A Circular Life Cycle Cost model: Quantifying the Financial Implications of projected level of Circularity in Real Estate Development projects

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Abstract

The construction sector significantly contributes to global waste generation and greenhouse gas emissions, leading to environmental issues such as climate change, global warming, and resource depletion. The conventional linear economy in the construction sector follows a take-make-waste approach, resulting in adverse environmental impacts. The concept of a circular economy (CE) aims to address these issues by promoting regenerative practices and closing the material use cycle through reuse and recycling. However, many companies hesitate to invest in circular approaches due to higher initial costs and limited knowledge. Consequently, research focusing on understanding the degree of circularity and its financial implications has become crucial in facilitating the global transition towards circularity in the built environment. This research delves into methods aimed at improving the comprehension of circularity in real estate development projects and understanding the associated costs. The primary objective is to devise a circular life cycle cost model (C-LCC) which seeks to bridge the gap between the evaluation of circularity and its financial implications throughout the life of a building. Unlike traditional business cases that only consider initial investment costs and potential revenue from building projects, this innovative model provides a comprehensive tool for evaluating the financial costs and benefits associated with varying degrees of circularity. An extensive literature review and interviews were conducted to establish a solid foundation for understanding the key concepts and principles of the circular economy and its application in the built environment. The developed C-LCC model is applied to a real estate development project, namely Coolbase in Rotterdam, to simulate the financial outcomes of various circular building design scenarios. This improves the understanding of the relationship between circularity and associated finances. The disparate simulations underscore the critical role of building design, material selection, and the degree of building disassembly as principal influences on the level of circularity and corresponding financial implications. The model illustrates the costs and benefits across various stages of a building's lifecycle, including the initial, operational, and end-of-life phases of a construction project, while emphasizing the potential benefits inherent in various circular design scenarios. In conclusion, this study provides valuable guidance for a more sustainable and circular future, with the model providing insight into the potential costs and benefits that depend on the degree of circularity. Moreover, the results can serve as a tool for decision-making for circular choices in real estate development.

Key terms: circular economy – life cycle cost – circular strategies – real estate development – financial residual value – design for adaptability

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1. Introduction

Sustainable development, the principle of meeting our needs without compromising those of future generations, is becoming increasingly relevant today (Verma, 2019). This concept aligns with the ethical principle of the Golden Rule: "Treat others as you would like to be treated by them yourself" (Barnum, 1888). When applied to the planet, sustainable development demands responsible stewardship of the earth to avoid depletion or damage and ensure future habitability.
The construction industry aims to incorporate sustainability by creating structures and infrastructures that benefit current and future generations without damaging the environment or depleting natural resources. However, despite these efforts, construction contributes significantly to environmental degradation due to globalisation, population growth, and urbanisation (Eberhardt et al., 2019).

A potential solution to this problem lies in the concept of circularity, which has recently gained prominence as a pathway towards sustainable built environments. This study delves into the possibilities of implementing circularity in the built environment and explores strategies that can promote its realisation. Companies encounter various obstacles in implementing circularity, with financial barriers being one of the most significant (Dabaieh et al., 2022). This research investigates the intersection of circularity and its financial implications for construction projects in real estate development. This thesis aims to bridge the gap in understanding how circular principles can be translated into economically viable practices, thereby potentially enabling broader sustainability goals in the construction industry (Eisenberger et al., 1977).

1.1 Global Development

The sector's operational CO_2 emissions and energy consumption have reached an all-time high, exceeding pre-pandemic peaks. Locally adapted sustainable designs, building practices and materials offer opportunities for the rapidly growing demand for housing worldwide. Governments must make more policy commitments, invest more, and implement roadmaps to achieve zero-emission, efficient, resilient buildings and the construction sector. Construction companies and architects should adopt sustainable building materials and practices. Stakeholders across the value chain are crucial in building our shared sustainable future (IPCC, 2023). To mitigate these negative impacts, it is critical that significant efforts be made to reduce emissions of these gases (Connection, 2021). Population growth and economic development are closely linked to climate change (UN, 2022b). The growth of the global population and economy has led to an increase in total consumption, and there is a clear link between income and per capita CO_2 emissions. High-income countries, with their consumptive lifestyles and production practices, tend to have higher emissions than middle- and low-income countries, where most of the world's population lives. (Ritchie et al., 2020).

The global population is projected to grow, with estimates predicting that the world's population will exceed 9 billion by 2050 and reach 10.4 billion by 2080 (UN, 2022c). The United Nations (UN) estimates that 55% of the population resides in urban areas. By 2050, urbanisation is expected to cause twice as many people to live in urban areas as rural areas (Ritchie & Roser, 2019). This increased urbanisation leads to a significant increase in demand for infrastructure and buildings, resulting in a corresponding increase in the consumption of products and services, with significant impacts on the global environment (van Heel, 2017).

The construction sector accounts for about 40% of global material consumption, of which 11% goes to producing building materials and products (Sizirici et al., 2021). This industry generates nearly half of all solid waste streams in developed countries. Approximately 10-15% of building materials are not utilized during construction, and due to the nature of the materials being hazardous or toxic, approximately 54% of demolition materials are disposed of in landfills (Eberhardt et al., 2021). Figure 1 illustrates the material consumption of the construction industry, which shows a sharp increase, along with associated environmental impacts, driven by the growing demand of the world population, the consumption of natural resources, and the generation of large amounts of waste (OECD, 2019)

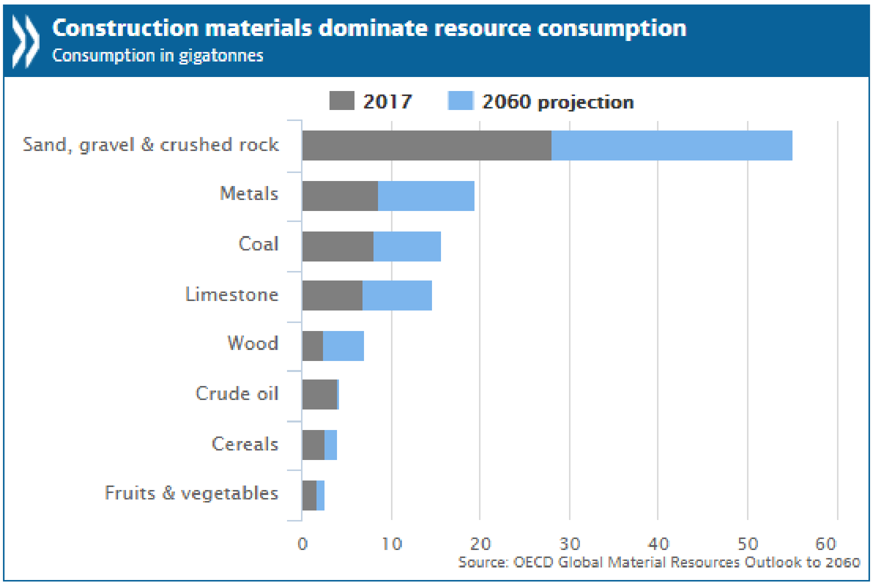

Figure 1 *Construction materials dominate resource consumption (OECD, 2019)*

Among all industries, construction consumes the most resources, produces the most waste and emits the most emissions (Ness & Xing, 2017). The construction industry is based on a linear economy, which is characterized by "take, make and waste" principle. The production of buildings requires large amounts of materials and energy resources, which are downcycled or end up as waste after the building is demolished. This leads to the depletion of the earth's resources (MacArthur, 2015). The conventional method of building is incompatible with the sustainability objectives established by the EU and UN. We must explore alternative building methods to combat climate change, reduce emissions, and conserve resources (Ghaffar et al., 2020).

A Circular Economy (CE), designed to be restorative and regenerative, presents a promising alternative to the traditional linear economy model. It has gained popularity in recent years and is being acknowledged by government agencies as a method of building economies without depleting resources at a rate that exceeds the earth's capacity (Kravchenko et al., 2019). This concept, wherein resources retain their optimal utility and value at all times, is gaining recognition as a means to achieve economic growth without exceeding the earth's resource replenishment capacity (MacArthur, 2015).

1.2 Circular Economy

The concept of circular economy (CE) gained prominence in China during the 1990s as a means of addressing economic growth and resource constraints. The primary goal of CE at that time was to optimize material flow recycling, and align economic growth and development with environmental and resource conservation (Winans et al., 2017). The concept of CE has since been recognized by organizations globally and continues to evolve. In the year 2013, the MacArthur Foundation published a report on the topic of CE which included the introduction of novel and cutting-edge ideas such as "cradle to cradle," "regenerative design," and "biomimicry." This report made a considerable impact on the advancement and expansion of the CE concept (MacArthur, 2013).

The notion of a circular economy (CE) has garnered considerable interest in recent times, both within academic circles and among practitioners. However, a universally accepted definition of CE remains elusive. Notably, Kirchherr et al. (2017) conducted an analysis of 114 distinct scientific definitions to explore the diverse concepts associated with CE. The Ellen MacArthur Foundation is widely acknowledged as a leading authority on circularity, and its definition is frequently cited in the literature. According to the Foundation, a circular economy is characterized by its "restorative and regenerative design, striving to maintain products, components, and materials at their optimal utility and value consistently while differentiating between technical and biological cycles." This definition underscores the significance of restoration and regeneration, as opposed to the conventional focus on end-of-life and recovery (MacArthur, 2013).

The illustration below, procured from the Ellen MacArthur Foundation, depicts the key principles that have been established by them in their understanding of the CE. The diagram depicts the flow of technology-based (blue line) and biologically based (green line) materials and products through the economic system. This diagram serves as a foundation for the principles of circular value creation, enabling the capture of benefits associated with circular products. The path towards restorative development necessitates the implementation of fundamentally innovative design solutions that consider the entire life cycle of a process and its impact on the environment, with a focus on reducing material, energy, and environmental costs (Ghisellini et al., 2016)

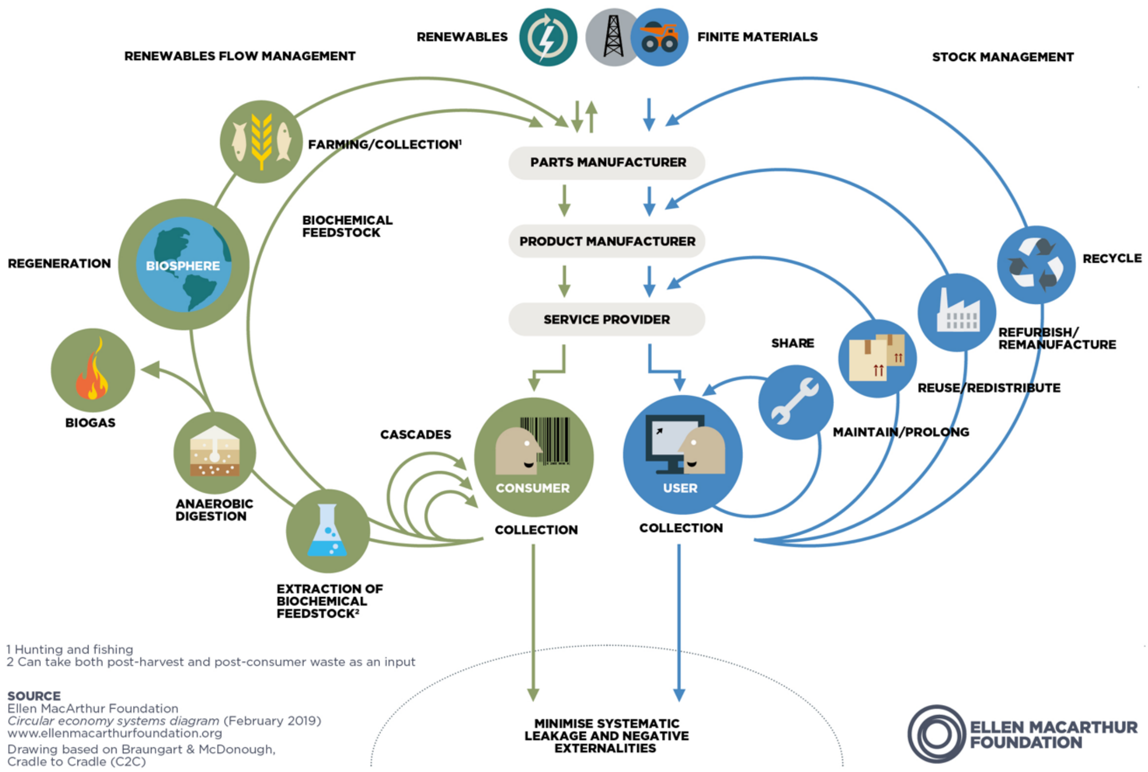

Figure 2 *The butterfly diagram (MacArthur, 2013)*

Despite substantial research and development in the construction industry aimed at integrating CE principles, there exists a gap in viable methodologies for embedding holistic performance assessments within circular business models industry (Antwi-Afari et al., 2021). Given the various interpretations of CE, establishing a consistent definition specific to the construction industry is crucial. Previous studies have identified several barriers impeding the integration of CE in the construction industry, including limited knowledge among stakeholders, a fragmented supply chain, and a lack of adoption incentives (Adams et al., 2017).

Stakeholders in the construction industry often prioritize immediate goals and profits over long-term sustainability objectives (Schoenmaker & Schramade, 2019). There is notable hesitancy within the construction sector towards investing in circular construction, primarily attributed to the belief that it incurs higher costs compared to conventional construction practices. For example, Brueton (2018) suggests that substituting raw materials such as steel, glass, and cement with more expensive biodynamic products increases overall initial costs. A survey of real estate developers highlighted financial constraints as the main obstacles to sustainable transition, leading to a reactive rather than proactive approach to sustainability (Lambert, 2021).

This reluctance often stems from a focus on short-term costs (initial expenditures) without adequately considering the potential long-term benefits of a CE approach, such as reduced operational and end-of-life costs. The establishment of long-term stakeholder partnerships and investment in collective gains may encourage stakeholders to overcome these barriers and commit to achieving a circular economy in construction. Exploring the potential cost benefits of circular construction could also facilitate its acceptance in the industry (Schoenmaker & Schramade, 2019).

1.3 Problem Statement

The construction industry significantly contributes to environmental degradation, characterized by extensive resource use, substantial waste production, and high emission levels. Despite a growing interest in applying circular economy (CE) principles to this sector, their practical implementation remains in its infancy, primarily focusing on waste minimization and recycling. A comprehensive CE approach that includes a thorough performance assessment within the circular business model is currently missing in the construction industry. Specifically, a systematic approach that contemplates every stage of a building's life cycle to evaluate its circularity impact is yet to be fully developed.

The industry is also reluctant to invest in circular construction due to perceived financial constraints. The common belief is that circular construction demands higher costs than traditional construction methods. This perception arises mainly from the lack of models that accurately map the degree of circularity to the related costs. Given the complex nature of circular principles and their diverse impacts on construction projects' economic, social, and environmental dimensions, developing such models is challenging. This lack of analytical tools is a significant obstacle to the widespread adoption of circular construction.

Furthermore, there needs to be more research that conducts comparative analyses of life-cycle costs and circularity levels of projects across various circular design scenarios. Investigating this domain could offer valuable insights, bridging the knowledge gap and fostering a better understanding of the financial implications of circular construction. Such understanding is pivotal in encouraging the uptake and advancement of circular practices within the industry.

To address these issues, this study aims to investigate a comprehensive circular life-cycle cost model that evolves across various levels of circularity. This model would encompass all life cycle management

activities, shedding light on the financial implications of circular interventions in the construction sector. By doing so, stakeholders in the industry could make more informed decisions about investments in circular projects, overcoming the financial barriers to adoption.
Moreover, considering the entire life cycle of a building, including demolition, recycling, and post-use, is crucial in the construction sector. To tackle this issue, it is important to develop a clear vision for incorporating CE principles into building practices, considering all life cycle management activities related to CE to enhance building circularity.

Finally, companies in the building sector often need to understand the available circular strategies and their potential impact on their business operations. Encouraging the adoption of circular practices necessitates deeper insights into the potential of circular interventions and their influence on the costs and benefits of projects. Such insights will assist in executing a comprehensive economic evaluation of construction projects while maximizing the benefits of CE. In sum, understanding possible circular intervention strategies and their contributions to life-cycle costs and circularity is crucial for transitioning towards a CE in the building sector.

1.4 Objectives

The primary aim of this research is to investigate the interplay between architectural design, circularity degree, and the corresponding lifecycle costs and benefits (LCC). We seek to develop a comprehensive Circular Life-Cycle-Cost (CLCC) model that encapsulates all lifecycle management activities across various circularity levels. This model aspires to function as an enlightening tool that improves understanding of the potential implications, costs, and benefits of circular strategies, thereby shedding light on the inherent value of circularity.

The CLCC model is envisioned to provide an all-encompassing and dynamic solution to the construction industry's fiscal and circularity challenges. By endorsing sustainability, minimizing waste, preserving resources, and fostering new business opportunities, the implementation of a circular economy within the construction sector has the potential to spearhead an environmentally responsible and economically prosperous future.

1.5 Research question

The purpose of this study is to delve into the intricacies of a comprehensive circular life-cycle cost model that evolves across diverse levels of circularity. The focus is on encompassing all life cycle management activities, aiming to shed light on the interplay between financial aspects and circularity within the construction sector. The question underpinning this investigation is as follows:

How can life cycle cost and circularity metrics be developed and framed for circular real estate development?

1.5.1 Research sub questions

To gain sufficient knowledge to answer the main research question, several sub-questions will first be be answered first.

SQ1: What are the principles of a circular economy in the built environment?

SQ2 : What are methodologies and assessment criteria for quantifying the degree of circularity in a building?

SQ3: What are the financial implications of applying circular strategies in real estate development projects?

SQ4: What are the main challenges and obstacles when conducting a life cycle cost analysis of a circular building?

1.6 Relevance

1.6.1 Scientific relevance

There is a lot of research on circular economy worldwide and publications are increasing every year. However, there seems to be a gap between scientific knowledge about CE and its practical implementation. A primary obstacle to the execution of circular construction projects is the perceived economic viability, which often leads to investor reticence. A prevalent assumption is that the costs associated with circular building exceed those of traditional construction. However, this assumption may not hold true when the complete life cycle of the building is factored into the equation. To make a fair comparison, a circularity measurement should also be part of the life cycle cost analysis. The available literature on implementing CE acknowledges the economic feasibility barrier, but does not explain how to overcome it or how to conduct a proper economic evaluation. This research aims to help fill this gap in knowledge.

1.6.2 Practical relevance

It is important to achieve a circular economy in the construction industry because it can have a significant impact on reducing waste, conserving resources and promoting sustainability. In addition, a circular economy can help achieve the government's goals of being circular by 2050. By using resources efficiently and reusing materials, a circular economy can help reduce demand for resources, reduce carbon emissions and contribute to a more sustainable future. In addition, a circular economy in the construction industry can create new business opportunities and jobs and promote innovation in the sector.

1.6.3 Societal relevance

The essence of developing a circular economy is preserving a balanced relationship between nature and human activities. Making circular projects economically feasible will encourage investors to undertake such projects, thus indirectly reducing global threats such as climate change, global warming, and resource depletion. Hence, it is believed that this field of study holds significant societal importance. The implementation of a circular economy is expected to strengthen communities as regenerative cycles become more integrated.

1.7 Research design

This research adopts an exploratory and interpretive stance, aiming to unearth novel insights into the intricate relationships between building design, degree of circularity, and life-cycle costs and benefits (LCC) within the context of the built environment. The integration of circular practices in the construction industry relies heavily on comprehending these complex relationships, and this investigation endeavors to add significant insights to this relatively uncharted area.

The primary objective of this study is the development of an instrumental tool capable of encapsulating these interrelationships. This tool could form the basis for assessing the potential of incorporating circular practices in contemporary building designs, and aid in determining the viability of investing in circular projects to achieve enhanced circularity levels. Furthermore, this research strives to offer empirical evidence to challenge prevailing misconceptions regarding the perceived inflated costs associated with circular construction (Oppen et al., 2021). This research emphasizes the generation of novel knowledge and insights through the design process itself. It involves the utilization of design principles, tools, and techniques to explore, investigate, and propose solutions to research questions or problems. The methodology employed in this study is research by design, which will be further elucidated in Chapter 5.

The conceptual model (Figure 3) provides a visual representation of the research's central themes. The model revolves around building design, LCC, and the Level of Circularity (LoC), connected by arrows indicative of their mutual influences. It's important to acknowledge that while certain materials may appear to be cost-effective initially, their long-term impact on the overall quality and performance of the building may not be as desirable (Alshamrani et al.). Therefore, fully comprehending the implications of these relationships is paramount for the practical implementation of circularity within the construction industry.

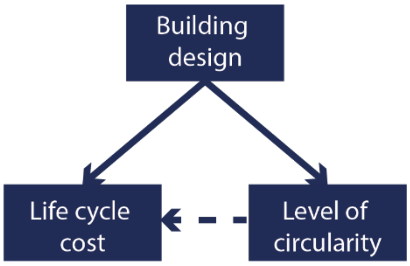

Figure 3 *Conceptual framework of the thesis (author)*

The research strategies and methods will adhere to the sequence proposed by Johannesson and Perjons (2014) , with a detailed account of these to be provided in Chapter 5: Methodology. Following this structure is crucial to ensure a comprehensive and coherent exploration of the research topic (Swedberg, 2020).

