective, the Decision Dashboard holds the most direct value, especially when used as a 'rule-of-thumb' tool. It allows design professionals to monitor high-level goals related to carbon, cost, and circularity without requiring deep technical expertise.

To enhance usability, the expert suggested developing a "Framework Light" version that provides basic comparative insights, for example, the impact of concrete versus timber, without extensive data input or technical interpretation.

An important point raised was the absence of "Cost" in the framework's title. Although cost is integrated into the tool, the expert recommended renaming it the Circular-Carbon-Cost Framework to better reflect its tripartite structure.

C. Value for Decision-Making

The tool was considered valuable in supporting better-informed decision-making during the early design phase, particularly when used at a high level. The expert emphasized that the CCF could help improve alignment and communication within design teams by offering clear and accessible insights into the impacts of material choices.

D. General Feedback

The expert expressed willingness to contribute further to the framework's development or its application in future projects. Most suggestions centered on improving usability, accessibility, and naming, with emphasis on strategic rather than detailed operational use.

Conclusion

The architect's feedback highlights the importance of balancing technical depth with intuitive usability. While the structure of the CCF is sound and promising, its presentation and naming could be improved to better support strategic-level decision-making. A simplified or light version of the framework could enhance its accessibility and uptake among early-phase design professionals.

This feedback has been taken into account during the ongoing refinement of the CCF.

2. Cost Advisor

Company:	Cost Advisory
Interviewee Function:	Cost Advisor
Date:	July 6 2025
Format:	Feedback reader

A. Clarity and Structure

The expert indicated that the purpose of the framework, supporting low-carbon decision-making within an agreed ambition level, is clear and fully supported. It was emphasized that establishing this ambition should originate from the client as a guiding principle for the design team.

The applied structure, from structure to skin, was seen as logical and reflective of a building's composition. To improve communication and avoid misinterpretations, the expert advised including a short contextual recap when presenting the framework to design teams.

B. Practical Applicability

From the perspective of cost advisors, the framework provides a useful overview of materials, their environmental scores, and associated costs. While not used directly as a calculation tool during quantity estimation, the resulting data can be integrated to assess both cost and environmental performance (e.g., CO₂ and MPG).

The expert sees value in using the framework as a communication tool within the design or policy team. In this context, cost estimations can serve as input for comparing different strategies. However, it was noted that the framework is not yet embedded in the standard cost estimation workflow and should be used with complementary tools.

C. Value for Decision-Making

The expert underscored the value of early and transparent communication about project goals. Setting clear ambitions early enables the design team to collectively steer the project in a targeted direction.

They welcomed the framework's role in facilitating exploration of multiple strategies and variants early in the process, helping to exclude less viable options and focus on promising directions. However, caution was raised about setting overly ambitious environmental targets too early, as preliminary designs often lack complete detailing.

To mitigate this, the expert recommends incorporating ranges or contingency values (e.g., a CO₂ or MPG buffer) to account for uncertainties. A preliminary cost estimate enriched with environmental values could serve as a reference point for this margin during the design phase.

D. General Feedback

The expert reiterated earlier feedback, noting that the current version of the framework is strongly scenario-oriented. What is currently missing is a basic contextual layer. Including parameters such as form factors, number of floors, and gross floor area would enable a more nuanced interpretation of results and improve comparability across projects.

For example, the higher costs and environmental loads of a tall and slender tower could be better understood when viewed in context of its high façade-to-floor ratio and heavier structural requirements. Such project-specific factors would enhance the clarity and robustness of decision-making supported by the framework.

Conclusion

The cost advisor's feedback reinforces the importance of integrating project context into the framework to improve interpretability and cross-project benchmarking. While not a primary tool for quantity takeoff or costing, the CCF holds value in communication and strategic decision-making, especially when combined with environmental data. The expert supports further development of the tool and recommends adding contingencies to improve its reliability in early design stages.

These suggestions have been considered in the ongoing refinement of the Circular-Carbon Framework.

3. Environmental Advisor

Company:	Environmental Advisor
Interviewee Function:	Sustainable Construction and Building Physics Expert
Date:	July 6 2025
Format:	Feedback reader

A. Clarity and Structure

The expert indicated that both the purpose and structure of the framework are clearly explained and easy to understand. No concerns were raised regarding the organisation or intent of the framework.

B. Practical Applicability

The expert sees strong potential for application of the framework in the early design phase, especially during concept development when data availability is limited. In particular, the tool could add value in the Sketch Design (SO) phase when different structural principles are being compared.

A key recommendation was to incorporate estimated material quantities per square meter of floor area based on basic design inputs, such as span width, material type, and number of floors. This would enable broader usability, allowing non-experts to input early-stage design concepts and receive meaningful feedback on carbon and circular performance.

Regarding the framework's layers:

Layer 1 – Input Parameters

- The framework could automatically propose a Paris Proof benchmark value based on the project year.
- It should differentiate between new construction, renovation, or hybrid developments, as this affects carbon performance thresholds and assumptions.