1.8 Research approach

The aim of this research is to explore the relationship between building design, the degree of circularity, and the associated life cycle costs and benefits (LCC). As the research is inherently exploratory, it is not possible to determine the outcomes in advance (Swedberg, 2020). The research design, as depicted in the figure below, outlines the various stages of the study. The research consists of four components: literature review, theoretical framework, interviews, development of the circular life cycle cost tool, and ultimately, a case study approach to examine different scenarios by modelling the

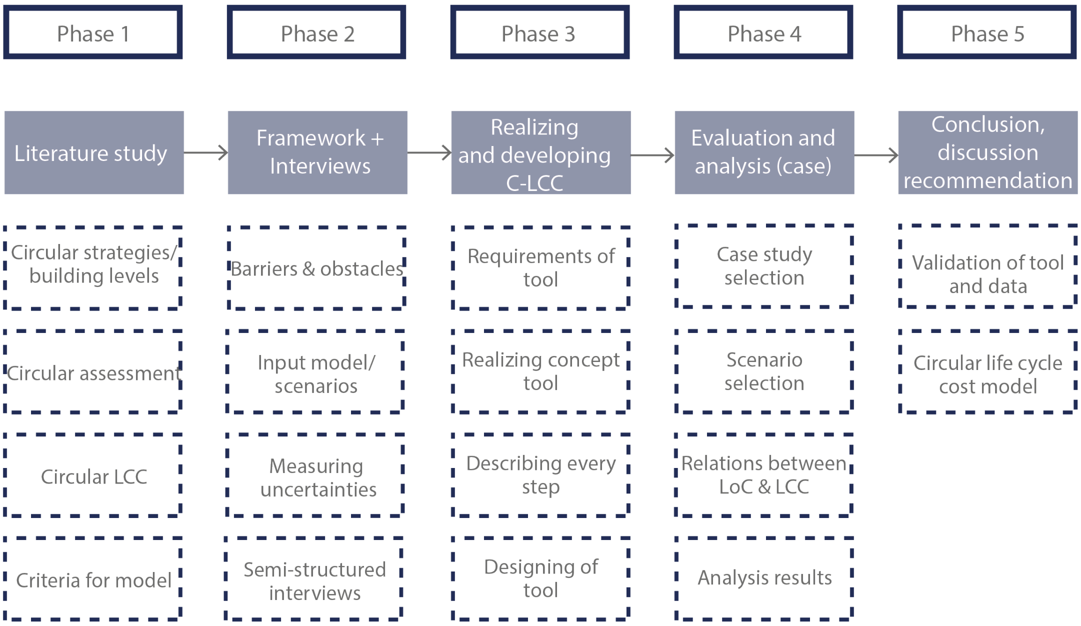

Figure 4 Research approach (author)

1.9 Thesis outline

The table below presents the research structure as depicted. This structure provides a definition and a detailed explanation of the individual chapters that comprise this thesis. Each chapter plays a critical role in this research, contributing to its integrity and depth:

Table 1 Thesis outline (author)

Introduction	The introductory section of the thesis outlines the importance and relevance of the circular economy in the construction sector, setting the stage for the research questions and objectives.
Research design	This chapter describes the research approach and design, illustrating how the study's goals were approached in a systematic and coherent manner.
Theoretical background	This section provides an in-depth exploration of the circular economy, its theoretical underpinnings, current understandings, and its potential financial implications within the construction industry.
Methodology	The methodology chapter explains the methods employed in the study, including data collection and analysis, along with justifications for chosen methods, ensuring the research's credibility and reliability.
Development of CLCC tool	This section of the thesis discusses the creation of the Circular Life Cycle Cost (CLCC) tool. It highlights the steps taken in the tool's development, the challenges faced, and the decisions made to overcome them.
Case study of Coolbase	The application of the CLCC tool is demonstrated using the Coolbase project as a case study, providing a practical perspective on the tool's functionality and its potential implications for circular construction.
Discussion	In this chapter, the findings from the CLCC tool application are discussed in a broader context, comparing them with existing literature, discussing the implications of the results, and highlighting potential areas of improvement.
Conclusion	The conclusion summarizes the thesis, underscoring the main findings, their implications, and the contribution of the study to the field of circular economy in the construction sector. It also provides recommendations for future research.

2. Theoretical background

This chapter provides a comprehensive review of the existing literature of CE to create greater clarity. In this study, the barriers and strategies will become clearer. The literature was obtained from scientific articles found through Scopus, Web of Science, Google scholar and Science direct. The analysis of the research topic was conducted by identifying key words such as "Circular AND Buildings," "Circular AND Economy," "Circular AND barriers," "Life cycle cost AND Circularity," "Investing AND Circular Buildings," "Assessment AND Circularity. 'Circularity AND decision-making'.

2.1. Circular economy in the built environment

The global construction sector is a major source of environmental problems and has a high negative impact on the environment (Guardian, 2019). The high CO2 emissions and high energy consumption produced by the sector have reached a historical low. There is a worldwide scarcity of resources, which will impact the construction sector as it is heavily dependent on resources (Braakman, 2019). Additionally, resource consumption is expected to double by 2060, leading to an increase in the current overuse (UN, 2022a).
The UN states that the construction and real estate sector must develop carbon-free strategies to transition to an emissions-free, efficient, and resilient sector in order to achieve climate goals (UN, 2022a). Currently, the sector is not on track to be carbon-free by 2050 (Bain, 2022). To achieve these goals, the sector must reduce its CO2 emissions throughout the entire value chain. The assessment of these emissions must take into account the entire life cycle of materials, including both operational emissions and the embedded emissions of materials.

The construction sector can address the aforementioned issues by adopting circular economy principles, which involve the circular use of construction materials. To gain a better understanding of circular economy concepts in the construction industry, a study will be conducted. Since the application of circular economy principles in this sector is still in its early stages of development and limited knowledge exists, this study aims to bridge the gap in understanding.

More than one-third of global material consumption - 38.8 billion tons - is used in the construction sector, with 23% of global emissions being produced (CircleEconomy, 2020) The materials produced and consumed by the sector are responsible for 35% of all waste produced in the world (Faezi, 2014). With a recycling and reuse rate of 88%, the Netherlands seems to be a leader in circularity, but this is largely due to downcycling. This means that the value and complexity of materials are reduced from what they could potentially offer in their lifetime (CircleEconomy, 2020). This does not meet the definition of a circular economy as outlined by MacArthur (Chapter 1.2). Based on this definition, there are several aspects that a circular built environment must fulfill. These are described in the CircleEconomy (2017) report as follows:

- Facilitate value chains that support the sustainable introduction of regenerative materials
- Design to reduce material use, with a focus on longer lifetimes and recycling at the end of life
- Ensure that buildings are operated in a circular manner. This scenario focuses on the longest phase of a building's life: the use phase
- Increase the share of materials Van Stijn (2023) at are reused in a high-quality manner

The principles mentioned align closely with the core strategies proposed by Bocken et al. (2016) for achieving circularity, which include narrowing resource flows, slowing down resource consumption, and closing material loops.

Van Stijn (2023) delineates three distinct tactics for the enhancement of resource utilization. The initial approach is labeled as 'compressing cycles', purposed towards the minimization of resource usage or the augmentation of resource efficiency. The subsequent strategy, 'extending cycles', aspires to decelerate the progression of resources by magnifying or elongating their serviceable lifespan, achieved through processes such as repair, reuse, or remanufacturing. Finally, 'cycling-back cycles' have the objective of reincorporating materials that have reached their end-of-life phase back into the production stream. The fundamental goal of these strategies is to escalate the intrinsic value of the materials, products, and elements through their perpetual cycling, thus leading to the preservation and enrichment of the natural resource reservoir.

In order to accomplish this objective, it is imperative to incorporate principles of reusability and recyclability into architectural design, and to employ materials that can be salvaged post the building's lifespan. This approach not only confers environmental advantages but also provides economic benefits by augmenting the worth of materials. Such considerations ought to be integrated at the inception or design stage of a building. This ensures that the intrinsic value is conserved throughout the building's lifecycle and even at its end-stage (Iyer-Raniga, 2019)

2.2 Circularity strategies

The philosophy of circularity integrates principles, frameworks, or tactics aimed at facilitating a transition towards a circular economy (Iyer-Raniga, 2019). This concept is highly applicable in the context of the built environment, where numerous principles for realizing circularity can be transformed into robust strategies to emulate a circular economy. A circular economy is typified by the reduction in the exploitation of natural resources and the mitigation of waste generation (Potting et al., 2017). Circularity strategies, characterised by their ability to close material loops and foster resource efficiency and optimisation, can provide substantial assistance in this endeavour. Numerous frameworks pertinent to the circular economy have been formulated and applied within the built environment (Cheshire, 2019). Bain (2022) report delineates five distinct strategies for the construction sector to champion a circular economy within the built environment. These circular strategies are rooted in the objectives of a circular economy, encompassing stream reduction (manufacturing products and services using fewer materials), stream deceleration (prolonging material usage and extending product life cycles), stream regeneration (utilizing clean materials), and stream recycling (reapplying materials through recovery and recycling processes). The execution of these strategies is anticipated to notably augment the industry's circularity, leading to a reduction in greenhouse gas emissions by an estimated 52%.

Alternative existing strategies frequently rely on R-frameworks outlined in academic literature and are in alignment with the aforementioned strategies proposed by Bain. These strategies, often referred to as the R’s, are prioritized based on varying degrees of circularity (Kirchherr et al., 2017; MacArthur, 2013). Table 1 encapsulates various R frameworks employed in literature by disparate agencies. The butterfly diagram, represented in Figure 2, is also predicated on these principles and proposes that reuse, remanufacturing, and recycling are particularly suited for the construction sector (MacArthur, 2013). The diverse R-frameworks can function as instruments to operationalize circularity in construction. Potting et al. (2017) devised an R-framework comprising strategies organized based on their impact on the circular economy in contrast to a linear economy (Figure 5). This framework is regarded as the most advanced in comparison to other existing frameworks that are shown in Table 2 (CB23, 2020a; Cramer, 2014; MacArthur, 2013; Potting et al., 2017).

Table 2 *Different R strategy frameworks (author)*

Butterfly model (MacArthur, 2013)	Circular strategies (Potting et al., 2017)	9R framework (Cramer, 2014)	R-principles (CB23, 2020a)
		Refuse	Refuse
	Rethink		
	Reduce	Reduce	Reduce
Reuse	Reuse	Reuse	Reuse
Maintenance/repair	Repair	Maintenance/repair	Repair
Refurbish	Refurbish	Refurbish	Refurbish
Remanufacture	Remanufacture	Remanufacture	Remanufacture
	Repurpose	Repurpose	Repurpose
Recycling	Recycling	Recycle	Recycle
Energy recover	Recover	Energy Recover	Recover
Landfill			

Figure 5 illustrates a ranking of different resource alternatives and their environmental impact, as per Potting's 10-R framework. In this framework, R9 possesses the least impact, while R0 holds the most. The top two strategies may not directly influence the reuse of products and materials, yet they can significantly affect circularity and are thus regarded as circularity strategies (Potting et al., 2017). The primary objective of these strategies is to minimize waste, prolong the lifespan of a building, and recover material at its end-of-life stage to complete the cycle. As depicted in the figure, the uppermost strategies exert the most influence in realizing a circular economy, while the bottom ones exert the least, hence aligning more closely with the traditional linear economy. The 10-R framework can enhance the economic value of an existing product at its end-of-life stage and contribute to mitigating environmental impact by providing materials with a second life (Mrad & Frölén Ribeiro, 2022). In a circular economy, the retention of value is crucial, and various strategies can aid in achieving this objective.

The recycling strategy is frequently mistaken for the reuse strategy (Horizon, 2023). Both are circularity strategies aimed at enabling the utilization of materials for construction purposes. However, recycling often emerges as a less efficient process, typically involving the transformation of products into materials of lesser quality and reduced functionality, a phenomenon known as 'downcycling'. Despite contributing to circularity, this principle does not maintain materials at their highest value and often demands substantial energy expenditure to facilitate the process (MacArthur, 2013). Conversely, reuse shares a similar objective with recycling, striving to employ products in another life cycle with minimal to no modification. In this strategy, the preservation of value is paramount, and energy involvement is significantly lower (Icibaci, 2019). While recycling can contribute towards a circular built environment, optimal reuse of existing products is considered one of the most potent circular strategies (Van Stijn, 2023).

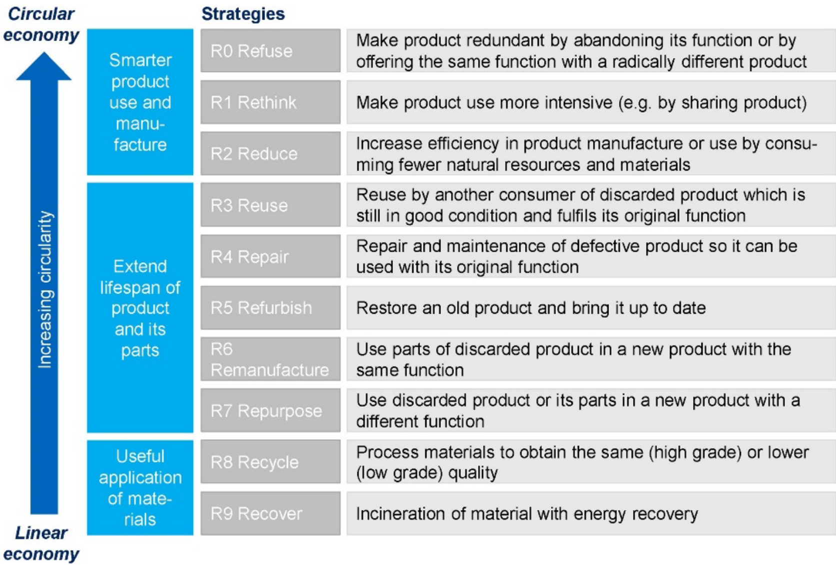

Figure 5 *The 10R-Framework (Potting et al., 2017)*

The definitions relevant to this study are as follows (CB23, 2020a; Cramer, 2014; MacArthur, 2013; Potting et al., 2017)

- Refuse/reduce: The reduction of raw material usage through prevention and reduction strategies.
- Rethink: The enhancement of product utilization by enabling a single object or sub-object to perform a greater number of functions.
- Reuse: The utilization of a product for its original purpose or with minimal modifications, through the process of repeated usage.
- Repair: The maintenance and fixing of a product to restore its functionality.
- Refurbish: The process of restoring a product to optimal working conditions through the replacement or repair of major components, and cosmetic modifications to enhance its appearance. Remanufacture: The disassembly and recovery process at the subassembly or component level, in which functioning and reusable parts are extracted from a used product and reassembled into a new one.
- Repurpose: The reuse of a product for a different purpose.
- Recycling: (1) functional recycling, the recovery of materials for their original or alternate purpose; (2) downcycling, the conversion of materials into a new product of reduced quality and functionality; (3) upcycling, the conversion of materials into a new product of increased quality and functionality. Energy recovery: The conversion of non-recyclable materials into usable heat, electricity, or fuel through waste-to-energy processes.
- Recover: recovering energy through direct and controlled combustion of raw materials that otherwise would become waste.

The interconnection between the distinct layers of a building, circular design approaches, and the key principles of the R-framework is depicted in the figure presented below. This investigation examines how the level of circularity correlates with financial considerations. A building comprises diverse stories, each with a distinct lifecycle that impacts circularity and finances. Therefore, it is imperative to compare them based on their adherence to the R-principles and the extent of circular design as these three factors are intricately intertwined and have an impact on both the cost center and degree of circularity of the project.

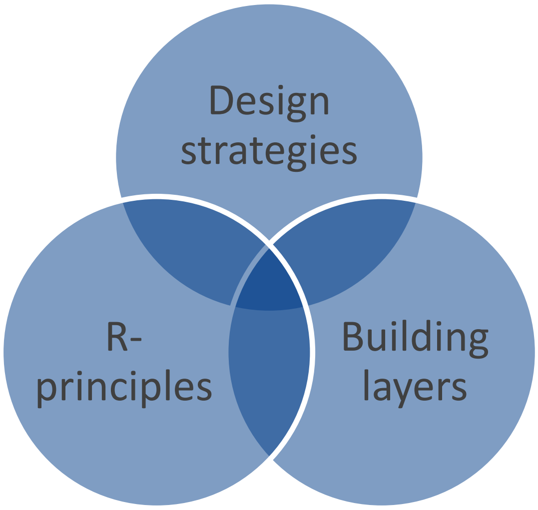

Figure 6 *Relation R-principles, buildings layers & design strategies (author)*

2.3 Circular buildings

Circular buildings are designed, built, managed, maintained and decommissioned according to principles of circular economy (CE). The existing CE research is often focused on macro- or micro-scale, neglecting the role and impact of individual buildings at the mesoscale, creating a gap in circular buildings research (Pomponi & Moncaster, 2017). From a CE perspective, current research primarily concentrates on short-lived manufactured products, neglecting the complexities inherent in buildings (Singh & Ordoñez, 2016). Circular buildings are optimized through a life cycle approach where the end-of-life phase is integrated into design and new ownership models where the building functions as a material bank are adopted (Leising et al., 2018). Buildings, as unique entities, are characterized by the diversity of materials and products that each have their own life cycle and interact in time and space.

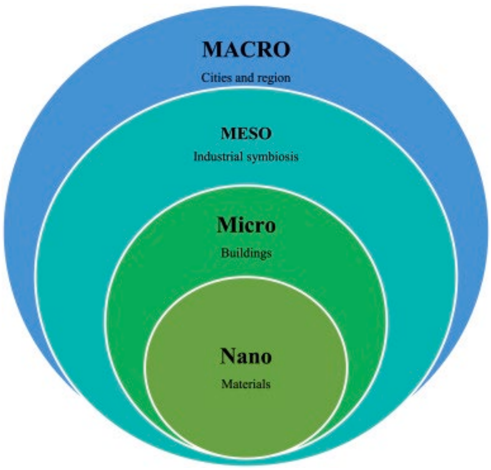

Figure 7 *C-indicator levels (Khadim et al., 2022)*

The long lifespan and changing uses of buildings result in greater uncertainty about future scenarios, making solutions for short-lived products more difficult to apply. Buildings are usually seen as permanent and completed structures, designed with a technical and functional lifespan of 50-75 years

(Debacker et al., 2016). Despite their long physical lifespan, they lack the flexibility to maximize their lifespan and are often demolished after an average lifespan of 20 years when they no longer meet the user's needs, necessitating a quicker return on investment (Debacker et al., 2016)

From a systemic viewpoint, buildings can be considered as meso level between macro-level urban agglomerations and micro-level building components. At the meso level, specific characteristics and challenges must be overcome to create circular buildings, including the composition and lifespan of materials, as well as possibilities for reuse and recycling (Pomponi & Moncaster, 2017). To create circular buildings, the design and construction processes must align with CE principles, taking into account the life cycle of materials/products and possibilities for reuse and recycling. Additionally, it is important to minimize the environmental and health impact of materials through careful consideration of their composition.

2.4 Circularity defined in building layers

The implementation of circular principles in the built environment is challenging due to the diverse characteristics that define a building. Building development is a complex process due to the dynamic nature and abstract structure of buildings, which are composed of various materials, components, and systems (Crawford, 2011). Throughout history, buildings have undergone modifications to adapt to climatic conditions, functional requirements, and cultural factors. Over time, buildings evolve in response to changing user demands, requiring a dynamic structure that can adapt to changing needs. To apply circularity to buildings, an approach that considers the lifespan and different components is necessary. Decomposing a building into its individual components rather than considering it as a whole simplifies the estimation of residual value (Slot, 2019). Brand (1995) model highlights the dynamic structure of buildings, positing that a building is comprised of layers with varying lifespans, each requiring replacement or repair at different times. The layers outlined in the model include:

- Site: geographic setting, urban location, and legally defined lot with an indefinite lifespan.
- Structure: foundation and load-bearing elements with a lifespan of 30-300 years.
- Skin: exterior surfaces with a lifespan of 50 years.
- Services: installations such as communication wiring, electrical wiring, plumbing, sprinkler, and HVAC with a lifespan of 7-15 years.
- Space plan: interior layout, including walls, ceilings, floors, and doors with a lifespan of 3-30 years. Stuff: furniture such as chairs, desks, phones, photographs, and lamps with a lifespan of less than 1 year.
- Stuff: mobile objects for the user’s use

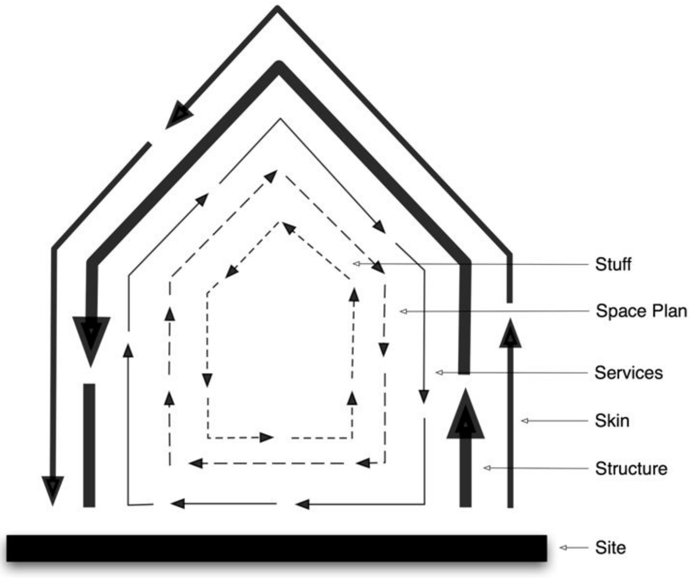

Figure 8 Building layers (Brand, 1995)

These building layers can be categorized based on their material hierarchy, with the first layers supporting the last layers and differentiating between the functional and technical life cycle of materials (Durmisevic, 2006). The material levels and their functional and technical life cycle impact the investment and environmental impact of the building (Brand, 1995). By designing and constructing buildings efficiently, it is feasible to realize circular buildings that take into account waste, pollution, quality, and usability. Each layer exhibits a distinct measure of circularity, reflecting the relationship between the user and the building. The diverse layers are employed in the built environment to facilitate an effective circular design, where each layer is evaluated for its utilized materials that are suitable for reuse, recycling, and recovery throughout the building's lifespan (Struiksma et al., 2020).