Layer 2 – Comparison Model

- Include concrete types with reduced cement content or alternative production methods, as these are essential for Paris Proof compliance.
- Account for significant variation in embodied carbon values between manufacturers, even when material specifications are identical.
- Where relevant, align the data sources with the Nationale Milieudatabase (NMD), which is required for official DGBC Paris Proof assessments. EPDs may be used as alternatives, provided that their assumptions are clearly communicated.
- Clarify the meaning of circularity indicators such as DfD, RBC, and BBM. These may be difficult to interpret for non-expert users and maybe could be simplified for better understanding.

C. Value for Decision-Making

The expert acknowledged the framework's potential to support more informed decisions in the early design phase. However, the current dashboard lacks visualisations. Including clear, well-structured graphs would improve interpretability and strengthen its role in team discussions and decision-making.

D. General Feedback

The expert expressed interest in seeing the final version of the framework and did not raise fundamental concerns about its direction. Suggestions focused on increasing clarity, integrating verified data sources, and enabling easier early-stage use.

Conclusion

The environmental advisor's feedback confirms the value of the framework for early-phase assessments while highlighting the importance of accurate data assumptions, Paris Proof alignment, and user accessibility. Key improvement areas include integrating Paris Proof benchmarks, referencing verified national databases, enhancing the explanation of circularity indicators, and visualising outputs. These suggestions have been considered for further development of the CCF.

4. Project Developer

Company:	Project Development Firm
Interviewee Function:	Development Manager
Date:	July 4 2025
Format:	Feedback reader

A. Clarity and Structure

The expert indicated that the purpose of the framework is clear: to support faster and better-informed decisions during the early design phases based on carbon, circularity, and cost considerations. Although the expert did not use the model hands-on, the logic and intended structure, particularly the side-by-side comparison of design scenarios, was understandable.

It was noted, however, that the framework appears relatively conceptual in nature. This makes it especially suitable for application in the Sketch Design (SO) and Preliminary Design (VO) phases, where strategic decisions are typically made.

B. Practical Applicability

The expert sees clear potential for applying the framework within real-world development projects, especially in light of ambitions to deliver carbon-neutral buildings while maintaining financial feasibility. The tool was seen as helpful in navigating the balance between sustainability goals and return on investment.

The outputs related to embodied carbon and financial cost were found to be particularly relevant. In contrast, the circularity index was considered less useful in the expert's current context, and the detailed material input component was not directly applicable.

The expert recommended extending the framework to account not only for material costs but also for full construction costs, including processing, labour, and time implications. These factors are decisive when evaluating the viability of design strategies. In addition, the material limitations of structural systems (e.g. timber, concrete, steel) should be considered. A valuable next step would be to connect the framework to conceptual design schemes, allowing users to assess how a conceptual massing or layout could be materialised, and what its corresponding carbon and cost performance would be.

C. Value for Decision-Making

The expert confirmed that the framework can support improved decision-making in early design stages. It was highlighted that the framework enables more data-driven choices within the design team, reducing ambiguity between alternatives and improving overall team alignment.

D. General Feedback

The expert concluded that the framework aligns well with its stated objectives and offered several suggestions for future enhancement:

- Explore linking the framework to conceptual BIM models through automated routines, potentially AI-driven, to allow for rapid generation and evaluation of materialisation strategies.
- Establish real-time connections with national environmental databases and construction cost indices, enabling dynamic and up-to-date performance assessments.

The expert expressed openness to further engagement and suggested testing the framework in a real-life project setting to inform its continued development.

Conclusion

The project developer's feedback highlights the framework's potential to guide trade-offs between circularity, carbon, and cost in commercial development contexts. To enhance its strategic value, it could be expanded to include construction execution considerations and be linked to conceptual design models. This would position the CCF as a more robust and practical tool for decision-making in carbon-conscious real estate development.

The insights shared have been considered in the further refinement of the CCF tool.

F

Case-study Results: Layer 2

Layer 2 - Base Case

Design Phase	Product choice			Base-case - Concrete							Circular Index Meter (CIM)			
	CO2 Related materials	Layer and Type	Unit	Quantity	CO2 Factor (kg CO2-eq/unit)	Total Upfront CO2 (kg)	Unit Cost (€)	Total Cost (€)	CIM Score	RBM (%)	BBR (%)	RBC (%)	DFD (%)	
			Parameters	Carbon		Cost (Range)		Circularity	AI-A3	AI-A3	Module C/D	Module D		
SO/VO	Concrete	Structure												
	C20/25	CEM 1	m³	6374	2.01E+02	1.28E+06	130	€ 828,620	0%	0%	0%	0%		
	C20/25	CEM 3\B	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%	-	
	C30/37	CEM 1	m³	16557	3.86E+02	6.39E+06	150	€ 2,483,550	23%	0%	0%	90%	0%	
	C30/37	CEM 3\B	m³	-	1.81E+02	-	130	-	-	0%	0%	61%	0%	
	C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%	-	
	C35/45	CEM 3\B	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%	-	
	C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%	-	
	C40/50	CEM 1 / CM3 (S0/S0)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%	-	
	C30/37	CX3/XD1/XF2 F4	m³	-	1.19E+02	-	185	-	-	30%	0%	0%	0%	
C20/25	CEM 1	m³	-	1.95E+02	-	175	-	-	-	0%	0%	0%		
SO/VO	Reinforced Steel													
	Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500SP / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500A Recycled	tonne	-	4.64E-01	-	680-720	-	-	18%	0%	95%	-	
	Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%	-	
	Rebar	B500C Recycled	tonne	-	4.57E-01	-	700	-	-	1%	0%	90%	0%	
Rebars	Used in Project	tonne	97	1.65E+03	1.60E+05	745	€ 72,265	0%	0%	0%	0%			
PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-		
SO/VO	Structural Steel	Structure												
	Sections	S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	750-1200	-	-	0%	0%	95%	-	
	Sections	S275	tonne	-	2.35E+03	-	750-1200	-	-	0%	0%	95%	-	
	Sections	S355	tonne	-	2.53E+03	-	750-1200	-	-	0%	0%	85%	-	
	Sections	S235 Scrap	tonne	-	5.60E+02	-	770-1220	-	-	100%	0%	100%	-	
	Sections	S275 Scrap	tonne	-	5.60E+02	-	780-1280	-	-	100%	0%	100%	-	
	Sections	S355 Scrap	tonne	-	5.60E+02	-	2500	-	-	100%	0%	100%	0%	
	Section	THQ Beam S355	tonne	900	6.42E+02	5.78E+05	2690	€ 2,421,000	45%	0%	0%	99%	80%	
	PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-	
SO/VO	Engineered Timber	Structure												
	CLT	Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%	-	
	LVL	Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%	-	
	GLT	Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%	-	
	CLT (Used)	Spurce	m²	-	6.80E+01	-	475	-	-	0%	100%	0%	80%	
PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-		
SO/VO/DO	Aluminum	Skin				8410317		€ 5,805,435	17%					
	Cladding System	EN AW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%	-	
	Cladding System	EN AW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%	-	
	Structural Framing	EN AW-6082	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%	-	
	Window & Wall Systems	EN AW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%	-	
	Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%	-	
	Curtain Wall	Anodized (Low Part)	m²	2767	3.30E+01	9.13E+04	550	€ 1,521,850	0%	0%	0%	0%	0%	
	Curtain Wall	Anodized (High Part)	m²	1224	3.39E+01	4.15E+04	900	€ 1,101,600	0%	0%	0%	0%	0%	
	SO/VO/DO	Glazing	Skin											
		Tvitec System Glass	Flat Glass	m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%	-
Saint-Cobain		Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%	-	
Stronglas		Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%	-	
Thermoplastiki		Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%	-	
Predari Vetri		Double Glass Recycled	m²	-	3.63E+01	-	600	-	-	0%	0%	99%	0%	
Stronglas		Insolated Triple Glazing	m²	-	1.58E+02	-	700	-	-	50%	0%	65%	0%	
Insulating Double Glazing		Single-Sided Safety Glass	m²	982	6.00E+01	5.89E+04	750	€ 736,500	0%	0%	0%	0%	0%	
Insulating glass	Triple Perform XTR70/33	m²	2627	5.56E+01	1.46E+05	450	€ 1,182,150	9%	34%	0%	0%	0%		
SO/VO/DO	Architectual Steel	Skin												
	Hot Dip Galvanized	DX, HX and S Grades	tonne	-	1.98E+03	-	810	-	-	60%	0%	95%	-	
	Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%	-	
	Cold-Rolled	DC01, DC03, DC04, DC06	tonne	-	3.39E+03	-	650-800	-	-	22%	0%	95%	-	
	Cold-Rolled	Xcarb CR Recycled	tonne	-	7.99E+02	-	710-730	-	-	0%	0%	98%	-	
	Cladding	Flat sandwich panel coated	tonne	24	6.04E+01	1.45E+03	444	€ 10,656	0%	0%	0%	0%	0%	
	Cladding	Galvanized steel	tonne	12	3.36E+01	4.03E+02	560	€ 6,720	25%	0%	0%	98%	0%	
	Cladding	Coated Steel	tonne	9	3.49E+01	3.14E+02	560	€ 5,040	25%	0%	0%	98%	0%	
							339953		€ 4,564,516	8%				
	TOTALS						8750270		€ 10,369,951	25%				

Figure F.1: Overview of the base-case in Layer 2 of the case-study (screenshot). Own illustration.