2.5 Design of circular buildings

The Ellen MacArthur Foundation defines circular design as "improvements in material selection and product design form the core of the circular economy" (MacArthur, 2013). Designing for a Circular Economy (DfCE) is closely related to Designing for Sustainability (DfS), with both approaches sharing the common goal of promoting sustainability and minimizing environmental impact. These approaches focus on developing products and systems that are both ecologically and socially responsible. The triple bottom line of people, planet, and profit (Van den Berg & Bakker, 2015) forms the basis for this relationship, as it recognizes that sustainable design must take into account social, ecological, and economic aspects to be truly effective.

There are two main design strategies, Design for Disassembly (DfD) and Design for Adaptability (DfAD). DfD focuses on designing buildings to facilitate future changes and eventual disassembly (Guy & Ciarimboli, 2003). DfAD seeks to extend the lifespan of a product by adapting it to changing circumstances (Schmidt III et al., 2011). The lifecycle of a building can be divided into four distinct stages: production phase, construction phase, usage phase, and end-of-use phase (TU-Delft, 2023). The design phase is crucial for achieving a circular building, as it lays the foundation for integrating circular principles and strategies throughout the building's entire lifecycle (Iyer-Raniga, 2019).

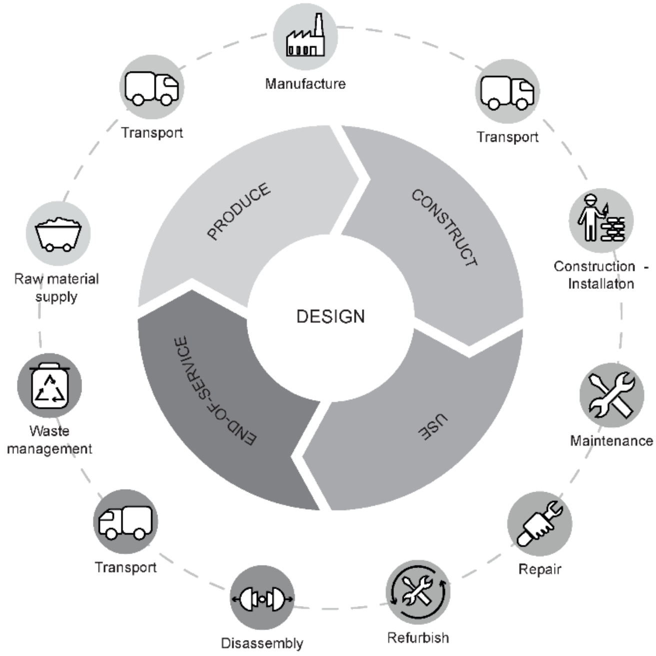

Figure 9 Life-Cycle of a Building (TU-Delft, 2023)

During the production phase, materials and components are selected for the construction process. Careful material selection is vital to minimize environmental impact and promote the circularity of the building. This includes choosing materials that are renewable, recyclable, and environmentally friendly, as well as using local sources to reduce the ecological footprint of transportation.

Next, in the construction phase, the selected materials and components are assembled according to the design. Here, product design plays a crucial role, as modular and adaptable designs enable buildings to be easily modified, repaired, or replaced when necessary. This also facilitates the integration of DfD and DfAD principles into the construction process.

Throughout the usage phase, it is essential to manage the building in a sustainable and efficient manner, considering energy and water consumption, maintenance, and any adjustments required to meet changing needs. This is where DfAD comes into play, by designing flexible and adaptable spaces that can evolve as user needs change.

Finally, in the end-of-use phase, the building is dismantled, recycled, or repurposed, depending on the circular strategies implemented during the design phase. DfD is applied here, designing buildings to facilitate disassembly and reuse of materials and components. This ensures that materials and parts can be responsibly recycled, reused, or redeployed in other projects.

By considering circular principles in the design phase and finding the right balance between material selection and product design, architects and designers can contribute to the realization of a circular economy and a more sustainable built environment. This helps to minimize the environmental impact of buildings and maximize the lifespan of materials and components, ultimately leading to more efficient use of resources and a reduction in waste streams, which ultimately leads to an improvement in the circular construction environment (MacArthur, 2013).

2.5.1 Levels of scale in construction

During the design phase, it is crucial to consider circular principles and strike the right balance between material selection and product design. This enables architects and designers to contribute to the realization of a circular economy and a more sustainable built environment. As a result, the environmental impact of buildings is minimized, the lifespan of materials and components is maximized, and resource utilization is optimized. Ultimately, this leads to a reduction in waste streams and an improvement in the circular construction environment (MacArthur, 2013) .

To better support the challenges of circular construction, it is important to differentiate between various levels of scale within the built environment. Circular construction is characterized by the reuse of materials. The built environment consists of multiple levels of scale, five of which have been defined by CB23 (2020a).

Table 3 Different levels of scale (CB23, 2020b)

Level of Scale	Description
Building	Constructed or to-be-constructed structures that form a single unit and serve a specific function, such as residential buildings, schools, hangars, viaducts, transmission towers, switching stations, or railways.
Element	(Abstract) components of a (construction) work that are distinguished solely based on a desired function, for example, spatial separation, load-bearing structure, lighting, heating, security.
Construction Product	Products that are brought to the construction site and, after processing, become part of an element, e.g., bricks, ready-mix concrete, windows, switches, or boilers. In the case of prefabrication, products are already manufactured into elements before being brought to the construction site.
Material	Processed raw material used for the production of construction products.
Raw Material	Unprocessed, crude substance. Through an artificial process, fossil raw materials are transformed into materials that are not easily reverted to their original state. For example, iron ore (raw material) being processed into iron (material).

By taking these levels of scale into account during the design process, architects and designers can develop more effective strategies and solutions to promote a circular construction environment and improve the sustainability of the built environment (CB23, 2020a)

In the quest for establishing a circular economy, the CB'23 framework has meticulously extracted six design principles from the array of 10 circular strategies elaborated in the preceding chapter. These principles serve as an all-encompassing set of guidelines to steer the circular design process, aligning it with the ambitions delineated during the initiation phase. By implementing these principles, stakeholders can effectively transition towards a sustainable and resource-efficient economy, minimizing waste generation and optimizing the value of products and materials throughout their lifecycles.

1. Design for prevention focuses on avoiding the use of products, elements, or materials by either forgoing construction, intelligently combining functions, or providing an entirely different solution. This strategy should be considered in conjunction with other strategies, such as life-cycle impact reduction and future-proofing.
2. Design for life-cycle impact reduction evaluates the consequences of circular material use on the environmental impact and performance throughout a product's life-cycle. This strategy entails assessing alternatives based on multiple criteria to determine the most favorable design variant with the lowest overall impact.
3. Design for future-proofing aims to create designs that are adaptable to future needs and requirements. Spatial-functional adaptivity allows for changes in function and space requirements, while technical adaptivity ensures components can be easily accessed, modified, or replaced.
4. Design with reused objects incorporates previously used objects in the design process, contributing to resource conservation and waste prevention. This strategy emphasizes higher-level reuse, such as elements, construction parts, structures, and buildings.
5. Design with secondary materials involves using materials that have been previously used or derived from waste streams of other production systems. These materials replace primary resources, protecting sources and preventing waste generation. The life-cycle impact of using secondary materials should be thoroughly assessed.
6. Design with renewable materials focuses on utilizing materials from renewable sources, such as sustainably managed forests, grasslands, and fertile soil. Sustainable management and stewardship practices ensure that these renewable resources are not depleted.

The six design principles, scrupulously extrapolated from the 10 circular strategies, coalesce into a cohesive framework that streamlines the planning and execution of circular projects. This methodical approach fosters a more systematic evaluation and optimization process, empowering stakeholders to conscientiously assess and implement sustainable solutions throughout the various stages of a project's life cycle. By incorporating these principles into the design process, it becomes increasingly feasible to address circularity at each stage, thereby enhancing resource efficiency, waste reduction, and value retention, ultimately facilitating the transition towards a circular economy (CB23, 2020a).

3. Assessment of circularity

In order to transition from a linear to a circular economy in the built environment, it is crucial to map the entire value chain of a building. This entails evaluating projects based on their level of circularity using circularity frameworks. These frameworks should provide insights into the degree of circularity throughout the entire life cycle of a building, thereby adhering to the principles of a circular economy and showcasing its potential (Tokazhanov et al., 2022)

Antwi-Afari et al. (2021) argue that a comprehensive methodology integrating performance assessment and the circular business model is lacking in the construction sector's circular economy (CE). To address this gap, a quantitative assessment technique is needed to effectively evaluate product performance within the context of the circular economy and provide insights into the value of circularity (MacArthur, 2015).

3.1 Creating Value within the Circular Built Environment

When implementing a circular economy in the built environment, value is created. Therefore, it is important to understand the impact of circularity on value and, consequently, on the degree of circularity when assessing it. The evaluation of circularity is often qualitative, as it is subjective (Tokazhanov et al., 2022). However, in order to improve the assessment process, the criteria used for evaluation should be more precise and less reliant on subjectivity. By incorporating quantitative assessment methods, the evaluation becomes more measurable, quantifiable, and authoritative (Tokazhanov et al., 2022).

Value creation is a subjective concept that varies based on individual perceptions. However, it is vital to understand it, as it elucidates the connection between performance, costs, benefits, and risks. This understanding allows for the establishment of criteria to better visualize circularity (Goldbohm et al., 2018). When one talks about creating value, the thought often gravitates towards economic value, but a circular economy can generate value beyond just the economic aspect (Tapaninaho & Heikkinen, 2022). The circular economy revolves around the concept of closing loops and optimizing the preservation of value within the lifecycle of products, materials, and resources while minimizing waste generation. By embracing this approach, the depletion of Earth's resources can be mitigated. Unlike the traditional financial-centric interpretation, the circular economy encompasses a more comprehensive notion of "value." This multifaceted perspective recognizes that value extends beyond monetary considerations and encompasses aspects such as unique characteristics, social impact, functional efficacy, and technological utility (AlbaConcepts, 2021).
The CB23 (2020a) report also emphasizes that circularity aims to achieve maximum value retention, not only focusing on economic value but also on functional, technical, and social value:

1 Functional value: This is the value that an object has due to the function(s) it serves. For circularity, not only the functional value of the first life cycle matters, but also the potential functional value from subsequent life cycles is crucial (Oppen et al., 2021)

2 Technical value: This is the potential value that the product or element has, where adaptability, detachability, and material choice play essential roles (Oppen et al., 2021)

3 Economic value: This is the potential profitability of a company or product. If an object or its components can be reused at a high quality, this translates into higher economic value in a circular economy.

4 Social value: This is an umbrella term that encompasses social and ecological aspects.

The different values are translated into various criteria to evaluate value in the table below:

Table 4 Functional, technical and economic value of circularity in built environment (Jeroen Verberne et al., 2021)

Functional value	Technical value	Economic value	Social Value
Current function of building	Adaptability of layers	Appraisal value of building	Function for society
Future function	Separating different layers	Life Cycle Value	Ecological aspects
Liveability of the building	Detachability of product/element	Residual Value of structure	Societal value
Current and future functions (skin)	Sustainability of building materials	Residual value of products	
Current and future functions (product)	Toxic materials	Residual value of materials	

In defining the functional value of a building product, it is imperative to delineate the current and potential functions of the product, along with its impact on the health and livability of the user environment. The reuse of products in the built environment poses a significant challenge due to the disparate life cycles of building materials, which often exceed their functional lifespan within a specific product (AlbaConcepts, 2021). To address this challenge, a building could be designed with functional layers, allowing the replacement of products with shorter lifespans and differing functions without impacting those with longer lifespans (Marsh, 2017). The functional value of a product hinges on its current and future performance but is also influenced by its technical value. If a product fails to meet required technical specifications or the anticipated quality, its functionality diminishes, leading to obsolescence (Marsh, 2017). Quantifying the functional value of a building remains challenging due to its abstract and intangible nature (Jeroen Verberne et al., 2021).

This research will primarily focus on technical and economic value. The technical value concentrates on the way products are developed, delivered, maintained, and reused. The technical potential for adaptability and the lifespan of a product or material are especially significant (Marsh, 2017). This technical potential also influences the functional value, thereby providing additional insight. The economic value focuses on product financing and the financial viability of circular interventions, including the associated costs and benefits. For instance, if a product can be reused at the end of its functional/technical life cycle, it translates to higher economic value (AlbaConcepts, 2021).

3.2 Methodologies to assess Circularity in the Built Environment

Traditionally, within the framework of a linear economy, investments in the construction sector are predominantly evaluated based on their financial outcomes (Eisenberger et al., 1977). The principal determinant in these assessments often revolves around the initial expenditures linked to the investment (Crej, 2018). This conventional approach emphasizes immediate financial implications, frequently neglecting potential long-term environmental and societal impacts. A linear economic model, such as this, primarily focuses on a 'take-make-dispose' process, which might not consider factors such as resource scarcity, waste generation, and the subsequent environmental repercussions. Hence, the imperative to transition towards more sustainable, circular models becomes evident, especially in the construction sector, where resource usage and waste generation are substantial (MacArthur, 2013). Given the increasing importance of implementing circularity in construction, it is crucial to accurately assess circularity so that it can be integrated into financial cost models.

Several methodologies have been identified that could provide a standardized means to measure the degree of circularity, thereby facilitating the exchange and comprehension of information (Khadim et al., 2022). The table below provides an overview of some methods used in academic literature to assess the degree of circularity. These methodologies were chosen based on their frequency of use.

Table 5 Circular indicators (author)

Indicator	Relation with CE
Madaster	Madaster is a circularity assessment framework that assesses material flows and detachability. The MCI focuses on the construction phase, use phase and End-of-life.
Environmental Impact Assessment (EIA),	Environmental Impact Assessment (EIA) is a tool used to assess the significant effects of a project or development proposal on the environment. EIA is primarily used at the early stage.
Life Cycle Assessment (LCA)	LCA is a method for assessing the environmental impacts of all stages of the life cycle of a commercial product, process or service.
Environmental Product Declaration (EPD)	An EPD is a document that contains information about the environmental impact of a particular building material. An EPD is used for evaluation or assessment of building materials.
BREEAM method	BREEAM is a sustainability label for achieving sustainable buildings with minimal environmental impact. is used at Design, Tendering, Implementation & Management stage
Cradle 2 cradle	The Cradle to Cradle design principle describes the safe and potentially infinite use of materials and nutrients in cycles.
Municipal Practice Guideline (MPG)	The MPG is a measure of building sustainability for the use of materials.
Material Circularity Indiator (MCI)	MCI measures how restorative a product's material flows are. The indicators can be used by product designers, as well as for internal reporting, purchasing decisions and business evaluation or assessment.
Environmental cost indicator (EQI)	The EQI (Environmental Cost Indicator) is a euro-denominated single-score metric that combines all environmental impacts of a product or project into a unified measure of its environmental shadow price or cost.
CB'23	Measure different aspects that are important in circular construction using indicators, where closing the cycle is important and the impact on the quality of the environment.

As can be seen from the above table, there are numerous methodologies in the construction sector that evaluate based on circularity. According to Zhang et al. (2021), existing methodologies for evaluating Building Circularity (BC) are ambiguous and inconsistent. To address this issue, Zhang et al. (2021) developed a new framework based on a comprehensive evaluation of existing literature and methodologies, such as MCI, LCA, the European Commission's Level(s) framework, and R-principles (CB23, 2020a). The framework consists of three main components: a material flow model, a Material Passport (MP), and a BC calculation algorithm.

The material flow model represents a new approach to BC evaluation, incorporating three circularity cycles and five indicators. The MP outlines the data required for BC evaluation, while the BC calculation algorithm provides a circularity grading system based on formulae. This new paradigm provides a comprehensive foundation for a coherent and consistent application of Circular Economy (CE) in the Architecture, Engineering, and Construction (AEC) industry. Further details regarding the framework and the three circularity cycles are presented in the next sub-chapters.

3.2.1 Material flow model

A novel conceptualization for Building Circularity (BC) has been put forward, integrating operations from the Architecture, Engineering, and Construction (AEC) sector with the tenets of the Circular Economy (CE). BC is portrayed as an inherent attribute of a building, symbolizing its circular potential across construction activities, with an objective to bolster environmental integrity, economic vitality, and social equity. This is achieved through strategic actions such as repair, reuse, refurbishment, remanufacture, and recycling. The material flow model serves as a tool for evaluating BC, grounded in the four core dimensions of CE as outlined by Kirchherr et al., 2017: environmental, economic, societal, and technological. Given the complexity in quantifying social aspects, they are not incorporated into the material flow paradigm. The material flow model is partitioned into four stages, reflecting the technical, economic, and biological life cycle of a building. Five principal indicators have been identified as catalysts of building circularity, as delineated in Figure 7.

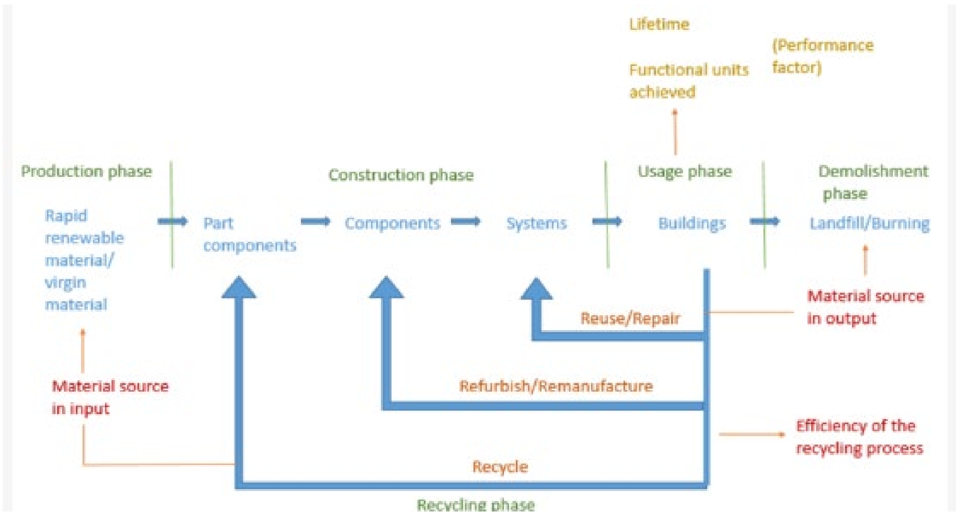

Figure 10 *The new material flow model. (Zhang et al., 2021)*

These indicators pivot around five 'R' strategies (refurbish, remanufacture, reuse, repair, and recycle), which delineate the origin and ultimate disposition of material resources within the material flow. The circularity degree of these indicators is ascertained by assigning a circularity quotient, with a higher weightage accorded to reuse over recycling (refer to the chapter on circular strategies for further details). The correlation between the stipulated BC indicators and the components of the material stream is graphically represented, as illustrated in Figure 8.

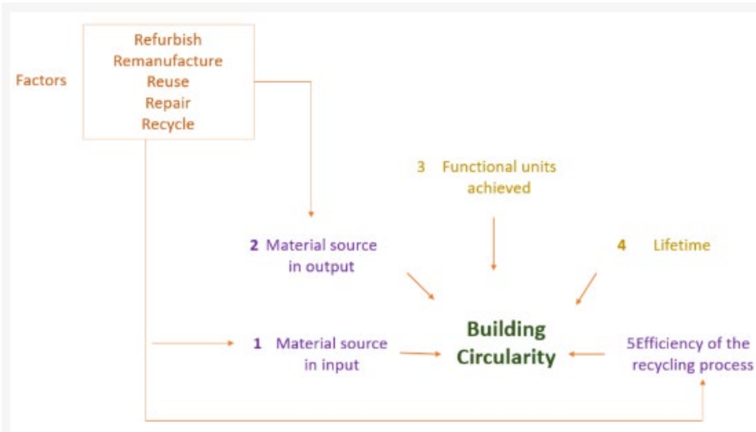

Figure 11 Factors and Indicators (1–5) for the new BC model. (Zhang et al., 2021)

The five R-strategy components are integrated into the material flow model and used to calculate the indicators in the BC evaluation model.

3.2.2 Material passport

The Material Passport (MP) is a comprehensive document that contains essential information about the materials and components used in a building construction project. The MP is designed to be a tool for Building Circular Assessment Method (BCA) by providing data that allows for precise statements to be made about the materials and components used. The MP differs from other similar documents in that it also records recycling information, which is critical in determining the circularity of the building's life cycle. The MP is divided into five sections, each providing different, but complementary, information about the materials and components (Zhang et al., 2021).

- basic information, such as the name, ID, size, and manufacturer.
- product characteristics, including weight, lifetime, functional units achieved, and a brief description of the material or component.
- circularity characteristics, such as the data for five factors in percent for input and output.
- environmental characteristics, such as CO2 emissions
- provides economic attributes, such as production and construction costs.

The MP provides a material flow model that includes resources, functional units, and lifetime, and reflects the recycling process's efficiency. The MP utilizes BAMB to establish complete information about the materials and components throughout their life cycle, including the recycling process. The MP's coding system and data structure, combined with new climate indicators, allow for data storage and analysis, making it a valuable tool for building circularity assessment (Honic et al., 2019).

3.2.3 BC-Calculation

The Building Circularity (BC) evaluation protocol offers advanced precision, underpinned by a comprehensive understanding of the BC paradigm and the determinants impacting a building's circularity, symbolically represented. This technique adheres to a material flow model that encompasses three distinct cycles: technical, biological, and economic. For assessment, five critical parameters are earmarked: material source input, material source output, realization of functional units, product lifespan, and recycling process efficiency. The computation of BC incorporates five 'R' strategies — refurbish, remanufacture, reuse, repair, and recycle — employed to gauge the circularity of material inflows and outflows. The aggregate circularity of a building is subsequently determined by integrating the circularities of its individual components (Zhang et al., 2021)

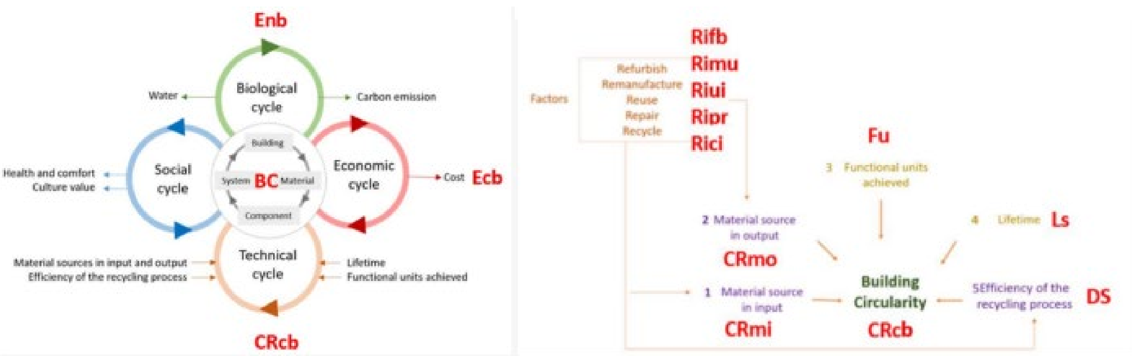

Figure 12 *Circularity cycles in the BC calculation method (Zhang et al., 2021)*

First, the materials' circularity is determined. The circularity of the whole is the total of the circularities of its constituent elements. To help you comprehend the BC computation, all symbols are explained

BC: Building Circularity	M: number of materials
CRcb: technical circularity percentage	N: number of components
Enb: environment impact	L: Number of systems
Ecb: economic impact	

Building Circularity is calculated using the equation below:

$$BC = \sum_{1}^{L} \sum_{1}^{N} \sum_{1}^{M} f(CRcb, Enb, Ecb)$$

The foundational equation for calculating Building Circularity (BC) is elaborated in detail within the appendix. This evaluation technique offers a comprehensive approach by integrating the technological, biological, and economic cycles within the proposed material flow model. The data incorporated in the material-specific computation encompasses component lifespan, disassembly factor, technical circularity grades, and weight per factor in the R-strategy. This innovative BC evaluation framework contributes to the sustainability of the construction sector by intertwining assessment cycles, indicators, and strategic elements. The method employs a novel data structure to aggregate and integrate data from various phases into the model and to implement multiple R-strategies. This framework enables the assessment of a project's Level of Circularity (LoC).

3.3 Assessment criteria for Circularity

To better delineate the considerations involved in developing a model that assesses the degree of circularity and its costs and benefits, the values defined in section 3.1 are utilized, based on their corresponding assessment criteria. In this context, the analysis is exclusively focused on the technical and economic aspects, adhering to the assessment methodology associated with these specific criteria.

3.3.1 Technical criteria

The technical value of a building product within the circular built environment is contingent on its capacity to fulfill present and anticipated future needs, as well as its technical lifespan. This lifespan is defined by the period over which a technical product remains functional and usable. Influencing factors might include general wear and tear, advancements in technology, and shifts in user demands (Méquignon & Haddou, 2014). Once a product ceases to function or hits its end-of-life stage, its technical value drops to zero, making it unable to serve its purpose. Quantifying technical value necessitates assessing diverse technical aspects across various building scales.

The criteria for the technical value encompass (Oppen et al., 2021):

1. Adaptability of the layers
2. Divisions of the different building layers
3. Adaptability of the building elements or products
4. Disassembly
5. Sustainability of the chosen materials and products
6. Toxicity of (raw) materials

In conclusion, the technical value of building products in a circular built environment is complex and multifaceted. It goes beyond mere functionality and includes factors such as adaptability, sustainability, and toxicity of materials, contributing to a more holistic understanding of product value.

4 Evaluation of financials in circular real estate projects

In a circular construction environment, it is important to quantify the economic value of circularity. While various initiatives exist to assess the economic value of circularity, there is currently no standardized methodology for assigning this value (Oppen et al., 2021). Circular business models differ from traditional business models; they operate over longer time horizons with multiple life cycles compared to linear business models, and their revenue streams often involve uncertain future cash flows. Current real estate financial models, typically short-term in nature and lacking consideration of future value and societal costs and benefits, no longer adequately capture the true value of circular construction (Fischer, 2018). As a result, these models fail to provide a fair comparison between traditional and circular alternatives (Jeroen Verberne et al., 2021). Consequently, real estate developers perceive financial barriers as the primary obstacle to transitioning to a circular economy (Lambert, 2021).

Despite the need to approach value in broader terms than just economics (Chapter 3.1), expressing value in economic terms alone can serve as a significant catalyst for circular construction. Currently, a linear approach appears more cost-effective in a conventional cost structure. The lower costs for a project throughout its lifecycle and benefits of circularity offer opportunities but are insufficiently incorporated into the business case (Jeroen Verberne et al., 2021). This ultimately results in missed value: components cannot be reused, and replacement or maintenance costs may be higher than in a circular scenario (Oppen et al., 2021). However, if we aim to push circular construction beyond the tipping point to become the new norm, an economic valuation of circularity is essential. Expressing value in economic terms can also increase the sense of urgency to engage in circular construction. Current and future risks such as escalating construction costs and resource scarcity can be effectively considered in determining value, making circular construction increasingly relevant (Oppen et al., 2021). Figure 13 below presents the key criteria established in the economic valuation of circularity translated with from the technical value (see 3.3.1 Technical criteria) (Oppen et al., 2021).

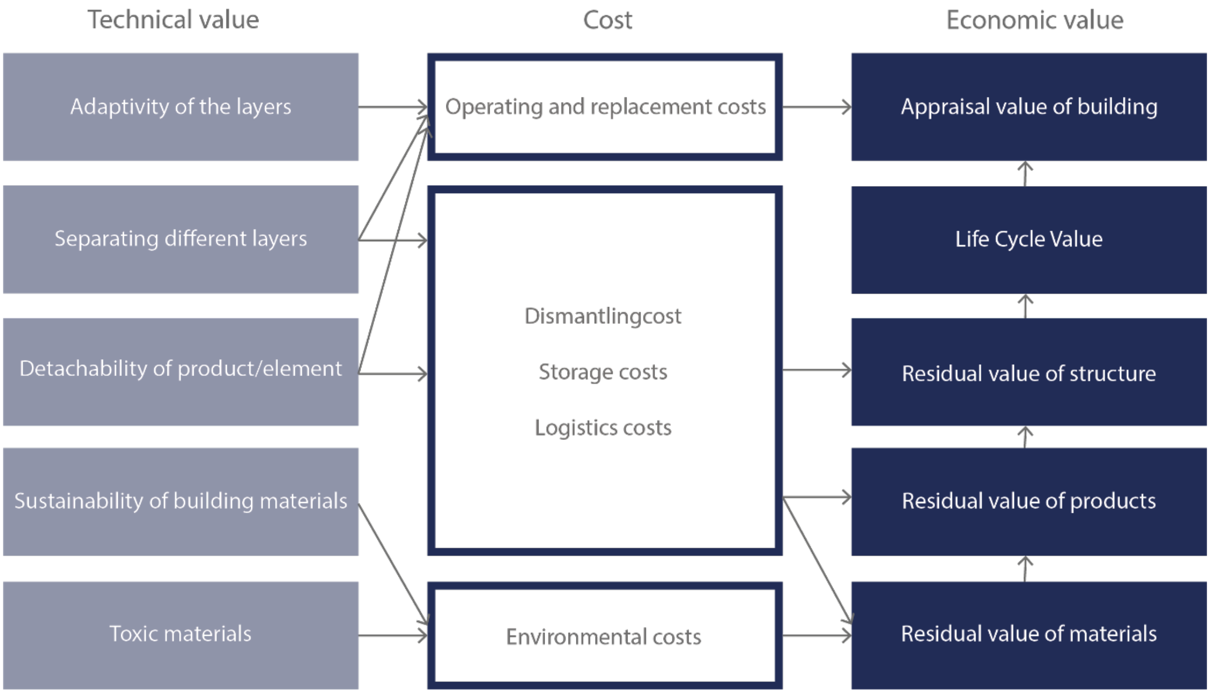

Figure 13 *Relationship between technical and economic value. Adapted from Jeroen Verberne et al. (2021)*

Residual value of materials, products and structure: An important factor that contributes to the residual value is the sustainability of the materials. The environmental cost indicator (ECI) can be used to express this. Another significant factor is the costs associated with preparing the materials for the next cycle. This involves considering dismantling time, storage costs, and logistical expenses. The concept of disassembly ability has an inverse relationship with dismantling time and a linear relationship with the residual value. Higher disassembly ability leads to a higher residual value of a product. The residual value of products is also influenced by the demand for secondary products and the quality of the product at the end of its lifecycle (Oppen et al., 2021).

The life cycle value is defined by the sales revenues, rental incomes, and end-of-life benefits, as stated in NEN-2699 (NEN, 2017). This encompasses the sales and rental revenues, as well as the end-of-life benefits. The residual value plays a significant role in circular business cases. Unfortunately, the inclusion of residual value in these calculations remains rare in practice. Ultimately, the appraisal value should reflect the value of the building as a whole, and many stakeholders emphasize the importance of giving circularity a better place in this valuation process to promote the circular construction economy (Oppen et al., 2021).

Furthermore, traditional buildings are likely to have higher adaption costs due to their single-function nature. Circular buildings, on the other hand, are more adaptable to changes and needs, potentially resulting in lower potential adaptation costs. In a Life Cycle Cost analysis, replacement and adaptation costs are also considered (NEN-2699). In a circular business case, both the life cycle value and costs need to be taken into account to create a holistic case (NEN, 2017).

Throughout its life cycle, money can flow in two directions: negative (representing costs) or positive (representing benefits). Positive money flows include income generated from the residual value of land or partial objects. When evaluating economic value, it is crucial to incorporate both types of money flows. This approach aligns with the Whole-Life Costing (WLC) method, which has been formalized in NEN-ISO 15686-5.69 (NEN, 2017). In contrast, the widely adopted Life Cycle Costing (LCC) method only considers outgoing cash flows. Consequently, the WLC method provides a more comprehensive assessment of the economic value associated with a (sub)asset by also considering the potential benefits at the end of its life or use phase (CB23, 2020b). In this study, the designation of LCC is used, as this qualification has more authority.

4.1 Life Cycle Costing

Circular business models have a longer time span with numerous life cycles compared to linear business models, and the revenue stream often has uncertain future cash flows (Alshamrani et al.). There are several long-term evaluation instruments such as Total Cost of Ownership (TCO) and Life Cycle Costing (LCC) which can be used to determine future financial values (Woodward, 1997). LCC is a strategy for calculating the total costs from cradle to grave, or over a certain period, which assists in decision making in the product development phase (Jansen et al., 2020)). The time value of money and the application of net present value (NPV), which discounts future inflows and outflows of money to show the present value of an investment, form the basis of LCC. According to Kravchenko et al. (2020), in order to perform a complete calculation, financial measurements must be aligned with a circular business model. The widely used Life Cycle Costing (LCC) methodology only takes into account outgoing cash flows. The WLC method thus gives a broader picture of the economic value of a (partial) object by also including end-of-life benefits, making this model more complete for circular analysis (CB23, 2020b).

In the evaluation of the material cycle for a circular economy, products must be repairable, reusable, upgradeable, demountable, and recyclable (Bocken et al., 2016). To use resources and products in a circular cycle, procedures for value preservation that take the lifespan of products into consideration must be incorporated.

The processes leading to costs must be established to arrive at a circular LCC; this is determined in the product stage (Iyer-Raniga, 2019). This includes not only lifecycle costs, but also potential savings and yields. The design, industrial model, and commercial model for the product will determine what those processes are and where they occur (Iyer-Raniga, 2019). The material cycle of a circular project is reduced, slowed, and closed (MacArthur, 2013). As a result, products will have a longer lifespan, be reusable, maintainable, and upgradeable. Additionally, these products must be disassembled and recycled/reused. These changes result in a life cycle assessment that differs from a standard linear assessment and ensures that cyclic factors are considered and explicitly specified, which often lacks in existing models. A life cycle cost (LCC) calculation that takes into account the entire life cycle of a product can support investment-decision making by examining different circular scenarios, thus better revealing the potential of circular construction (Giorgi et al., 2019). Models that aim to capture economic value often only consider investment and consumption costs. A comprehensive model includes the costs and benefits of the life cycle during and at the end of its lifetime; only then can the model provide a full picture of value preservation (CB23, 2020a).

There are different LCC approaches to evaluate individual factors such as functional value, environmental, and economic performance. A method that combines all factors in the calculation is lacking (Jansen et al., 2020). Figure 14 shows the calculation framework that serves as the basis for Wouterzoon's (2020) CE-LCC model. This model handles multiple usage cycles and various stakeholder domains involved in the life cycle of a circular product and serves as a very comprehensive LCC calculation in terms of circularity. The model has many similarities with Zhang's Building Circularity model (2021).

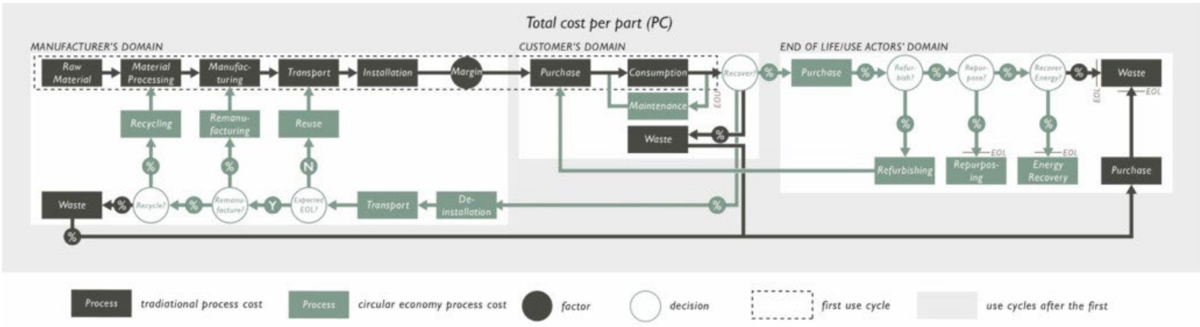

Figure 14 The overall structure of use cycles of a part in the CE-LCC model (Jansen et al., 2020)

The evolution of Life Cycle Cost (LCC) through various stages of circularity must be comprehended for accurate financial estimation of circular measures. A comprehensive LCC calculation empowers businesses to implement Circular Economy (CE) principles and assess the financial implications of circular solutions (Braakman et al., 2021). Buildings with reduced life-cycle environmental impacts often present immediate economic advantages such as reduced operating and maintenance costs, delayed depreciation, and improved asset values (Brueton, 2018). Yet the relationship between the degree of circularity and LCC remains unclear and estimation is difficult. Clarity on this issue can motivate the construction sector to advance towards a circular economy and set targets for circularity levels by determining the financial viability of circular projects over their entire life cycle (Braakman et al., 2021)

Wouterzoon's CE-LCC model emphasizes the assessment of life cycle costs throughout the entire lifespan and serves as a noteworthy illustration of holistic cost analysis (Jansen et al., 2020). However, this model does not incorporate potential savings and benefits, thereby deviating from the principles of the Whole Life Costing (WLC) methodology and failing to adequately account for residual value. Given that residual value plays a significant role in a circular business model, its exclusion in this model is a noteworthy limitation (CB23, 2020b).

4.2 Phases in Circular Life Cycle Costing

The Whole-Life Costing (WLC) methodology takes into account the total economic costs and potential benefits of a product, along with their associated costs and benefits throughout its lifespan, enabling a comparative evaluation of cost-effectiveness among different alternatives throughout the product's life cycle (Di Maria et al., 2018). In the literature, the focus is primarily on the LCC method, which has been employed to analyze various building designs, considering both initial costs and projected future operational expenditures (Bhochhibhoya et al., 2017). The principles of the LCC method closely align with those of the WLC method, except that the latter does not include the consideration of benefits. In this study, the initial costs encompass all expenses related to material procurement and construction of the building. The functional unit of this research comprises different layers of the brand, such as structure, exterior, and spatial design, under various scenarios. The system boundaries for each scenario extend from raw material input in the initial phase to product manufacturing (construction phase), usage phase (operational), and ultimately, disposal, recycling, remanufacturing, or reuse in the end-of-life (EoL) phase. The costs and benefits of each phase are described below (Table 6). The table below shows the life-cycle stages of building products. This can help define the costs and benefits in each phase.

Table 6 Life-cycle stages of a construction product/material. Adapted from CB23 (2020b)

Life cycle phase	Code	Process
Initial Phase	A1	Resource extraction
	A2	Transport
	A3	Production
Construction phase	A4	Transport
	A5	Construction and installation process
Operation phase	B1	Use
	B2	Maintenance
	B3	Repairs
	B4	Replacements
	B5	Renewal
	B6	Operational energy consumption
	B7	Operational water consumption
End-of life phase (dismantling)	C1	Demolition
	C2	Transport
	C3	Waste treatment
End-of life phase (benefits)	D	Residual, recovery and recycling value

4.2.1 Initial Phase

The cost of the initial phase includes the expenditure on the purchase of construction components for the supply of materials on site. Construction component costs are defined from the foundation/investment costs at t=0 (Oppen et al., 2021).

4.2.2 Construction Phase

Construction phase costs consist of labor and equipment expenses required to build the structure, along with general construction costs calculated for risks and profit. The baseline component construction costs rely on the contractor's budget plan, while alternative component costs are derived from the same data and adjusted when changes in construction time and equipment are necessary (Oppen et al., 2021).

4.2.3 Operational Phase

Operational phase costs encompass maintenance and replacement of building components throughout their lifespan, excluding indirect influences on water and energy consumption. Building maintenance primarily involves labor costs for inspection, repair, cleaning, or painting visible building components. Operational costs also account for the replacement of (non-)visible components when their technical or functional lifespan is exceeded, including purchase and labor costs for disassembly and reassembly of the component. These costs may be higher in a traditional design than in a circular design (CB23, 2020b)

4.2.4 End-of-Life Phase within a CE

EoL costs take into account expenses for dismantling, logistics, and reutilization of building components after their lifespan. In the current linear economy, this is typically referred to as debris costs, where materials are depreciated to no value and disposal costs persist. Within a Circular Economy (CE), materials are preserved after their useful life due to their consideration of technical value, resulting in a higher residual value (Jeroen Verberne et al., 2021). Higher original value is captured in closer loops by prioritizing reuse, remanufacturing, and recycling (McKinsey & Company, 2016). Incorporating this value in the EoL phase results in lower LCC for circular buildings. The present value of all lifecycle phase costs minus the potential benefits throughout the building's lifespan is determined by the following equation:

$$LCC = \frac{\sum Ct}{(1 + i - j)^t} \tag{1}$$

Where,
Ct = value of costs at EoL at year t
t = year of cash flow
i = discount rate
j = inflation rate

Since the Life Cycle Cost (LCC) analysis relies on estimates and assumptions, it is crucial to test the sensitivity of the results based on changes in key variables. This can be accomplished by simulating scenarios with varying discount rates, component lifespans, energy prices, or maintenance costs. Sensitivity analysis aids in identifying the main cost drivers and uncertainties within the analysis and can also contribute to the development of risk mitigation strategies (Pernetti et al., 2021).