Layer 2 - Strategy 1

Design Phase	Product choice			Strategy 1 - Hybrid (As-Built Scenario)							Circular Index Meter (CIM)							
	CO2 Related materials	Layer and Type		Unit	Quantity	CO ₂ Factor (kg CO ₂ -eq/unit)	Total Upfront CO ₂ (kg)	Unit Cost (€)	Total Cost (€)	CIM Score	RBM (%)	BBR (%)	RBC (%)	DFD (%)				
SO/VO	Concrete	Structure		Parameters		Carbon		Cost (Range)		Circularity	A1-A3	A1-A3	Module C/D	Module D				
			C20/25	CEM 1	m³	-	2.01E+02	-	130	-	-	0%	0%	0%	0%			
			C20/25	CEM 3/8	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%	-			
			C30/37	CEM 1	m³	-	3.86E+02	-	150	-	-	0%	0%	90%	0%			
			C30/37	CEM 3/8	m³	-	1.81E+02	-	130	-	-	0%	0%	61%	0%			
			C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%	-			
			C35/45	CEM 3/8	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%	-			
			C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%	-			
			C40/50	CEM 1 / CM3 (SO/50)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%	-			
			C30/37	CK3/XD1/XF2 F4	m³	5127	1.19E+02	6.10E+05	185	€ 948,495	7.5%	30%	0%	0%	0%			
SO/VO <td rowspan="10">Reinforced Steel</td> <td rowspan="10"></td> <td>C20/25</td> <td>CEM 1</td> <td>m³</td> <td>6374</td> <td>1.95E+02</td> <td>1.24E+06</td> <td>175</td> <td>€ 1,115,450</td> <td>0%</td> <td>0%</td> <td>0%</td> <td>0%</td>	Reinforced Steel		C20/25	CEM 1	m³	6374	1.95E+02	1.24E+06	175	€ 1,115,450	0%	0%	0%	0%				
			Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500SP / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-			
			Rebar	B500A Recycled	tonne	-	4.64E-01	-	680-720	-	-	18%	0%	95%	-			
			Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%	-			
			Rebar	B500C Recycled	tonne	-	4.57E-01	-	700	-	-	1%	0%	90%	0%			
			Rebars	Used in Project	tonne	45	1.65E+03	7.44E+04	745	€ 33,525	0%	0%	0%	0%	0%			
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-			
			SO/VO <td rowspan="10">Structural Steel</td> <td rowspan="10">Structure</td> <td>Sections</td> <td>S235 (H, I- and U- Profiles)</td> <td>tonne</td> <td>-</td> <td>7.19E+02</td> <td>-</td> <td>750-1200</td> <td>-</td> <td>-</td> <td>0%</td> <td>0%</td> <td>95%</td> <td>-</td>	Structural Steel	Structure	Sections	S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	750-1200	-	-	0%	0%	95%	-
Sections	S275	tonne				-	2.35E+03	-	750-1200	-	-	0%	0%	95%	-			
Sections	S355	tonne				-	2.53E+03	-	750-1200	-	-	0%	0%	85%	-			
Sections	S235 Scrap	tonne				-	5.60E+02	-	770-1220	-	-	100%	0%	100%	-			
Sections	S275 Scrap	tonne				-	5.60E+02	-	780-1280	-	-	100%	0%	100%	-			
Sections	S355 Scrap	tonne				-	5.60E+02	-	2500	-	-	100%	0%	100%	0%			
Section	THQ Beam S355	tonne				900	6.42E+02	5.78E+05	2690	€ 2,421,000	45%	0%	0%	99%	80%			
PSA 2	PSA 2	-				-	-	-	-	-	-	-	-	-	-			
SO/VO <td rowspan="10">Engineered Timber</td> <td rowspan="10">Structure</td> <td>CLT</td> <td>Spurce</td> <td>m³</td> <td>-</td> <td>-6.75E+02</td> <td>-</td> <td>450-700</td> <td>-</td> <td>-</td> <td>12%</td> <td>100%</td> <td>0%</td> <td>-</td>	Engineered Timber	Structure				CLT	Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%	-
						LVL	Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%	-
			GLT	Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%	-			
			CLT (Used)	Spurce	m³	10501	6.80E+01	7.14E+05	475	€ 4,987,975	45%	0%	100%	0%	80%			
			PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-			
			SO/VO/DO <td rowspan="10">Aluminum</td> <td rowspan="10">Skin</td> <td>Cladding System</td> <td>EN AW-5005</td> <td>m²</td> <td>-</td> <td>1.53E+01</td> <td>-</td> <td>120-130</td> <td>-</td> <td>-</td> <td>0%</td> <td>0%</td> <td>95%</td> <td>-</td>	Aluminum	Skin	Cladding System	EN AW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%	-
						Cladding System	EN AW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%	-
						Structural Framing	EN AW-6082	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%	-
						Window & Wall Systems	EN AW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%	-
						Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%	-
Curtain Wall	Anodized (Low Part)	m²				2767	3.30E+01	9.13E+04	550	€ 1,521,850	0%	0%	0%	0%	0%			
Curtain Wall	Anodized (High Part)	m²				1224	3.39E+01	4.15E+04	900	€ 1,101,600	0%	0%	0%	0%	0%			
SO/VO/DO <td rowspan="10">Glazing</td> <td rowspan="10">Skin</td> <td>Twitec System Glass</td> <td>Flint Glass</td> <td>m²</td> <td>-</td> <td>3.06E+00</td> <td>-</td> <td>10-25</td> <td>-</td> <td>-</td> <td>0%</td> <td>0%</td> <td>30%</td> <td>-</td>	Glazing	Skin				Twitec System Glass	Flint Glass	m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%	-
						Saint-Cobain	Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%	-
						Stronglglas	Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%	-
			Thermoplastiki	Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%	-			
			Predari Vetri	Double Glass Recycled	m²	-	3.63E+01	-	600	-	-	0%	0%	99%	0%			
			Stronglglas	Insulated Triple Glazing	m²	-	1.58E+02	-	700	-	-	50%	0%	65%	0%			
			Insulating Double Glazing	Single-Sided Safety Glass	m²	982	6.00E+01	5.89E+04	750	€ 736,500	0%	0%	0%	0%	0%			
			Insulating glass	Triple Perform XTR70/33	m²	2627	5.56E+01	1.46E+05	450	€ 1,182,150	9%	34%	0%	0%	0%			
			SO/VO/DO <td rowspan="10">Architectural Steel</td> <td rowspan="10">Skin</td> <td>Hot Dip Galvanized</td> <td>DX, HX and S Grades</td> <td>tonne</td> <td>-</td> <td>1.98E+03</td> <td>-</td> <td>810</td> <td>-</td> <td>-</td> <td>60%</td> <td>0%</td> <td>95%</td> <td>-</td>	Architectural Steel	Skin	Hot Dip Galvanized	DX, HX and S Grades	tonne	-	1.98E+03	-	810	-	-	60%	0%	95%	-
						Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%	-
Cold-rolled	DC01, DC03, DC04, DC06	tonne				-	3.39E+03	-	650-800	-	-	22%	0%	95%	-			
Cold-rolled	Xcarb CR Recycled	tonne				-	7.99E+02	-	710-730	-	-	0%	0%	98%	-			
Cladding	Flat sandwich panel coated	tonne				24	6.04E+01	1.45E+03	444	€ 10,656	0%	0%	0%	0%	0%			
Cladding	Galvanized steel	tonne				12	3.36E+01	4.03E+02	560	€ 6,720	25%	0%	0%	98%	0%			
Cladding	Coated Steel	tonne				9	3.49E+01	3.14E+02	560	€ 5,040	23%	0%	0%	98%	0%			
	TOTALS							339923	€ 4,564,518	6%								
								3559249	€ 14,070,961	28%								