Estimating the residual value of building elements or products poses a significant challenge, as academic literature has yet to establish a definitive method for its calculation. Consequently, the estimated cost within a life-cycle cost model does not represent the actual cost, but rather relies on assumptions and estimates that may be subject to various uncertainties. In light of these potential inaccuracies, caution is advised when estimating residual value to ensure the LCC model's overall precision. This difficulty in accurately estimating residual value highlights the complexity of incorporating it into LCC models, especially within the context of a Circular Economy, where material value retention plays a crucial role in determining the cost-effectiveness of alternative building designs (Jiang et al., 2022).

4.3 Valuing residual value in circular buildings: challenges and methods

The evaluation of circular buildings is a critical aspect to consider, particularly the residual value or reuse value of the property and the integrated materials and products. However, there is a lack of clear frameworks and definitions to work with. This research aims to explore methods and techniques for measuring and valuing products and materials in the construction sector in order to gain a better understanding of residual value.

Literature reveals that there are various obstacles that make the measurement and valuation of circular residual value complex. These obstacles are related to the uncertainty surrounding the circular transition and future valuation. In current practice, forecasting tools are primarily used to estimate the expected value of circular objects in the future, which means that an estimation of the potential (residual) value of a circular object is made at year 0 for the end of its lifespan.

The ability to value future worth offers opportunities to design projects in advance with the aim of achieving the highest possible residual value. Practical case studies demonstrate that anticipating disassembly and reusability can lead to a five-fold increase in residual value at the end of the lifespan. However, applying forecasting requires taking into account the time effect, as the calculated residual value often lies far in the future, leading to valuation challenges.

Appraisers use the net present value (NPV) method, in which free cash flows are discounted to the present value at a current discount rate. The depreciation effects of the NPV method result in calculations generally involving periods of about fifteen years. When cash flows lie further in the future, these cash flows approach zero, causing circular projects with a long lifespan to lose their value for investments from a financial perspective.

Several methods have been developed to approach residual value, each with their own approach. Below is an overview of the models and their key features:

1. TNO Residual Value focuses on refurbishment costs and considers four key elements: maintenance, repair, and restoration; modifications; disassembly; and other associated costs. These elements are essential in bringing a product to its optimal condition, meeting new requirements, removing specific components, and considering additional expenses such as equipment, certification, transaction, transportation, logistics, and storage. The residual product value, calculated by subtracting refurbishment costs from the production cost of a new product, provides insights into the remaining economic value after refurbishment (TNO, 2021).
2. Alba Concepts focuses on two aspects: the reuse value at the product level and the recycling value at the material level. The reuse value is determined based on various factors, including the initial purchase cost, potential loss in value over time, any quality reduction, costs associated with dismantling, refurbishment expenses, transportation costs, storage expenses, and the number of times the product has been replaced. On the other hand, the recycling value is calculated based on the market value. This includes factors such as the current market price for the product, as well as the weight of its individual components. By considering both the reuse and recycling values, Alba Concepts aims to assess the economic worth of a product at different levels, taking into account its potential for reuse and the market value of its recyclable materials (AlbaConcepts, 2021).
3. Madaster's focuses on maximizing the use of reused and recycled materials and understanding their technical life cycle. It assesses the degree of reuse and recycling at different levels, such as materials, elements, and objects. The platform also facilitates material registration, optimizes residual value, and incorporates financial analysis for decision-making (Madaster, 2021).
4. Functional value refers to the overall value derived from an object's function, taking into account its initial value and potential value in subsequent life cycles. Technical value assesses how the functional value translates into technical aspects such as adaptability, detachability, and responsible material choices. The concepts of degradation, spatial functional adaptive capacity, and technical adaptive capacity are also considered. By evaluating both functional and technical value, a comprehensive assessment of the material and product can be achieved (CB23, 2020b).

Each methodology has its unique measurement approach, specifically focusing on end-of-life assessment. Alba Concepts differentiates itself by incorporating their proprietary detachability index into their financial residual value model. This detachability index provides a valuable indicator of a product's ability to be ransomed, which significantly influences its residual value (Alba-Concepts, 2019).

4.3.1 Assess financial residual value

Alba Concept has developed a fundamental framework for determining the financial residual value of (construction) products and materials, intended for universal application. The calculation method focuses on the product level of reuse value. The financial residual value of products (reuse value) is often higher than the financial residual value of materials to be recycled or downcycled (recycling value). This method provides visibility into the potential reuse value and recycling value, aiming to encourage the highest quality reuse of products and materials. Assessing the financial residual value is challenging and relies on assumptions and future expectations. By defining the residual value as accurately as possible, it contributes to the promotion of a circular construction economy. The model is built on a total cost of ownership approach and aligns well with a whole life cycle method (AlbaConcepts, 2021)
The calculation model distinguishes between two levels:

Product Level (reuse value) based on theoretical value.
Material Level (recycling value) based on market value.

Reuse Value: To determine the reuse value of a material or product, the theoretical value is considered. The theoretical value of reuse is the value of a product or used materials, reduced by a set of corrective factors. The reuse value (RV) of a product is calculated as follows:

$$RV = (PC - L - QR - DC - RC - TC - SC) * NM \qquad (2)$$

Where:

- PC purchase cost (material) [€]
- L loss [€]
- QR quality reduction [€]
- DC dismantling costs [€]
- RC reconditioning costs [€]
- TC transportation costs [€]
- SC storage costs [€]
- NM number of times the product is replaced [unit]

Enclosed is a comprehensive elucidation of the precise formulations employed in the calculations. When establishing the acquisition cost considerations are given to the labor share and material percentage. Determining the extent of loss necessitates making an estimate of the proportion lost during the end-of-life period, which inherently entails uncertainty. Brand's layers are utilized within the calculation methodology to enhance precision in defining this value. The degradation in quality is delineated based on the aging curve, a formula that depicts the progression of a product's condition over its lifespan and is also influenced by fire-related layers. The disassembly cost is contingent upon the product's detachability and the labor proportion required for the disassembly process. The detachability index V2 is employed to evaluate the ease of disassembly (Alba-Concepts, 2019). Upon reaching the end-of-life stage, potential overhaul costs may be incurred to restore the product to its functional state. Transport and storage costs are determined by considering factors such as the hourly rate, distance to be traveled, and the overall volume/weight of the product.

Recycling Value: To determine the recycling value of a material or product, the market value is considered. The recycling value as market value is the value of a product or material, which is determined by supply and demand. This is the real value based on current and actual transactions. The recycling value (RW) of one product is calculated as follows:

$$RW = fhSPI * kgi \tag{3}$$

Where:

- SPi scrap price of product component i per kg [€]
- kgi weight of product component i [kg]
-

The recycling value is defined based on the material's scrap price per kilogram. The scrap price can fluctuate, and it is important to consider price increases and decreases.

These two values provide a good indication of the estimated financial residual value of a product at the end of its lifecycle. However, this financial residual value remains uncertain as it is based on estimations and partially relies on assumptions. Integrating the financial residual value can enhance a circular business case and accelerate the transition to a circular economy in the construction industry (CB23, 2020b).

5 Methodology

This chapter delves into the methodological considerations of the research, elaborating on the various techniques and strategies utilized in this study. As noted in Chapter 1, the research structure follows the sequence proposed by Johannesson and Perjons (2014). This structure ensures a coherent and comprehensive exploration of the research topic: investigating the correlation between building design, the level of circularity, and the associated life-cycle costs and benefits (LCC).

This research employs the research by design method, which integrates research and design to generate new knowledge about the problem at hand (Roggema, 2016). Through the act of designing, this method facilitates the creation of novel insights. In this study, the application of research by design is specifically directed towards the development of a circular life cycle cost (LCC) model.
The research design begins with an extensive literature review, wherein relevant information is gathered and synthesized to support the research hypothesis. This literature review serves as the foundation for understanding the contextual framework and identifying key concepts and principles of circularity in relation to life cycle costs. Subsequently, the research employs the research by design approach through interviews. Careful selection of interviewees is conducted, and interview questions are developed to obtain in-depth insights into the circular aspects of life cycle costs within the specific research context. The interviews yield valuable information and insights, which are then integrated into the development of the circular LCC model tool.

The knowledge and insights gained from the literature review and interviews form the basis for the tool's development. By utilizing the research by design method, the tool is designed and implemented, with a focus on incorporating circularity principles. The tool is developed to function as a practical instrument capable of evaluating and analyzing the circular aspects of life cycle costs.
Ultimately, the developed tool undergoes testing in a case study to assess its reliability and effectiveness. The results of the case study are analyzed and evaluated to demonstrate the potential and efficacy of the tool. These findings, combined with the insights from the literature review and interviews, contribute to the development of the circular LCC tool aligned with circularity principles.
By the end of this chapter, readers gain a clear understanding of the methodological rigor employed to ensure the reliability and validity of the methods and approach. This establishes the foundation for the subsequent chapters, where the research findings and implications are presented, and the developed LCC tool is introduced and discussed.

5.1 Literature review

A literature review provides a summary and evaluation of existing work on a specific subtopic (Knopf, 2006). Conducting a literature review is crucial for establishing the relationship between new research and previous findings (Randolph, 2009). In the context of this research, the literature review serves as the foundation for gaining a deeper understanding of the strategies influencing the potential degree of circularity in construction projects and how circularity can be assessed. It sheds light on the barriers and implementation strategies related to the adoption of the circular economy (CE) in the construction industry, serving as a theoretical framework. The literature review establishes a framework for developing a circular cost model, which subsequently serves as the basis for developing a Circular Life Cycle Cost model. The findings from the literature review form the basis for empirical research, providing methodological insights, highlighting uncertainties and barriers, offering recommendations for future research, and supporting the underlying theory. The literature review, along with the interviews, aims to generate insights for a better understanding of the degree of circularity and the associated costs and benefits in a construction project.

5.2 Interviews

When developing a tool and testing it on a case study with various scenarios, it is crucial to gather specific case-related information. Semi-structured interviews serve as an effective method for obtaining in-depth insights into participants experiences and expertise (Evans & Lewis, 2018). These interviews are particularly valuable for capturing expert perspectives on the research topic (Gill et al., 2008) and identifying common emerging ideas (Creswell & Poth, 2016). By utilizing semi-structured interviews, this study will benefit from a comprehensive understanding of the strategies and challenges related to circularity in the construction industry. These interviews provide rich insights that complement other research methods, such as the literature review, enhancing the overall depth and validity of the findings. The inclusion of diverse perspectives through semi-structured interviews contributes to a well-rounded analysis of the research topic, ensuring a robust and nuanced exploration of the subject matter.

5.2.1 Semi-structures interviews

The literature review focused on developing a model for circularity in the construction industry has identified various strategies and indicators. However, it remains unclear which of these strategies and indicators are most suitable, as there are many uncertainties involved in defining a model due to future predictions and assumptions. To develop a comprehensive model, it is crucial to obtain insights from stakeholders. This can be achieved through conducting semi-structured interviews with experts in the field (Creswell & Poth, 2016). These interviews can provide valuable insights into the challenges and strategies related to circularity in the construction industry and complement the information obtained from the literature review. During my internship at FSD, I have access to these experts and will utilize their perspectives to create a more comprehensive model by integrating the findings from the literature review with empirical data from the semi-structured interviews.

5.2.2 Interviewer selection

To assist the researcher in a case study, respondents for interviews are selected based on their potential knowledge and how it can contribute to collecting the puzzle pieces (Aberbach & Rockman, 2002). Semi-structured interviews are valuable for gathering opinions and experiences (Longhurst, 2003). The focus of this research is to better understand the impact of a building's degree of circularity on costs throughout the entire life cycle, with the development of a tool for this purpose. This tool will be tested using a specific case study. Therefore, it is crucial to consider the experiences and obstacles encountered by individuals involved and stakeholders. In this case, internal experts and stakeholders would be appropriate sources of knowledge. Given that the research topic partially resides in uncharted territory and its implementation occurs within a construction project, it is beneficial to engage a wide range of stakeholders from the construction and waste industries.

5.2.3 Interview preparation

In order to ensure that the results coherently contribute to the main research question's objective, the interviews will be conducted in an integrated manner. The topics and questions discussed with the interviewees will be based on the theoretical framework derived from the literature study. This research mainly investigates how circularity is mapped and its influence on a project's costs and benefits. It aims to gain insights into the obstacles encountered during the interviews and how to tackle these barriers. Given that the research focuses on developing a tool to visualize the level of circularity in a building and the costs and benefits throughout its life cycle, it is crucial to ask questions about these topics, with particular interest in queries related to financial, technical, strategic aspects, and especially cost definition.

Establishing effective research inquiries is paramount when preparing for semi-structured interviews (Turner III, 2010). Drawing from the literature (McNamara, 2006), (several critical factors are distinguished that ought to be contemplated when designing these queries: (1) the inquiries should invite elaboration, (2) impartiality should be maintained in the questioning, (3) the interviewer should limit themselves to one question at a time, (4) the articulation of the questions should be unambiguous, and (5) the deployment of "why" queries should be strictly limited to essential instances. These factors will be thoroughly considered in the design and execution of the semi-structured interviews. Probing for more detailed responses can be accomplished using both verbal and non-verbal methods (Kallio et al., 2016). Verbal probing may include articulating the interviewee's perspective or indicating an interest in their specialized knowledge (Whiting, 2008), while non-verbal probing might involve the strategic use of silence to encourage the interviewee to verbalize their thoughts (Whiting, 2008). Both forms of probing will be employed to secure unbiased views from the interviewees.

5.3 Data analysis

The qualitative data to be analyzed for this thesis are the semi-structured interviews. A data analysis method is needed to analyze the semi-structured interviews. This part of the research examines and reflects on the Data Management Plan (DMP). In this research, data are collected, documented, stored and shared. The data are crucial to scientific progress and must be handled with care to provide a transparent study. The goal of data management is accurate verification of results. Data for the empirical study will be collected through interviews. The data analysis software used in ATLAS.ti.

5.3.1 Data collection

In this research, a significant amount of data is being collected to arrive at the research findings. Valuable information is obtained through interviews, which are meticulously gathered and stored for analysis (see next chapters). When applying the developed model to the case study, data needs to be obtained from the building. The data obtained from FSD and Niersman is confidential and requires careful handling. In the process of developing scenarios, alternative construction products need to be selected to run the scenarios. Obtaining this data is not readily available. In this research, contact is made with the respective manufacturers to acquire this data, aiming to ensure the highest possible validity. An overview containing information on each construction product is included in the appendix. By adopting these measures, the data collection process is conducted with care, ensuring a high level of validity and reliability. The collected data will be analyzed and interpreted to address the research questions and draw conclusions

5.3.2 Data protection

The objective of this research is to safely procure pertinent data by implementing a data management plan, established in conjunction with TU Delft's data steward. To ensure the accuracy of the data, interviews will be conducted with representatives from 8 chosen organizations. The investigator's approach will be one of professionalism and dependability to elicit the most informative responses, with companies being informed of the research intent through formal communication methods. Collected data may encompass personal details, which will be anonymized to safeguard participant identities. All data will be securely housed at TU Delft's SurfData repository, a facility meeting legal mandates, upholding stringent security measures, and conducting routine data backups to mitigate loss risk. While this study will not focus on evaluating personal data, such information may still be collected. Interview transcripts may inherently include individual identifiers. Measures will be taken to anonymize this data to the furthest extent possible to maintain participant confidentiality. Upholding personal data privacy is of paramount importance, a topic that will be further explored in the following chapter for ethical considerations. Data will be securely housed at TU Delft's SurfData facilities. These repositories are stringently safeguarded, meet all legal requisites, and can accommodate various data types, including sensitive and personal information. Opting for TU Delft's facilities ensures a high level of data security, and allows for the centralized storage of diverse data types. Additionally, the routine backup procedures these servers employ substantially reduce the risk of data loss.

5.3.3 Ethical considerations

In my role as a researcher, I will be actively involved in the collection, processing, and safekeeping of data throughout the course of my study. Upholding the principles of scientific rigor and integrity, I am committed to ensuring that the data is meticulously analyzed and the results are scientifically deduced. It is also crucial to respect the privacy of the participants during the interview process. Participants' consent will be sought before initiating any recordings, and such records will be responsibly disposed of upon the conclusion of the thesis research. All data, regardless of its online or offline format, will be securely stored. The research will be conducted responsibly and justifiably, keeping the best interests of the participants at the forefront. The ethics section will address two pivotal concerns: issues related to data subjects and research participants, and issues inherent to the research itself. The validity of the research question, the suitability of the methodology, the appropriateness of the selected research participants, and the confirmation of proper data handling will all be scrutinized to ensure the highest ethical standards are upheld.

6 Development of CLCC tool

This chapter illuminates the process of developing an tool to measure the level of circularity and associated life-cycle costs within construction projects. This tool builds upon the findings from the literature review and expert interviews, applying their insights to a practical setting. The chapter outlines the design, structure, and functionality of this tool, with a focus on how it integrates aspects of circularity and Life-Cycle Costing (LCC) into building design.

6.1 Synthesis of literature and interviews

Given the challenge of mapping circularity due to the lack of universally accepted methodology (refer Section 3.2), this model utilises the R-strategies suggested by Potting et al. (2017): Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. These strategies emerged as key components from the literature review and expert interviews in the construction industry.

The in-depth exploration of R-strategies highlighted five that are especially relevant to the construction industry: Reduce, Reuse, Repair, Refurbish, and Recycle. These strategies, integral during the design and end phases of a building, help quantify a project's circularity level. They provide tangible ways to achieve the dual goals of a circular economy: reducing resource overuse and minimising waste generation. Furthermore, successful strategy implementation significantly reduces greenhouse gas emissions, contributing to the fight against climate change.

However, it's important to understand the nuanced differences between recycling and reuse in the end of life phase. While both aim for extended use of construction materials, recycling often results in downcycling, creating materials of lower quality. On the other hand, reuse, which focuses on preserving the original material value with minimal changes, aligns more closely with circular economy principles.

Assessing circularity in buildings necessitates a comprehensive approach that considers their lifespan and diverse components. Brand's (1995) model, which categorises buildings into layers with different lifespans, informs the proposed framework. This layering considers the products' lifecycle and impacts used and their contributions to the building's overall lifespan and residual value.

The proposed model critically recognises building components' lifespan and their potential for disassembly and adaptability, a design principle that encourages a circular flow of building materials, minimises waste, and preserves material value. It thus enables buildings to adapt to changing needs, extending their useful life and reducing environmental impacts.

Lastly, the assessment tool incorporates both technical and economical values to provide a comprehensive understanding of a building's circularity. The technical value relates to a building's physical lifespan, component quality, and their disassembly and reuse potential. In contrast, the economic value assesses a building's cost-effectiveness over its lifecycle, including adaptability to changing user needs, societal trends, and technological advancements. The following diagram summarises the key elements that, according to the literature and interviews, contribute to implementing circularity and criteria included in the model. These elements, linked to each R-strategy, serve as benchmarks in this model, aiding in the integration of circularity in the built environment and forming the basis for modelling scenarios in the succeeding chapter.

This model serves as an effective tool for assessing and enhancing circularity in the built environment, emphasizing life cycle costs to improve its applicability in real-world scenarios. By incorporating both technical and economical values in the assessment, it provides a more comprehensive understanding of a building's circularity and contributes towards a sustainable built environment. It thus paves the way for the next chapter, where we model various scenarios based on the strategies outlined above.

Table 7 *Synthesis interviews & literature (author)*

Level	#R	Activity	Life cycle phase
9	Refuse	Do not buy / do not use	Initial: decisions about material choice and building design directly influence the quantity of resources required
8	Rethink	Increased functionality through enhanced utilization.	Initial: design decisions can optimize the functional utility of each element.
7	Reduce	Use less and for longer	Initial: decisions about material choice and building design directly influence the quantity of resources required
6	Reuse	Buy 2nd hand and focus on reuse value	Initial & EoL-phase: design for disassembly
5	Repair	Repair product instead of replacing it or preparing it for reuse	Operational & EoL-phase: extend life or repair product for reuse
4	Refurbish	Return for service under contract or dispose	Operational & EoL-phase: extend life or repair product for reuse
3	Remanufacture	Return for service under contract or dispose	EoL-phase: Disassembly and recovery processes
2	Repurpose	Use discarded product or its parts in a new product with a different function	EoL-phase: Disassembly and recovery processes
1	Recycle	Process materials for "2nd" life or buy 2nd hand	EoL-phase: technical value no longer satisfies or procurement of recycled products
0	Recover	Buy and use product with energy recovery	EoL-phase: preventing from becoming waste

6.2 Design and Functionality of the tool

A circular Life Cycle Cost (LCC) analysis constitutes a comprehensive evaluation of the economic expenditures and gains of a product over its entire life span. It extends beyond traditional LCC models by not only tracking all costs but also accounting for potential savings and revenues during all phases. Figure 15 provides a visual representation of the distinct costs associated with each life phase of a building, from raw material acquisition to product disposal, recycling, or repurposing.