Figure F.2: Overview of the strategy 1 in Layer 2 of the case-study (screenshot). Own illustration.

Layer 2 - Strategy 2

Design Phase	Product choice		Strategy 2 - Bio-based							Circular Index Meter (CIM)			
	CO2 Related materials	Layer and Type	Unit	Quantity	CO ₂ Factor (kg CO ₂ -eq/unit)	Total Upfront CO ₂ (kg)	Unit Cost (€)	Total Cost (€)	CIM Score	RBM (%)	BBR (%)	RBC (%)	DFD (%)
			Parameters		Carbon		Cost (Range)		Circularity	A1-A3	A1-A3	Module C/D	Module D
SO/VO	Concrete	Structure											
	C20/25	CEM 1	m³	-	2.01E+02	-	130	-	-	0%	0%	0%	0%
	C20/25	CEM 3/B	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%	-
	C30/37	CEM 1	m³	-	3.86E+02	-	150	-	-	0%	0%	90%	0%
	C30/37	CEM 3/B	m³	-	1.81E+02	-	130	-	-	0%	0%	61%	0%
	C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%	-
	C35/45	CEM 3/B	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%	-
	C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%	-
	C40/50	CEM 1 / CM3 (50/50)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%	-
	C30/37	CX3/XD1/XF2 F4	m³	-	1.19E+02	-	185	-	-	30%	0%	0%	0%
C20/25	CEM 1	m³	-	1.95E+02	-	175	-	-	0%	0%	0%	0%	
SO/VO	Reinforced Steel												
	Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-
	Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-
	Rebar	B500SP / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-
	Rebar	B500A Recycled	tonne	-	4.64E+01	-	680-720	-	-	18%	0%	95%	-
	Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%	-
	Rebar	B500C Recycled	tonne	-	4.57E+01	-	700	-	-	1%	0%	90%	0%
	Rebars	Used in Project	tonne	-	1.65E+03	-	745	-	-	0%	0%	0%	0%
SO/VO	Structural Steel												
	Structure												
	Sections	S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	750-1200	-	-	0%	0%	95%	-
	Sections	S275	tonne	-	2.35E+03	-	750-1200	-	-	0%	0%	95%	-
	Sections	S355	tonne	-	2.53E+03	-	750-1200	-	-	0%	0%	85%	-
	Sections	S235 Scrap	tonne	-	5.60E+02	-	770-1220	-	-	100%	0%	100%	-
	Sections	S275 Scrap	tonne	-	5.60E+02	-	780-1280	-	-	100%	0%	100%	-
	Sections	S355 Scrap	tonne	-	5.60E+02	-	2500	-	-	100%	0%	100%	0%
	Section	THQ Beam S355	tonne	900	6.42E+02	5.78E+05	2690	€ 2,421,000	45%	0%	0%	99%	80%
	PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-
SO/VO	Engineered Timber												
	Structure												
	CLT	Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%	-
	LVL	Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%	-
	GLT	Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%	-
	CLT (Used)	Spurce	m³	2202	6.80E+01	1.50E+06	475	€ 10,450,950	45%	0%	100%	0%	80%
	PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-
SO/VO/DO	Aluminum												
	Skin												
	Cladding System	EN AW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%	-
	Cladding System	EN AW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%	-
	Structural Framing	EN AW-6082	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%	-
	Window & Wall Systems	EN AW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%	-
	Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%	-
	Curtain Wall	Anodized (Low Part)	m²	2767	3.30E+01	9.13E+04	550	€ 1,521,850	0%	0%	0%	0%	0%
	Curtain Wall	Anodized (High Part)	m²	1224	3.39E+01	4.15E+04	900	€ 1,101,600	0%	0%	0%	0%	0%
	SO/VO/DO	Glazing											
Skin													
Tvitec System Glass													
Flat Glass		m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%	-	
Saint-Gobain		Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%	-
Stronglamin		Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%	-
Thermoplastiki		Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%	-
Predari Vetri		Double Glass Recycled	m²	-	3.63E+01	-	600	-	-	0%	0%	99%	0%
Stronglamin		Insolated Triple Glazing	m²	-	1.58E+02	-	700	-	-	50%	0%	65%	0%
Insulating Double Glazing		Single-Sided Safety Glass	m²	982	6.00E+01	5.89E+04	750	€ 736,500	0%	0%	0%	0%	0%
SO/VO/DO	Insulating glass												
	Triple Perform XTR70/33	m²	2627	5.56E+01	1.46E+05	450	€ 1,182,150	9%	34%	0%	0%	0%	0%
	Architectural Steel												
	Skin												
	Hot Dip Galvanized	DX, HX and S Grades	tonne	-	1.98E+03	-	810	-	-	60%	0%	95%	-
	Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%	-
	Cold-Rolled	DC01, DC03, DC04, DC06	tonne	-	3.39E+03	-	650-800	-	-	22%	0%	95%	-
	Cold-Rolled	Xcarb CR Recycled	tonne	-	7.99E+02	-	710-730	-	-	0%	0%	98%	-
	Cladding	Flat sandwich panel coated	tonne	24	6.04E+01	1.45E+03	444	€ 10,656	0%	0%	0%	0%	0%
	Cladding	Galvanized steel	tonne	12	3.36E+01	4.03E+02	560	€ 6,720	25%	0%	0%	98%	0%
Cladding	Coated Steel	tonne	9	3.49E+01	3.14E+02	560	€ 5,040	25%	0%	0%	98%	0%	
	TOTALS												
	</												