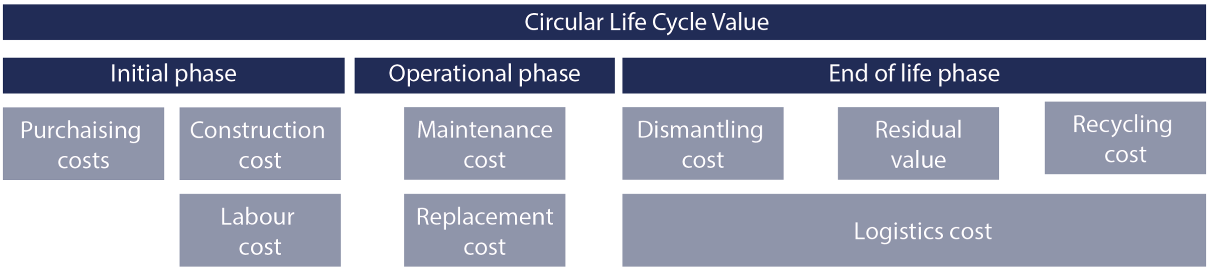

Figure 15 Circular life cycle cost structure (author)

1. Time Value Considerations in LCC Models

To effectively formulate a life cycle costing model, one must acknowledge the intrinsic relationship between time and value. Ignoring this relationship may result in seemingly favorable cost reductions, irrespective of their timing, overshadowing alternatives that may be more costly upfront (Bradley et al., 2018). Thus, understanding the time value of money and the concept of discounting becomes crucial for models that forecast multiple user cycles spanning extended return on investment (ROI) periods. In the proposed LCC model, all costs are taken into account concerning their present value, employing adjustable discount rates to facilitate diverse scenario analysis. Moreover, the model caters to potential inflation effects. The calculation of present value, as described in Equation 1, accounts for the future value (FV), discount rate (i), inflation rate (j), escalation rate of materials (k), and time in years (t).

2. The Multicycle Approach of Circular LCC

The circular LCC model acknowledges the recurring cycles intrinsic to a product's life span, beginning with procurement and construction and concluding at the end-of-use phase. Each usage cycle's duration is determined by the anticipated technical lifespan, as validated by each construction product's manufacturer. This model accounts for the instances of product replacement throughout its lifecycle, resulting in the calculation of a product's total cost considering inflation, interest, and the escalation price of materials.

3. The Phases of Circular LCC

- Initial Phase: The primary costs encompassed in this phase are purchase and labour costs related to construction materials or products, and additional expenditures like transportation and waste handling. Strategic decisions during this phase, such as selecting durable and recyclable materials or employing efficient construction techniques, can impact the overall circularity and cost-effectiveness of a building across its life span.
- Construction Phase: This phase requires establishing maintenance schedules for each product and determining the timing for eventual replacement. It also involves evaluating the reuse

and recycling value of the product, increasing the overall uncertainties of cost calculation compared to the initial phase.

- End-of-Life Phase: EoL costs are crucial in a circular lifecycle cost model, accounting for the unique costs and potential profits during the product's final phase. This phase involves a range of actions, including disposal, reuse, recycling, or recovery, with distinct costs and potential revenue streams.

In conclusion, the design of our circular LCC model fosters adaptability to dynamic conditions and assumptions within the circular economy. It allows adjustments for the escalation rate of materials, discount rate, and labour costs in relation to the circularity of a material. This flexibility ensures the model's robustness, providing a reliable tool to guide cost-effective decisions for a sustainable built environment.

6.2.1 Understanding the Mathematics of the Life Cycle Cost Model

This chapter delves into the mathematics and technical principles of the Life Cycle Cost (LCC) model, tying in closely with the preceding Chapter 6.2, which presented the overall structure of the model in a circular economy context. The LCC model consists of various formulas that incorporate economic and operational factors across the lifespan of a product or material.

The Concept of Present Value:
The notion of present value plays a critical role in the Life Cycle Cost (LCC) model, serving as a conduit to understanding the time value of money. Time is a pivotal element that must be considered in any cost model or economic framework, including our LCC model. If the relationship between time and value is ignored, cost reduction, regardless of when it occurs, may seem more favorable than alternatives that are more costly (Bradley et al., 2018).

Therefore, it becomes crucial to emphasize the value of time and the concept of discounting in models that contemplate multiple user cycles over extended return on investment (ROI) periods. This understanding illuminates why a dollar today is worth more than a dollar tomorrow, and that an investment in the future, such as the replacement of a building product, needs to be included and discounted to its present value to understand the total cost. This section will further highlight the importance of discounting in LCC analysis, a tool used to determine the present value of future cash flows, thereby ensuring the model remains grounded in economic reality and can accurately evaluate potential investments and expenses over time.

- Break down the equation for calculating the present value:

$$Present\ value = \frac{FV}{(1 + i - j - k)^t} \tag{4}$$

Where PV is the present value, FV is the future value, i is the discount rate, j is the inflation rate, k is the escalation rate, and t is the time period.

The Total Cost Calculation of a product:
In a circular life cycle cost model, multiple usage cycles must be considered as discussed in the literature review. The life cycle of a product in the model initiates with the purchasing and construction phase, transitions into the operational phase, and ultimately reaches the end-of-use phase (EOL). The duration of each usage cycle is determined by the product's expected technical lifespan, defined and validated by the manufacturer. Since multiple use cycles occur within a product's

life cycle at the product level, this influences the calculation of a product's total cost. This calculation involves assessing how often a product is replaced throughout its life cycle. These values are aggregated, with consideration for factors such as inflation, interest, and escalation price of materials. To understand this in a more concrete manner, we introduce the total cost (TC) calculation of a product. The total cost of a product is computed by accounting for costs incurred at different time periods, factoring in inflation rates. The formula for this calculation is:

$$TC\ product = \sum [TCtimeperiod * (1+j)^{tc} + TCtimeperiod * (1+j)^{tc} + \cdots]. \quad (5)$$

In this equation, TC_product represents the total cost of the product over its lifecycle, tc refers to the specific time period, and j symbolizes the inflation rate. By applying this formula, we can determine how the costs associated with each phase of the product lifecycle accumulate to yield the total cost of the product. This mathematical representation ensures a robust calculation that aligns with the principles of a circular economy.

Costs in Different Phases:
The LCC model separates the lifecycle of a product into different phases, each with its specific costs.
Initial phase

Initial phase:
The initial phase of the Circular Life Cycle Cost model includes several key costs: the purchase price of construction materials or products, labor costs, and additional material expenses such as transportation and waste handling. Strategic decisions made during this phase, like choosing durable and recyclable materials or efficient construction techniques, can impact the building's overall circularity and cost-effectiveness throughout its lifespan. In the model, these are the costs that are most certain, these are taken from the contractor's cost estimate

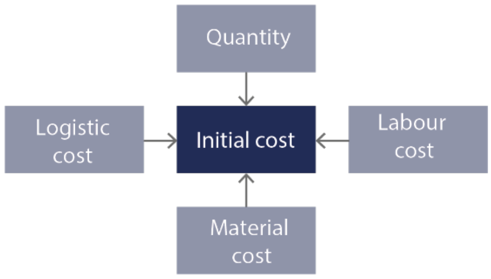

Figure 16 Influence initial cost (author)

Construction phase :
When delineating costs during the operational phase, increased uncertainties emerge. This phase necessitates the determination of maintenance schedules for each product and the timing of its eventual replacement. For every construction element, maintenance requirements need to be established, typically sourced from the construction product manufacturer. Simultaneously, the technical lifespan for each construction product must be identified to ascertain the appropriate replacement timeline. During this process, the potential reuse and recycling value of the product should be evaluated. These two values can be computed using the formulas presented in Equation (7 & 8) . Maintenance costs (MC) are calculated using the following formula and depend on labour costs.

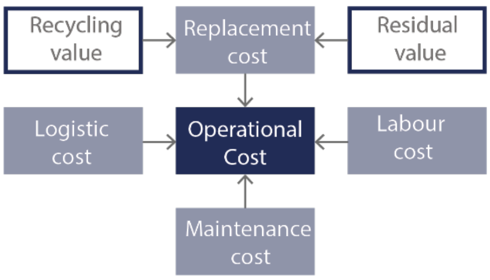

Figure 17 Influence operational cost (author)

$$MC = quantity * \frac{Labour\ cost}{quantity} \quad (6)$$

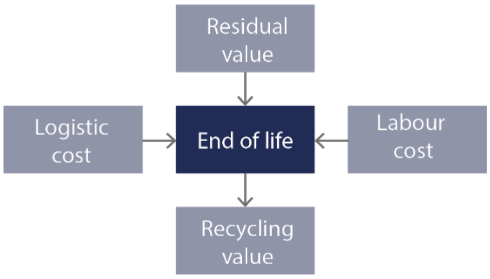

Figure 18 *Influence EoL cost (author)*

End-of-Life phase: The determination of end-of-life (EoL) costs is a vital component in a circular lifecycle cost model as it pertains to the distinct costs and potential returns during the product's terminal phase. This phase comprises various actions, including disposal, reuse, recycling, or recovery, each carrying unique costs and prospective revenue streams, distinct from traditional cost models. Upon reaching its life's end, a product in a building may hold reuse or recycling value. The residual value is influenced by the product's quality reduction, product loss, dismantling costs, refurbishment costs, and transportation costs. If the reuse value does not outweigh the economic and technical value, products can also be recycled. These costs are mainly dependent on demolition costs, the scrap price of the material, and transportation costs. Therefore, this phase does not only generate costs but can also present revenues.

Estimating costs and revenues can be challenging as it involves future predictions, and uncertainty plays a dominant role in their definition. In the model, these uncertainties are kept as minimal as possible by defining the value for each cost item using substantiated formulas. The model also takes into account the Layers of Brand, which have a significant influence on a product's detachability and the product replacement cycle.

Calculating the Reuse Value:
This section aims to demonstrate how to calculate the reuse value (RV) of a product using the formula (AlbaConcepts, 2021):

$$RV = (PC - L - QR - DC - RC - TC - SC) * NM \qquad (7)$$

- Understanding the components of this formula: purchase cost (PC), loss (L), quality reduction (QR), dismantling costs (DC), revision costs (RC), transportation costs (TC), and storage costs (SC).
- Providing real-world examples for each component to ensure practical understanding.

Calculating Recycling Value:
This part of the chapter deals with the calculation of the recycling value (RW) using the formula:

$$RW = \sum Sp_i * kg \qquad (8)$$

- Explain the concept of scrap price (SPi) and the role of the weight of the product component (kg) in determining the recycling value.
- Discuss the factors influencing the scrap price and how to collect reliable data for this parameter.

Adapting the Model to Different Scenarios:
The final section will discuss how different scenarios can be factored into the LCC model:
- Explore how material inflation and the escalation rate can impact calculations.
- Discuss the influence of the discount rate on the LCC, showing how changes in this rate can significantly alter outcomes.

- Illustrate how labor costs can be adjusted based on the degree of circularity of a material, reflecting on the potential savings associated with

6.2.2. Detailed Breakdown of Cost (& potential revenue) components

The circular life cycle cost model involves detailed examination of various cost components across multiple usage cycles. These cost components include purchase costs, maintenance costs, replacement costs, operational costs, dismantling costs, waste handling costs, transportation costs, and storage costs. Each of these cost components is distinct, and their calculation necessitates specific formulae. This section will provide an in-depth explanation of these costs, the formulae used for their calculation, and the factors influencing these costs. It will also highlight how these costs contribute to the total cost of a product in the circular life cycle cost model (AlbaConcepts, 2021).

The purchase cost (PC) is the initial cost involved in acquiring the product, which is typically provided in the cost estimate. However, if not available, it can be calculated using the following formula:

$$PC = C_m * \%\, material \tag{9}$$

- Cm: the purchase cost of the product [€]
- % material: the material proportion or percentage of material (based on layers Brand) [%]

Loss refers to the proportion of the product lost during reuse, expressed as a percentage of the purchase cost. The loss (L) of one product is calculated as follows:

$$L = PC \; * \%\, loss \tag{10}$$

- PC: purchase cost of material [€] (formula)
- % loss: The proportion of the product that is lost at the end of its lifespan [%]
- The percentage loss is defined per layer of Brand. A window frame has a higher loss (skin) compared to a steel beam (structure).

As a product progresses through its life cycle, it may experience degradation, leading to a reduction in quality. This quality reduction (QR), defined as a percentage of the purchase value of the product, can be calculated using the formula:

$$QR = PC \; * \%\, quality \tag{11}$$

- PC: represents the purchase cost (material) [€] (3)
- % quality represents the proportion of quality reduction [%] ()

To define the quality of a product, the theoretical condition is determined based on the aging process (NEN2767). The theoretical condition is determined using the aging curve, which indicates the condition progression as a function of the lifespan of a product. The formula for this is as follows:

$$\% \, quality = 1 + \left(\frac{1}{2}\right) \log(1 - \frac{Tt}{L}) \tag{12}$$

- Tt: the theoretical age (years)
- L: the full lifespan (years)
- This translates into quality condition scores, where 1 represents a low condition score and 6 represents a high condition score (AlbaConcepts, 2021).

The dismantling cost (DC) pertains to the cost of disassembling a product at the end of its life cycle. This cost is computed based on the required disassembly time, the average hourly rate, and an adjustment factor corresponding to the product's detachability. If a product exhibits a high degree of detachability, the labor duration for disassembly decreases relative to that of assembly and vice versa.

$$DC = \frac{0,5}{D_i} * C_m * \% \, labour \tag{13}$$

- D_i : detachability index [-]
- C_m : purchase price product [€]
- % share labour [%]

The percentage of labor can be obtained through the estimation provided by the constructor. If not available, it is defined based on the layers. The disassembly feasibility, Di, is calculated using the disassembly index developed by Alba Concepts. This index is defined by the type of connection, accessibility, edge confinement, and intersections.

The revision costs (RC) are tied to the product's quality reduction and often entail inspection and repair. These costs, which increase with a higher quality reduction, can be calculated as RK=QR*% revision, where % revision represents the proportion of corrective maintenance.

$$RC = QR * \% \, revision \tag{14}$$

- QR: the quality reduction [€, according to formula (5)
- % revision: the proportion of corrective maintenance [%] (dependent on the layers of Brand)

Transportation costs (TC) and storage costs (SC) form another integral part of the circular life cycle cost model. Transportation costs are determined based on the maximum volume and weight of the transport vehicle, the total volume and weight of the product, and the distance traveled. Storage costs, on the other hand, are calculated based on the average storage cost per square meter per month, the average storage duration in months, and the ground surface area of the product. Calculation of transportation costs (TC):

$$TC = \left(\text{Base fare} + (\text{kilometre rate} * \text{Distance} + \text{Per hour rate} * \text{Total hours})\right) * \frac{Weight}{Max\ kg} \tag{15}$$

- Base fare is the upfront charge [€]
- Per kilometer rate is the cost per km traveled [€/km]
- Distance is the total distance to be traveled [km]
- Per hour rate is the transporter's hourly rate [€/hour]
- Total hours include loading and unloading time [hour]
- Weight is the total weight [kg]

- Max kg is the maximum weight the transport vehicle can carry [kg]
- Volume is total volume of product [m3]
- Max Volume is the maximum volume the transport vehicle can carry [m3]

Secondly, if the ratio of the maximum volume in cubic meters (m3) of the transport vehicle (MaxVolume) to the total volume of the product (Volume) is less than or equal to the ratio of the maximum weight in kilograms (kg) of the transport vehicle (Max kg) to the total weight of the product (Weight), the transportation costs (TC) for one product are calculated as follows:

$$TC = \left(\text{Base fare} + (\text{kilometer rate} * \text{Distance} + \text{Per hour rate} * \text{Total hours})\right) * \frac{Volume}{MaxVolume} \quad (16)$$

The storage costs refer to the expenses involved in the temporary warehousing of the product. These costs are determined based on the average storage cost per square meter per month and the average storage duration in months. The storage costs (SC) for a single product are calculated as follows:

$$SC = Cl * T * Oproduct \quad (17)$$

- Cost location (Cl) is the expense of the storage location [€/m2/month]
- Storage duration (T) is the duration of storage [month]
- Product ground area (O product) is the ground surface area of the product [m2].

The reuse value is defined using these formulas. It should be noted that these values are estimates and not based on actual data.

To determine the recycling value for a material or product, its market value is taken into consideration. The recycling value as a market value is essentially the worth of a product or material, which is dictated by the principles of supply and demand (read: transaction value). This is the real value, founded on current, actual transactions. The recycling value (RW) of a single product is calculated as follows:

$$RW = \sum Sp_i * kg \quad (18)$$

- Scrap Price_i (SPi): the scrap price of product component i per kilogram [€],
- Weight (kg): is the weight of product component [kg].

The various scrap prices are dependent on the material being utilized. These scrap prices are defined per material in the appendix. It should be noted that scrap prices can fluctuate over time, and therefore, future price changes must be taken into consideration. This is an example of a speculation; the model will contain numerous assumptions and speculations that must be taken into account. These will be discussed further in the following sections.

The financial residual value is perceived as the aggregate of the reuse and recycling values. In the model, it must be defined what percentage of the material is designated for reuse and what percentage for recycling. This assessment can be challenging. The report illustrates the importance of the layers of Brand and the detachability when defining potential reuse. These two values are utilized to make an estimation. The subsequent formula displays how the financial residual value is composed of the two components, reuse and recycling:

$$Financial\ residual\ value = (RV * \%\ reuse) + (RW\ \%\ recycling) \quad (19)$$

- RV represents the reuse value [€]
- % reuse represents the proportion of reuse [%]
- RW represents the recycling value [€],
- % recycling represents the proportion of recycling [%]

When defining various costs and potential revenues, several variables may influence the final outcomes. One crucial variable to consider is the inflation rate, which is incorporated into the model. For each product or material, the escalation rate can be adjusted, allowing for calculations under different scenarios and assumptions. The initial costs of circular products may be higher; however, these costs may converge with conventional products in the future as demand for circular products increases. To account for these potential shifts, the model allows for easy adjustments of prices. Additionally, the discount rate can be modified within the model to enable diverse analyses. Labour costs and the labour proportion of circular products may be lower due to a higher disassembly index, indicating greater ease of disassembly in circular products. In the model, labour costs can be adjusted in relation to the degree of circularity of a material. This flexibility ensures that our model remains robust and adaptable to changing conditions and assumptions in the circular economy.

6.3 Uncertainties, barriers and obstacles in the development of the tool

The development of a circular life cycle cost tool for the built environment faces various uncertainties, barriers, and obstacles. These challenges arise from the complex nature of integrating circularity principles, time value considerations, and multiple usage cycles within a comprehensive cost analysis framework. Additionally, the lack of available data further complicates the accurate assessment of life cycle costs and benefits. This chapter aims to explore and shed light on the uncertainties, barriers, and obstacles encountered in the development of the circular life cycle cost tool.

1. Time Value Considerations: One of the main challenges in developing the circular life cycle cost tool is accounting for the intrinsic relationship between time and value. Failure to consider this relationship can lead to misleading cost reductions that overshadow more costly alternatives. Understanding the time value of money and the concept of discounting is crucial for accurately forecasting costs and evaluating return on investment over extended periods.
2. Uncertainties in Cost Estimation: The process of estimating costs in a circular life cycle cost model involves uncertainties. Factors such as defining costs, residual value, and availability of data for model input pose challenges. The reliance on assumptions and expectations, such as interest rates and inflation, can introduce uncertainties and highlight the need for more accurate data and refined cost estimation methodologies.
3. Lack of Data: Obtaining reliable and comprehensive data for model inputs, such as scrap prices, inflation rates, and escalation rates, can be a challenge. The accuracy and relevance of the data used in the model are crucial for producing reliable cost calculations and outcomes.
4. Complexity of Circular Strategies: Implementing circular strategies in the built environment requires clear definitions and consensus. However, there is a lack of agreement on what the circular economy means for the built environment. Distinguishing between different circularity strategies, such as reuse and recycling, is essential for effective and efficient application, but achieving consensus on definitions and approaches can be a barrier.

5. Evaluation of Reuse and Recycling Value: Assessing the value of reuse and recycling in the circular life cycle cost model involves uncertainties. Factors such as product loss, quality reduction, dismantling costs, refurbishment costs, transportation costs, and scrap prices influence the financial implications of these actions. Estimating these costs and revenues accurately is challenging due to uncertainties and the need for future predictions.
6. Limited Consistency and Standardization: The lack of universal metrics and accepted standards for measuring circularity in buildings poses challenges in quantifying the degree of circularity. Developing a universally accepted metric that encompasses circular strategies is crucial for accurate assessment and comparison of circularity across buildings and projects.
7. Adaptability to Dynamic Conditions: The circular life cycle cost model needs to be adaptable to dynamic conditions and assumptions within the circular economy. Factors such as material inflation, escalation rates, discount rates, and labor costs need to be adjustable to accommodate different scenarios. Ensuring the model's flexibility and robustness requires considering various factors that can change over time.
8. Complexity of Cost Components: The circular life cycle cost model involves a detailed breakdown of cost components across different phases, including purchase costs, maintenance costs, replacement costs, operational costs, dismantling costs, waste handling costs, transportation costs, and storage costs. Calculating these costs accurately and accounting for factors such as inflation, interest rates, and labor costs can be complex and require detailed analysis.
9. Limited Availability of Reuse and Recycling Data: Gathering reliable data on the reuse and recycling value of building products and materials can be a challenge. The availability of data on product durability, reuse potential, and recycling processes may vary, making it difficult to assess the financial implications accurately.
10. Need for Consistent Methodologies: Developing consistent methodologies and formulas for cost calculations, such as present value, reuse value, and recycling value, is essential for ensuring the reliability and comparability of results. Consistency in methodologies allows for accurate assessments and informed decision-making in the context of circular life cycle cost analysis.

7. Case study of Coolbase

In this chapter, we will evaluate the developed circular Life Cycle Cost (LCC) tool using a case study as a testing ground to ascertain the potential value of the model. The model aims to provide insights into the influence of circular strategies, namely the potential degree of circularity, on the potential costs and benefits throughout the lifespan of a construction project. Implementing the model in a case study aids in the development of more extensive knowledge in this area. Additionally, the tool seeks to clarify whether circular interventions are indeed more expensive than traditional projects and, if so, to illuminate where these specific costs are incurred. The tool is tested by applying various circular strategies that have been previously elaborated. This chapter initially presents the generic results derived from interviews. Subsequently, we introduce the case study and discuss the different circular scenarios that emerged from the interviews and strategies. These scenarios are contrasted with the traditional base scenario of the case. The life cycle cost and circularity evaluation is carried out for each alternative according to the methodology delineated in the previous chapter. We will begin by presenting the generic results.

7.1 Identified Interventions from Interview Insights

Table 8 *Identified interventions (author)*

Strategy	Site	Structure	Skin	Services	Space plan
Reduce	Minimize intensive construction material usage	Reduce usage of concrete and steel	PV panels for facades of buildings	Smart systems that reduce energy usage	reducing the overall space needed.
	Prefabrication and Modular Construction	Reducing the amount of material used in the structure through efficient design	reduce the demand for virgin resources→ wood for example	Using water-efficient appliances, fixtures, and fittings in the building can significantly reduce the water demand	As much as possible shared space
	materials with lower embodied carbon	prefabrication and modularity reduce construction waste	Biobased materials usage instead of conventional materials	Implementing highly efficient HVAC systems	
Reuse	Instead of demolishing existing structures, adaptive reuse involves repurposing and renovating existing buildings	This approach involves designing structural components such that they can be easily disassembled and reused in the future.	Reuse of old window frames and façade systems	Reusable of Electrical Components	Using demountable partitions for interior walls allows for easy reconfiguration of spaces.
	salvage valuable materials from existing structures or site elements	Reuse of structural materials from deconstructed buildings (	Use of reused bricks	Modular HVAC systems	add wooden cladding to wall, which are made of certain percentage of reusable materials
	Making the structure demountable	By designing and constructing with standardized	Modular façade systems	Designing building services in a modular and	Circular kitchens

		structural components	with design for disassembly	standardized way, allowing for easy disassembly and reassembly	
Repair	Site Infrastructure Repair	strengthening existing structural components instead of replacing them entirely.	Surface Repair and Refinishing	Equipment and System Maintenance	Flooring Restoration
			Cladding Repair		Instead of demolishing and reconstructing walls or ceilings, repair strategies can be utilized
			Window and Door Repair		
Refurbish	Site	Structure	Skin	Services	Space plan
		Repair damaged sections of the structure	Refurbish exterior cladding	Upgrade electrical systems with more sustainable options	
		Improve structural efficiency with advanced materials or techniques	Recondition brickwork or other exterior finish materials		
			Restore window frames and glasses		
Recycle	Use of recycled concrete	Use of recycles concrete and reclaimed steel	Recycled aluminium and steel for frames	recycling copper piping from plumbing systems or recycling steel components from mechanical systems to be used in the manufacturing of new building service elements.	Focus on renewable/ biobased materials
	Asphalt used in site with 100 recycled asphalt	Use of recycled polymer	Use of biobased materials		Use of recycled materials such as recycled carpets and tiles
	a waste management system on the construction site	Use of timber for structure.	Wooden materials (recycled)		Modular and Flexible Space Design
	valuable site elements such as bricks, stones, or landscaping features can be salvaged		Recycled aluminium and steel for frames		Use of glass for glazing as recycling is at a high

7.2 Description of the case study

At my internship company FSD, they have several development projects running, here I picked a project based on challenges and opportunities. It involves a 16-storey building in Rotterdam with a gross floor area of almost 7000 m2 and over 20000m3. The building will be delivered in a traditional construction method where it does meet BREAM requirements. The building consists of a construction of concrete and steel and has a curtain wall skin. The building is very interesting as initially the building was to be delivered in timber construction (FSD, 2023).

Given the financial limitations, a conventional construction method was ultimately selected, thus preventing the building from achieving optimal circularity. The case was chosen because of the challenge of making such a complex building circular. Moreover, compared to other projects at FSD, the project is already at an advanced stage and a lot of information is available. For instance, the contractor's initial cost calculations are available. The wood construction calculations are also available, so this can serve as a basis for a scenario with wood construction. The cost estimates are very specific, clearly describing for each building element what the costs consist of such as price of materials, equipment, logistics costs and labour hours required for construction.

Figure 21 *Render artist impression of Coolbase (FSD, 2023)*

7.3 Development of scenarios

The formulated scenarios are contrived with the explicit objective of enhancing the building's circularity relative to the baseline instance. This enhancement is sought through the strategic implementation of circular interventions within one or more building strata for each scenario. The corresponding alterations in activities, juxtaposed against the base case, are curated based on the insights derived from interview responses.

As shown in the figure below, the scenarios are mainly defined on the strategies Reduce, Recycle and Re-use. This is because this is a new construction project and these strategies have the most influence on circularity (interviews) The strategies refurbish and repair recur in each scenario, as they mainly focus on extending the life cycle of a product (operational phase). The strategies reduce, recycle and re-use focus more on the initial phase and end-of-life phase.

Table 9 Scenarios and their interventions (author)

Scenario	Interventions
Scenario 1 (Reduce)	Reduce use of products such as concrete and steel (structure)
Scenario 2 (Reduce)	Substitution of primary raw materials with biobased renewables
Scenario 3 (Recycle)	Substitution of new materials with reclaimed materials
Scenario 4 (Reuse)	Keep working with traditional materials, but with a high probability of reuse in the end

The selection of circular strategies in specific scenarios is based on insights gained during the research. These scenarios are potentially feasible to implement in the built environment and each has different impacts on the financial aspects in each phase. The results of the case study will determine the life cycle costs per scenario. The next chapter will elaborate on the life cycle costs compared to the base scenario for each scenario.

7.3 Application of scenario’s to the Case Study

The subsequent section provides a comprehensive analysis of the scenarios. Each scenario encompasses the key building elements, classified according to their respective layers. Given that the complete cost estimate comprises over 37 building interventions and encompasses a vast array of more than 100 distinct building elements, a condensed selection has been included for conciseness. While the model incorporates all elements in its assessment, including them all within this section would result in unnecessary confusion. Each scenario is constructed based on the layers of Brand, where the site, structure, skin, services and space plan serve as underlays and structure (Brand, 1995). For each scenario, the words in bold in the overview are elements that have been replaced compared to the base scenario. An overview of all materials used in the scenarios is attached in the Appendix.

<u>Base scenario:</u>

The base case is derived from the preliminary design where most of the methods used are traditional or rather linear construction methods. Below is an overview from the main building elements per scenario.

Table 10 Base scenario interventions (author)

Structure	Skin	Space plan
Foundation: concrete (cast-in-place) Foundation piles: concrete Floors: Concrete wide slab floor (cast-in-place) + concrete Columns: precast concrete columns Beams: concrete beams Walls: sand-lime brick elements Stairs: concrete stairs Metal structural work: Roof: part metalwork and a concrete roof	Window frames: steel frames Door: steel Windows/doorframes: aluminium and wood Window/door glass: HR ++ Gutter: aluminium Window sill: aluminium Roofcovering: bituminous roofing Facade: Glass curtain wall Wall cladding: wood finishing	Floor finish: PVC floor Interior wall finish: traditional plaster and paint Internal walls: sand-lime brick, gibo and metal stud walls Interior door frames: wooden frames Interior doors: steel casing Interior fencing: steel balustrade Inner sills: natural support Window sill: wood Wall tiles (toilet + bathroom): ceramic tiles Floor tiles (toilet + bathroom): ceramic tiles Stairs: Steel spiral staircase

Below is a schematic representation of the case study. In which the dominant role of glass giving can be clearly seen.

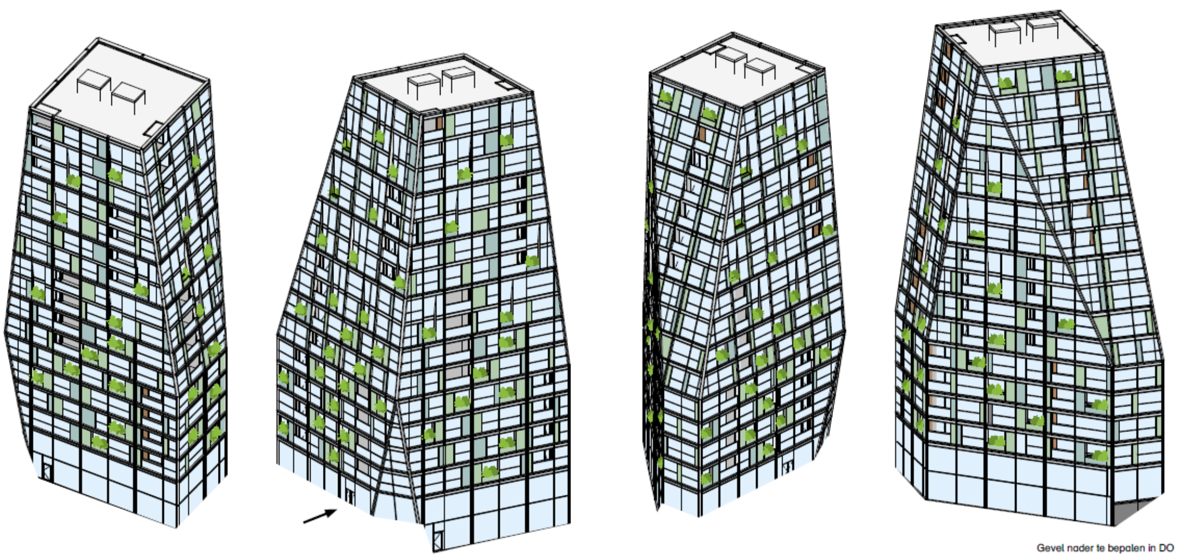

Figure 22 Various 3D models of project Coolbase (FSD, 2023)

<u>Scenario 1:</u> Reduce use of products such as concrete and steel (structure)

This scenario centers around the reduction of concrete utilization. Given that it involves a high-rise building constructed using conventional methods, the predominant materials employed in the structure are concrete and steel, rendering it non-circular. In this particular scenario, the aim is to substitute the concrete and steel elements with wood to the greatest extent feasible. Initially, the building would be realized using timber construction, as advised by the structural engineer(FSD, 2023). The construction comprises a concrete core and plinth, accompanied by a timber tower. As you can see this scenario focuses on the layer structure (Figure 23)

Table 11 Scenario 1 and interventions (author)

Structure	Skin	Space plan
Foundation: concrete (cast-in-place) Foundation piles: concrete **Floors**: CLT-timber **Columns**: CLT-column if possible, otherwise concrete **Beams**: CLT-timber beams if possible otherwise steel beams **Walls**: CLT - timber **Stairs**: concrete stairs Metal structural work: Roof: part metalwork and a concrete roof	Window frames: steel frames Door: steel Windows/doorframes: aluminium and wood Window/door glass: HR ++ Gutter: aluminium Window sill: aluminium Roofcovering: bituminous roofing Facade: Glass curtain wall Wall cladding: wood finishing	Floor finish: PVC floor Interior wall finish: traditional plaster and paint Internal walls: sand-lime brick, gibo and metal stud walls Interior door frames: wooden frames Interior doors: steel casing Interior fencing: steel balustrade Inner sills: natural support Window sill: wood Wall tiles (toilet + bathroom): ceramic tiles Floor tiles (toilet + bathroom): ceramic tiles Stairs: Steel spiral staircase

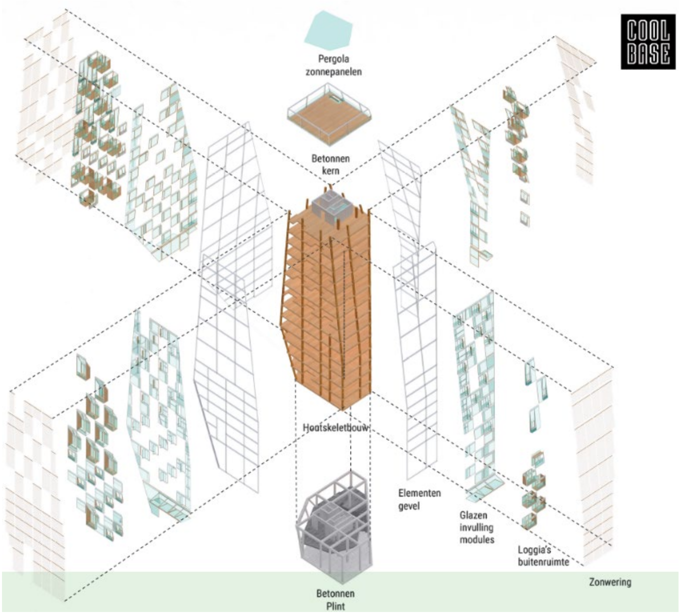

Figure 23 Explosion drawing of concrete core and timber frame construction (FSD, 2023)

Scenario 2: Substitution of primary raw materials with biobased renewables

This scenario focuses on the substitution of primary raw materials with bio-based renewables across various layers of the building, with a particular emphasis on the structure, skin, and space plan layers. The objective here is to enhance the building's circularity by significantly minimizing the reliance on non-renewable resources. It's noteworthy that bio-based renewables, due to their ability to be regenerated, possess substantial potential for fostering sustainability and circularity in the building sector.

Table 12 Scenario 2 and interventions (author)

Structure	Skin	Space plan
Foundation: concrete (cast-in-place) Foundation piles: concrete **Floors**: Concrete wide slab floor (cast-in-place) + concrete Columns: precast concrete columns Beams: concrete beams **Walls**: Hemp building blocks **Stairs**: wooden stairs Metal structural work: Roof: part metalwork and a concrete roof	**Window frames**: wood (Platoowood) **Door**: Wood **Windows/doorframes**: Wood (platoowood) Window/door glass: HR ++ Gutter: aluminium Window sill: aluminium **Roofcovering**: Biobased (Derbigu) Facade: Glass curtain wall Wall cladding: wood finishing	**Floor finish**: Marmoleum floor **Interior wall finish**: Loam, cork and bio-based paint **Internal walls**: Hemp building blocks **Interior door frames**: wooden frames **Interior doors**: wood **Interior fencing**: wooden balustrade Inner sills: natural support **Window sill**: wood **Wall tiles (toilet + bathroom)**: natural hydrated lime (tadel paint) **Floor tiles** (toilet + bathroom): wooden and bamboo tiles **Stairs**: Wooden spiral staircase

Figure 25 Loam finishing with tadel paint (Ecowonen, 2023)

Figure 24 Impression of Platowood (Platowood, 2023)

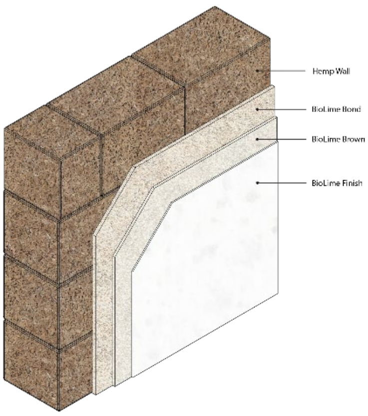

Figure 26 Hemp building blocks (Isohemp, 2023)

Scenario 3: Substitution of new materials with reclaimed materials

This scenario underscores the extensive usage of reclaimed materials as replacements for new ones across different layers of the building, specifically the structure, skin, and space plan layers. This approach intends to reinforce the building's circularity by exploiting the potential of materials already in the production-consumption cycle. A key strength of using reclaimed materials is that it contributes to waste reduction and encourages resource efficiency, which are pivotal tenets of circularity. In terms of the building's structure, reclaimed materials find usage in diverse forms. Notably, circular or recycled concrete is chosen for the foundation, highlighting the possibility of reusing materials even in structural applications.

Table 13 Scenario 3 and interventions (author)

Structure	Skin	Space plan
Foundation: Circular/recycled concrete Foundation piles: concrete **Floors**: VBI hollow-core slab floor ''green'' Columns: precast concrete columns **Beams**: used steel beams **Walls**: 2nd hand sand-lime brick elements + Xella sand-lime brick **Stairs**: c2c stairs Metal structural work: Roof: part metalwork and a concrete roof	**Window frames**: Bohaco system **Door**: Úsed doors **Windows/doorframes:** used frames Window/door glass: HR ++ Gutter: aluminium Window sill: aluminium **Roofcovering**: citumen roofing Facade: Glass curtain wall **Wall cladding**: Fireclay bricks + ''Armstrong'' ceilingsystem	**Floor finish:** ''Drowa'' floor **Interior wall finish**: traditional plaster and ''rigo''paint **Internal walls:** Knauf system **Interior door frames**: used frames **Interior doors**: used doors **Interior fencing:** used fencing (sparq) Inner sills: natural support Window sill: wood **Wall tiles (toilet + bathroom):** Mosa tiles **Floor tiles (toilet + bathroom):** Mosa tiles **Stairs**: C2C stairs

Figure 29 Knauf wall system (Knauf, 2023)

Figure 27 2nd hand steel columns (BioParner5, 2022)

Figure 28 2nd hand frames (Gebruiktematerialen, 2023)

Scenario 4: Keep working with traditional materials, but with a high probability of reuse in the end

This scenario proposes a different approach to enhancing circularity, where the focus lies in employing traditional building materials that possess high potential for reuse. The choice of materials within the structure, skin, and space plan layers is determined not merely by their conventional functions, but also by their prospective ability to be disassembled and reintegrated into future structures, thereby extending their lifecycles

Table 14 Scenario 4 and interventions (author)

	Skin	Space plan
Foundation: concrete (cast-in-place) **Foundation piles**: Pekko piles and beams **Floors**: Peikko floors + Cemwoed **Columns**: Peikko columns **Beams**: Peikko beams **Walls**: CLT- walls (Peikko) **Stairs**: wooden stairs **Metal structural work:** Steelframe ConXL and Con XR Roof: part metalwork and a concrete roof	**Window frames:** Profix mechanical connection **Door**: Berkvens zero door **Windows/doorframes:** Profix mechanical connection **Window/door glass**: HR ++ demontable Gutter: aluminium Window sill: aluminium **Roofcovering**: EPDM Facade: Glass curtain wall **Wall cladding**: Alkonder cladding (Lease)	**Floor finish:** Studiowea tiles Interior wall finish: traditional plaster and paint **Internal walls**: CLT **Interior door frames:** Profix mechanical connection **Interior doors:** Berkvens zero door **Interior fencing:** Sparq **Inner sills:** natural support dry connection Window sill: wood **Wall tiles (toilet + bathroom)**: solid surface tiles **Floor tiles (toilet + bathroom):** solid surface tiles **Kitchen:** the new makers Stairs: Steel spiral staircase

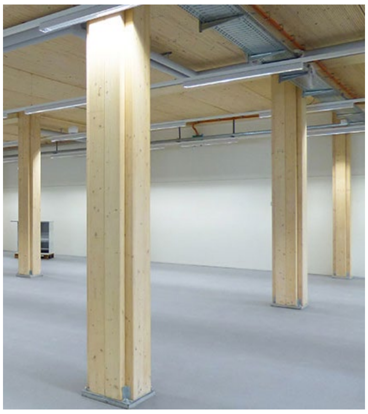

Figure 32 Deltabeam and columns by Peikko (2023)

Figure 30 Cross laminated timber by Katus (2023)

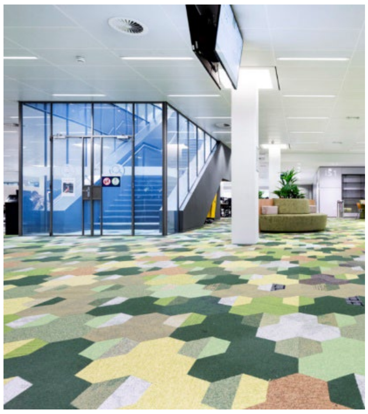

Figure 31 Circular flooring system by Studiowea (2023)

7.4 Analysis of the case study

In the forthcoming scientific analysis, the outcomes from the application of a purposefully-developed Life Cycle Cost (LCC) tool across a variety of construction scenarios, each representing a distinct degree of circularity, are scrutinized. Every scenario encapsulates a unique strategy: the reduction in the utilization of particular materials, the substitution of primary raw materials with renewable bio-based materials, the replacement of new materials with reclaimed ones, and a preferential focus on the reuse of traditional materials. These strategies signify different levels of circularity, each presenting unique benefits and challenges. This initial analysis assumes an interest rate of 4 percent, representative of past rates and projected for the future, along with a 50-year timespan for the initial LCC calculation, and an inflation rate of 2 percent based of past rates and expectations (OECD, 2023).