Layer 2 - Strategy 3

Design Phase	Product choice		Strategy 3 - Promote Recycled Content							Circular Index Meter (CIM)			
	CO2 Related materials	Layer and Type	Unit	Quantity	CO ₂ Factor (kg CO ₂ -eq/unit)	Total Upfront CO ₂ (kg)	Unit Cost (€)	Total Cost (€)	CIM Score	RBM (%)	BBR (%)	RBC (%)	DFD (%)
			Parameters		Carbon		Cost (Range)		Circularity	A1-A3	A1-A3	Module C/D	Module D
SO/VO	Concrete	Structure											
		C20/25	CEM 1	m³	-	2.01E+02	-	130	-	-	0%	0%	0%
		C20/25	CEM 3/B	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%
		C30/37	CEM 1	m³	-	3.86E+02	-	150	-	-	0%	0%	90%
		C30/37	CEM 3/B	m³	5127	1.81E+02	9.28E+05	130	€ 666,510	15%	0%	0%	61%
		C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%
		C35/45	CEM 3/B	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%
		C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%
		C40/50	CEM 1 / C43 (50/50)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%
		C30/37	CX3/XD1/XF2 F4	m³	-	1.19E+02	-	185	-	-	30%	0%	0%
SO/VO	Reinforced Steel	Structure											
		C20/25	CEM 1	m³	6374	1.95E+02	1.24E+06	175	€ 1,115,450	0%	0%	0%	0%
		Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%
		Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%
		Rebar	B500SP / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%
		Rebar	B500A Recycled	tonne	-	4.64E+01	-	680-720	-	-	18%	0%	95%
		Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%
		Rebar	B500C Recycled	tonne	45	4.57E+01	2.06E+01	700	€ 31,500	23%	1%	0%	90%
		Rebars	Used in Project	tonne	-	1.65E+03	-	745	-	-	0%	0%	0%
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
SO/VO	Structural Steel	Structure											
		S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	-	750-1200	-	-	0%	0%	95%
		S275	tonne	-	2.35E+03	-	-	750-1200	-	-	0%	0%	95%
		S355	tonne	-	2.53E+03	-	-	750-1200	-	-	0%	0%	85%
		S235 Scrap	tonne	-	5.60E+02	-	-	770-1220	-	-	100%	0%	100%
		S275 Scrap	tonne	-	5.60E+02	-	-	780-1280	-	-	100%	0%	100%
		S355 Scrap	tonne	900	5.60E+02	5.04E+05	2500	€ 2,250,000	50%	100%	0%	100%	0%
		Section	THQ Beam S355	tonne	-	6.42E+02	-	2690	-	-	0%	0%	99%
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
SO/VO	Engineered Timber	Structure											
		CLT	Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%
		LVL	Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%
		GLT	Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%
		CLT (Used)	Spurce	m³	10501	6.80E+01	7.14E+05	475	€ 4,987,975	45%	0%	100%	0%
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
		PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-
SO/VO/DO	Aluminum	Skin											
		Cladding System	ENAW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%
		Cladding System	ENAW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%
		Structural Framing	ENAW-6082	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%
		Window & Wall Systems	ENAW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%
		Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%
		Curtain Wall	Anodized (Low Part)	m²	2767	3.30E+01	9.13E+04	550	€ 1,521,850	0%	0%	0%	0%
		Curtain Wall	Anodized (High Part)	m²	1224	3.39E+01	4.15E+04	900	€ 1,101,600	0%	0%	0%	0%
		Glazing	Skin										
		Tvitec System Glass	Flat Glass	m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%
SO/VO/DO	Glazing	Saint-Cobain	Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%
		Stronglases	Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%
		Thermoplastiki	Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%
		Predari Vetri	Double Glass Recycled	m²	982	3.63E+01	3.56E+04	600	€ 589,200	25%	0%	0%	99%
		Stronglases	Insolated Triple Glazing	m²	2627	1.58E+02	4.15E+05	700	€ 1,838,900	29%	50%	0%	65%
		Insulating Double Glazing	Single-Sided Safety Glass	m²	-	6.00E+01	-	750	-	-	0%	0%	0%
		Insulating glass	Triple Perform XTR70/33	m²	-	5.56E+01	-	450	-	-	34%	0%	0%
		Architectual Steel	Skin										
		Hot Dip Galvanized	DX, HX and S Grades	tonne	12	1.98E+03	2.38E+04	810	€ 9,720	39%	60%	0%	95%
		Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%
SO/VO/DO	Cladding	Flat sandwich panel coated	DC01, DC03, DC04, DC06	tonne	-	3.39E+03	-	650-800	-	-	22%	0%	95%
		Cladding	Xcarb CR Recycled	tonne	-	7.99E+02	-	710-730	-	-	0%	0%	98%
		Cladding	Galvanized steel	tonne	24	6.04E+01	1.45E+03	444	€ 10,656	0%	0%	0%	0%
		Cladding	Coated Steel	tonne	9	3.36E+01	3.14E+02	560	€ 5,040	25%	0%	0%	98%
		Cladding	Coated Steel	tonne	-	3.49E+01	-	560	-	-	0%	0%	98%
		TOTALS					609041	€ 5,076,966	17%				
		TOTALS					3998046	€ 14,128,401	43%				

Figure F.4: Overview of the strategy 3 in Layer 2 of the case-study (screenshot). Own illustration.

Layer 2 - Strategy 4

Design Phase	Product choice		Strategy 4 - Smart Circular							Circular Index Meter (CIM)				
	CO2 Related materials	Layer and Type	Unit	Quantity	CO ₂ Factor (kg CO ₂ -eq/unit)	Total Upfront CO ₂ (kg)	Unit Cost (€)	Total Cost (€)	CIM Score	RBM (%)	BBR (%)	RBC (%)	DFD (%)	
			Parameters	Carbon			Cost (Range)		Circularity	AI-A3	AI-A3	Module C/D	Module D	
SO/VO	Concrete	Structure												
	C20/25	CEM 1	m³	-	2.01E+02	-	130	-	-	0%	0%	0%	0%	
	C20/25	CEM 3/B	m³	-	1.61E+02	-	115-150	-	-	1%	0%	50%	-	
	C30/37	CEM 1	m³	-	3.86E+02	-	150	-	-	0%	0%	90%	0%	
	C30/37	CEM 3/B	m³	-	1.81E+02	-	130	-	-	0%	0%	61%	0%	
	C35/45	CEM 1	m³	-	3.56E+02	-	140-160	-	-	0%	0%	90%	-	
	C35/45	CEM 3/B	m³	-	2.53E+02	-	160-180	-	-	0%	0%	50%	-	
	C40/50	CEM 1	m³	-	4.26E+02	-	150-170	-	-	0%	0%	90%	-	
	C40/50	CEM 1 / CM3 (50/50)	m³	-	1.44E+02	-	170-190	-	-	4%	0%	61%	-	
	C30/37	CK3/XD1/XF2 F4	m³	5127	1.19E+02	6.10E+05	185	€ 948,495	7.50%	30%	0%	0%	0%	
SO/VO	C20/25	CEM 1	m³	6374	1.95E+02	1.24E+06	175	€ 1,115,450	0%	0%	0%	0%	0%	
	Reinforced Steel													
	Rebar	B500A	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500B	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500S P / B500C	tonne	-	3.68E+02	-	630-670	-	-	17%	0%	98%	-	
	Rebar	B500A Recycled	tonne	-	4.64E-01	-	680-720	-	-	18%	0%	95%	-	
	Rebar	B500B Recycled	tonne	-	2.97E+02	-	680-720	-	-	17%	0%	95%	-	
	Rebar	B500C Recycled	tonne	45	4.57E-01	2.06E+01	700	€ 31,500	23%	1%	0%	90%	0%	
	Rebars	Used in Project	tonne	-	1.65E+03	-	745	-	-	0%	0%	0%	0%	
	PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-	
SO/VO	Structural Steel	Structure												
	Sections	S235 (H, I- and U- Profiles)	tonne	-	7.19E+02	-	750-1200	-	-	0%	0%	95%	-	
	Sections	S275	tonne	-	2.35E+03	-	750-1200	-	-	0%	0%	95%	-	
	Sections	S355	tonne	-	2.53E+03	-	750-1200	-	-	0%	0%	85%	-	
	Sections	S235 Scrap	tonne	-	5.60E+02	-	770-1220	-	-	100%	0%	100%	-	
	Sections	S275 Scrap	tonne	-	5.60E+02	-	780-1280	-	-	100%	0%	100%	-	
	Sections	S355 Scrap	tonne	900	5.60E+02	5.04E+05	2500	€ 2,250,000	50%	100%	0%	100%	0%	
	Section	THQ Beam S355	tonne	-	6.42E+02	-	2690	-	-	0%	0%	99%	80%	
	PSA 2	PSA 2	-	-	-	-	-	-	-	-	-	-	-	
	SO/VO	Engineered Timber	Structure											
CLT		Spurce	m³	-	-6.75E+02	-	450-700	-	-	12%	100%	0%	-	
LVL		Spurce	m³	-	1.21E+02	-	250-600	-	-	0%	100%	100%	-	
GLT		Spurce	m³	-	-6.15E+02	-	450-550	-	-	0%	100%	0%	-	
CLT (Used)		Spurce	m³	10501	6.80E+01	7.14E+05	475	€ 4,987,975	45%	0%	100%	0%	80%	
PSA 2		PSA 2	-	-	-	-	-	-	-	-	-	-	-	
SO/VO/DO	Aluminum	Skin				306&201.565	€ 3,323,420	25%						
	Cladding System	EN AW-5005	m²	-	1.53E+01	-	120-130	-	-	0%	0%	95%	-	
	Cladding System	EN AW-1050	m²	-	1.47E+01	-	55-65	-	-	41%	0%	100%	-	
	Structural Framing	EN AW-6082	kg	-	3.08E+00	-	225-275	-	-	81%	0%	100%	-	
	Window & Wall Systems	EN AW-6060	m²	-	4.95E+00	-	9-11	-	-	42%	0%	95%	-	
	Window & Wall Systems	Hydro CIRCAL® 75 Recycled	m²	-	1.86E+00	-	40-50	-	-	80%	0%	93%	-	
	Curtain Wall	Anodized (Low Part)	m²	2767	3.30E+01	9.13E+04	550	€ 1,521,850	0%	0%	0%	0%	0%	
	Curtain Wall	Anodized (High Part)	m²	1224	3.39E+01	4.15E+04	900	€ 1,101,600	0%	0%	0%	0%	0%	
	SO/VO/DO	Glazing	Skin											
		Twitec System Glass	Flat Glass	m²	-	3.06E+00	-	10-25	-	-	0%	0%	30%	-
Saint-Cobain		Tinted Glass	m²	-	7.17E+00	-	40-140	-	-	0%	0%	0%	-	
Stronglase		Laminated Glass	m²	-	3.82E+00	-	60-300	-	-	23%	0%	50%	-	
Thermoplastiki		Double Glass	m²	-	3.51E+01	-	120-150	-	-	0%	0%	100%	-	
Predari Vetri		Double Glass Recycled	m²	982	3.63E+01	3.56E+04	600	€ 589,200	25%	0%	0%	99%	0%	
Stronglase		Insolated Triple Glazing	m²	-	1.58E+02	-	350	-	-	50%	0%	65%	0%	
Insulating Double Glazing		Single-Sided Safety Glass	m²	-	6.00E+01	-	750	-	-	0%	0%	0%	0%	
Insulating glass		Triple Perform XTR70/33	m²	2627	5.56E+01	1.46E+05	450	€ 1,182,150	9%	34%	0%	0%	0%	
SO/VO/DO		Architectural Steel	Skin											
	Hot Dip Galvanized	DX, HX and S Grades	tonne	-	1.98E+03	-	810	-	-	60%	0%	95%	-	
	Hot Dip Galvanized	Xcarb HDG Recycled	tonne	-	8.76E+02	-	740-750	-	-	0%	0%	98%	-	
	Cold-Rolled	DC01, DC03, DC04, DC06	tonne	-	3.39E+03	-	650-800	-	-	22%	0%	95%	-	
	Cold-Rolled	Xcarb CR Recycled	tonne	-	7.99E+02	-	710-730	-	-	0%	0%	98%	-	
	Cladding	Flat sandwich panel coated	tonne	24	6.04E+01	1.45E+03	444	€ 10,656	0%	0%	0%	0%	0%	
	Cladding	Galvanized steel	tonne	12	3.36E+01	4.03E+02	560	€ 6,720	25%	0%	0%	98%	0%	
	Cladding	Coated Steel	tonne	9	3.49E+01	3.14E+02	560	€ 5,040	25%	0%	0%	98%	0%	
		TOTALS					3384881	€ 13,750,636	37%					

Figure F.5: Overview of the strategy 4 in Layer 2 of the case-study (screenshot). Own illustration.