The primary aim of this analysis is to elucidate how these circular strategies, each embodying a unique approach towards circularity, impact the aggregate LCC of a building throughout its lifecycle. This involves comparing the associated LCC of each scenario against the base scenario, thereby enabling a more quantifiable understanding of the financial implications of adopting circular strategies.

Table 15 *Comparing LCC by different scenarios (author)*

	Initial	OMR	EoL	LCC
Base scenario	€16.167.163	€ 10.546.832	€739.210	€27.453.205
Scenario 1	€19.732.210	€10.873.504	€430.827	€31.036.541
Scenario 2	€16.431.246	€10.810.324	€456.432	€27.698.001
Scenario 3	€16.096.237	€ 10.578.266	€516.590	€27.191.093
Scenario 4	€16.750.672	€10.050.970	€ -8.873	€ 26.792.769

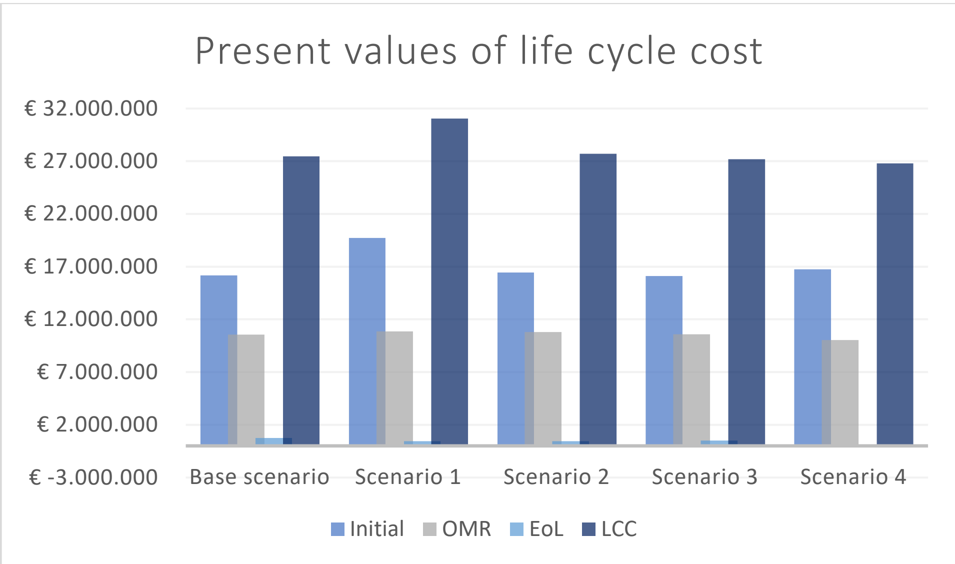

Figure 33 *Modelling the outcome of LCC of different scenario's (author)*

In the table and figure above, various scenarios are articulated through cost and benefit perspectives spanning the entire lifecycle of a building. Evidently, each scenario has distinct impacts on the individual lifecycle phases and the comprehensive LCC.
In Scenario 1, the focus lies in minimizing the usage of concrete - a prevalent building product - by substituting it with materials that better align with the tenets of a circular economy. This approach results in a considerably higher LCC than the base scenario. Subsequent sections provide a detailed examination of these cost allocations.
In Scenario 2, the emphasis is on maximizing the utilization of bio-based materials known for their superior circular performance. Intriguingly, the LCC for this scenario mirrors closely to that of the base scenario, indicating that incorporating renewable materials does not necessitate substantial financial compromise.
Scenario 3 targets the optimal use of reclaimed materials, chiefly sourced from buildings approaching the end of their lifecycle. This strategy, as evidenced by the LCC calculation, proves more cost-efficient than the base scenario, endorsing the economic viability of repurposing used materials. Lastly, Scenario 4 revolves around the principle of reusing materials in the end-of-life phase. This necessitates the building products to possess a high degree of adaptability and to be easily disassembled without quality degradation. Notably, this scenario exhibits the lowest LCC among all others, a consequence largely attributable to the financial advantages realized in the end-of-life phase.

These findings indicate a consequential link between circular strategies and LCC, with the reclamation and reuse of materials emerging as potentially advantageous practices in cost management over a building's lifecycle.

7.4.1 Cost-analysis in initial phase

The impact of various scenarios on initial costs is significant, as indicated in the figure below. Scenario 1 stands out, requiring an investment about 20 percent greater than the base scenario. In this scenario, concrete usage is minimized as much as possible, replaced with timber construction. Due to the complex form of the building, more construction material is required, and wood prices are substantially higher than those of concrete (primarily in-situ concrete in the base scenario) (Delft, 2022).

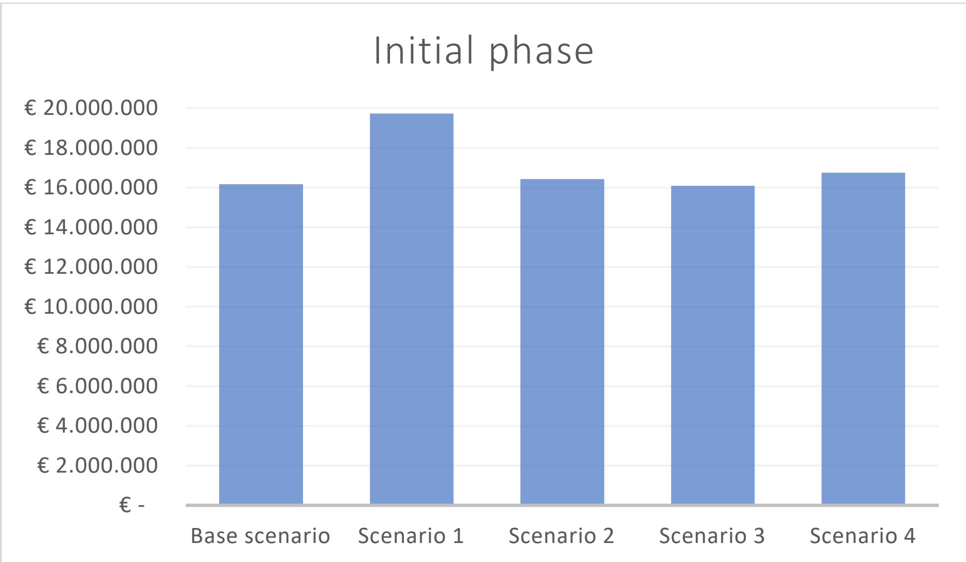

Figure 34 Cost in initial phase (discounted) for different scenarios (author)

Despite the elevated initial costs, this scenario contributes significantly to a building's circularity level, given that reducing is the second most influential factor on the R-ladder's degree of circularity (Potting et al., 2017). The heightened LCC of Scenario 1 is attributed to these high initial costs. However, should the costs of this alternative decrease relative to concrete, it could present a compelling scenario. Therefore, this scenario will be further developed in the next chapter.

The initial costs of the other scenarios are relatively close to the base scenario, at most 4 percent more expensive, a significant departure from the 10 to 20 percent often cited in media discussions regarding circular construction projects. Scenario 2 employs as many bio-based materials as possible, predominantly used in the building's shell and space planning. The purchase price of bio-based materials is typically higher than traditional construction products (10 – 15 %) (van der Hoeven, 2023), yet Scenario 2 exemplifies how minimal extra investment can considerably influence a building's circularity. The CO2 footprint of these bio-based materials is markedly lower than traditional materials like plaster, concrete, and steel (van der Hoeven, 2023).

In Scenario 3, used or recycled products are maximized, yielding the lowest initial investment. This is attributable to the substantially lower material costs of second-hand products compared to new ones, particularly when used columns and beams are employed, substantially reducing initial costs. The final scenario, Scenario 4, maximizes the use of demountable products that can be replaced after their technical lifespan. The initial investment is costlier due to the novelty of this design approach and the relatively lower supply compared to traditional construction products. However, the LCC of this scenario is the lowest among all scenarios due to its superior performance in the OMR and EoL phase, making it the most cost-effective scenario in the long run.

7.4.2 Cost-analysis in OMR phase

The computation of Operational, Maintenance, and Replacement (OMR/use-phase) costs predominantly encompasses the maintenance and replacement of products. As figure 21 shows, these costs are quite close to each other. As discussed previously in Chapter 6, defining these costs is complex and must account for various factors, which heightens uncertainty. The associated finances can consist of both costs and revenues. These revenues, or more appropriately, savings, are due to the potential residual and/or recycling value of the product when replacement is due.

Scenario 1's costs are approximately 3 percent higher than the base scenario. In this scenario, the use of concrete is minimized, primarily replaced with wood. Concrete requires less maintenance compared to wood and has a longer technical lifespan, which can reduce these costs (Rijksoverheid, 2023). The costs in Scenario 2 are 2.5 percent higher than the base scenario. In this scenario, bio-based materials are used as much as possible. These products have a shorter lifespan than traditional materials, leading to increased OMR costs.

Scenario 3 is comparable to the base scenario. In this scenario, similar construction products are used as in Scenario 1, but they are second-hand or recycled. The quality of these products is lower than those in the base scenario, which may lead to slightly higher costs in this phase (Circulairebouweconomie, 2021). Scenario 4 performs best compared to the base scenario. The savings are evident here due to the high degree of demountability of the products, resulting in lower labor costs than in the base scenario. Furthermore, the chosen construction products require little maintenance, although it should be noted that this leads to significantly higher initial costs in this scenario.

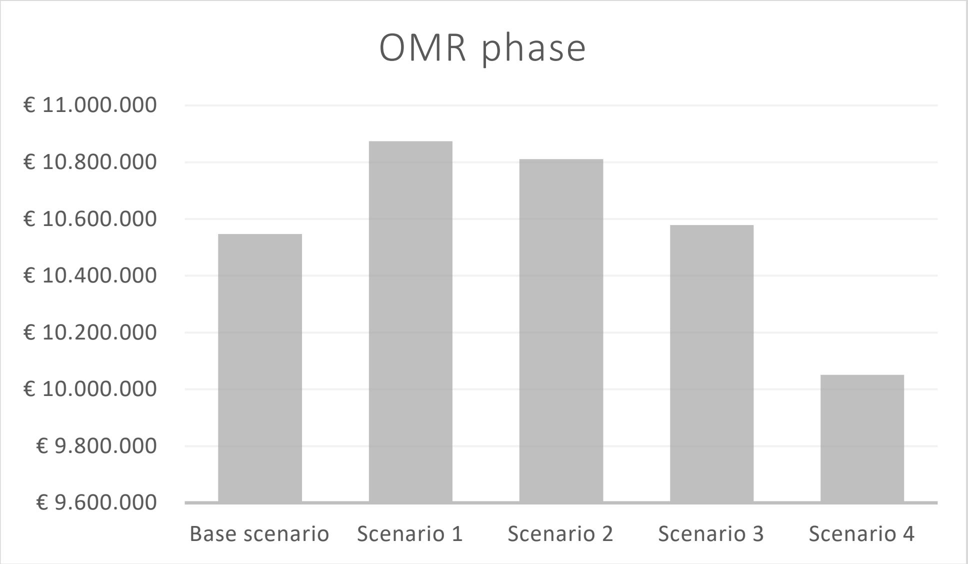

Figure 35 *Cost in OMR (discounted) for different scenarios (author)*

7.4.3 Cost-analysis in EoL phase

Calculating the costs and benefits during the end-of-life (EoL) phase presents the greatest challenge due to the high level of uncertainty involved. As previously discussed, the product lifespan and residual quality need to be determined in the design phase. This value, realized only 50 years in the future, is subject to various external factors. The EoL phase is predominantly determined by the extent of reuse, recycling, and disassembly costs, potentially offering benefits in the form of reuse or recycling (CB23, 2020a). In terms of recycling, the salvage price of a material significantly impacts the cost/benefit balance. In this analysis, current salvage prices are used, which are discounted for inflation.

The EoL costs for the base scenario are by far the highest as it does not account for reuse (see Figure 36). The entire construction primarily consists of wet connections that are difficult to disassemble. The benefits in this scenario are determined by the potential recycling value.
In scenario 1, considerable savings are evident. This scenario heavily employs timber construction, which has a high degree of disassembly potential, enabling easy function adjustments without causing damage. As a result, it often has a higher residual value than traditional construction products.
In scenario 2, the costs are also considerably lower. Bio-based materials are used in this scenario, taking into account the extent of disassembly potential. This results in a cost-saving of nearly 300,000 Euros. Scenario 3 offers the least savings compared to the base scenario. This scenario uses many of the same construction products as the base scenario but prioritizes products with high recycling potential.

Scenario 4 focuses on disassembly-friendly construction with an eye on reuse, translating into potential profits compared to the base scenario. It uses as many construction products as possible that are easily disassembled and retain their quality. Additionally, various construction products have a contract with the supplier to repurchase the product at the same value (akin to a lease contract but involving purchase). Scenario 4 has the highest potential compared to the base scenario in terms of EoL costs, and these savings in this phase have led to a very low life-cycle cost (LCC), despite high initial investments. In the next chapter, various scenarios will be further explored, taking into account price escalations of different materials, in which this scenario continues to dominate.

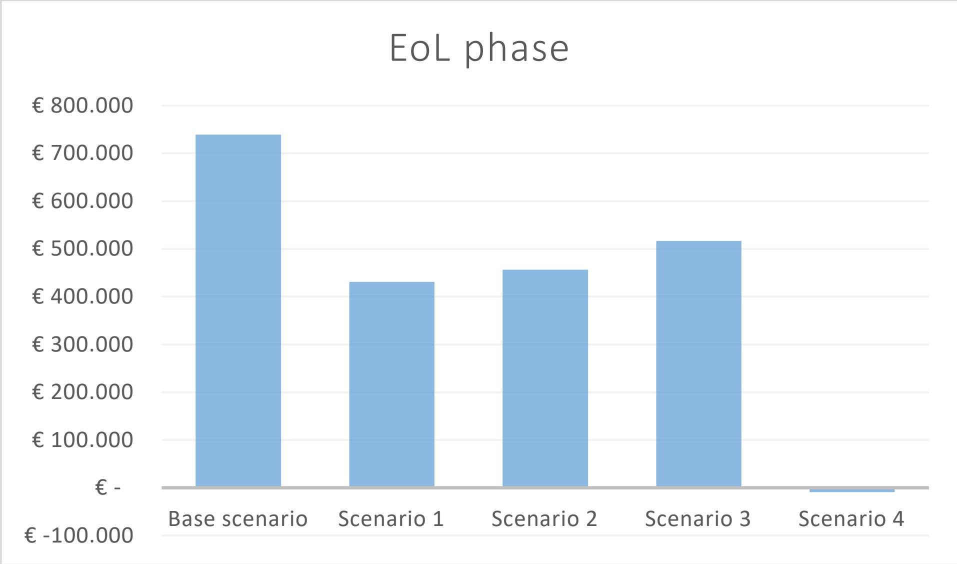

Figure 36 Cost in EoL (discounted) for different scenarios (author)

7.4.4 LCC-analysis with escalation rate for concrete

The modelling using the developed Life Cycle Cost (LCC) tool factoring in a 20 percent price increase on concrete provides several insightful implications for building construction scenarios.

Table 16 Comparison of LCC costs with a price increase of concrete (author)

Concrete	Initial	OMR	EoL	LCC	Δ LCC %
Base scenario	€ 16.167.163	€ 10.546.832	€739.210	€ 27.453.205	2,6 %
Base scenario - escalation rate	**€ 16.931.396**	**€ 10.606.383**	**€ 637.927**	**€ 28.175.707**	
Scenario 1	€ 19.732.210	€ 10.873.504	€ 430.827	€ 31.036.541	0,6 %
Scenario 1 – escalation rate	**€ 19.892.845**	**€ 10.890.976**	**€ 426.753,78**	**€ 31.210.574**	
Scenario 2	€ 16.431.246	€ 10.810.324	€ 456.432	€ 27.698.001	0,6 %
Scenario 2 – escalation rate	**€ 16.589.210**	**€ 10.827.593**	**€ 452.358,64**	**€ 27.869.162**	
Scenario 3	€16.096.237	€ 10.578.266	€516.590	€27.191.093	0,9 %
Scenario 3 – escalation rate	**€ 16.309.030**	**€ 10.605.420**	**€ 508.335**	**€ 27.422.786**	
Scenario 4	€16.750.672	€10.050.970	€ -8.873	€ 26.792.769	0,4 %
Scenario 4 – escalation rate	**€ 16.838.898**	**€ 10.069.571**	**€-11.504**	**€ 26.896.965**	

Concrete, being one of the most extensively used and environmentally impactful materials in building construction, plays a significant role in a building's life cycle costs and carbon footprint (Guardian, 2019). The application of a 20 percent price increase across all phases of the project not only raises the initial investment but also the potential savings realized in the end-of-life phase, illustrating the complex, multifaceted economic impacts of material pricing.

The higher costs in the end-of-life phase highlight an important dynamic - the economic ramifications of building design decisions persist long after construction is complete. Concrete's environmental footprint may prompt regulatory action such as a tax, leading to an increase in its price, making alternative, environmentally friendly materials more economically attractive.

The base scenario shows the most significant increase in LCC with the concrete price increase, likely because it heavily depends on concrete usage. Interestingly, the LCC of the four circular scenarios shows only a marginal increase. This may indicate that these scenarios are less dependent on concrete or are employing strategies that effectively mitigate the impacts of such price volatility, hence demonstrating better economic resilience in the face of changing market conditions. Considering the current trajectory towards greater environmental accountability and the potential for related regulatory interventions, these insights underline the economic viability and the strategic importance of adopting more circular strategies in building design and construction. Such approaches, as shown in the circular scenarios, could offer more robust mitigation against potential price increases of environmentally impactful materials like concrete, while also contributing positively towards environmental sustainability.

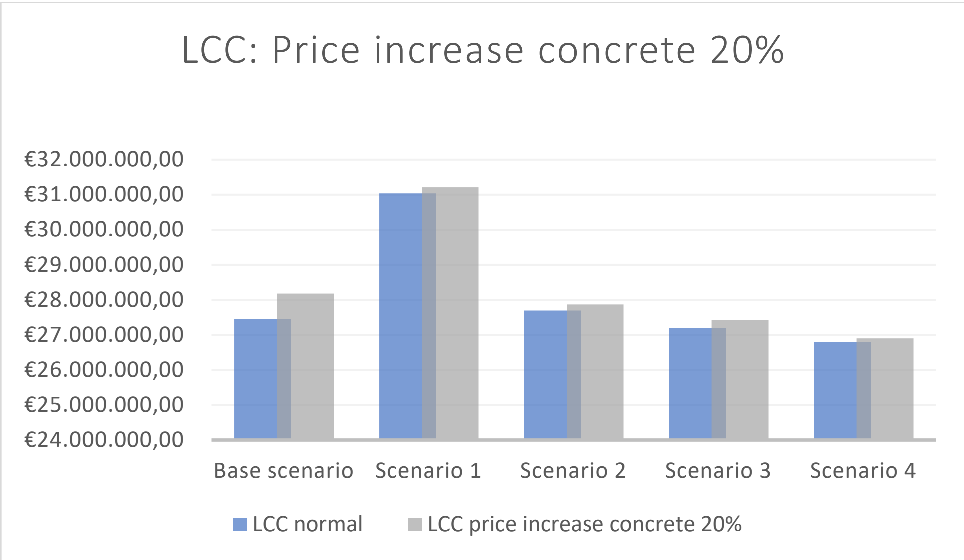

Figure 37 *LCC cost with a price increase of concrete (author)*

7.4.5 LCC-analysis with escalation rate for biobased materials

Biobased materials, recognized for their lower environmental impact and renewable nature, are emerging in modern construction (van der Hoeven, 2023). In this analysis, a hypothetical 20 percent price reduction for all biobased materials in various scenarios is modeled, reflecting future market trends that could potentially reduce the cost of these materials. Such a change could significantly influence the overall Life Cycle Cost (LCC).

Table 17 Comparison of LCC costs with a price decrease of biobased materials (author)

Biobased	Initial	OMR	EoL	LCC	Δ LCC %
Base scenario	€ 16.167.163	€ 10.546.832	€739.210	€ 27.453.205	0,0 %
Base scenario - escalation rate	**€ 16.167.163**	**€ 10.546.831**	**€ 739.210**	**€ 27.453.204**	
Scenario 1	€ 19.732.210	€ 10.873.504	€ 430.827	€ 31.036.541	-5,1%
Scenario 1 – escalation rate	**€ 18.482.937**	**€ 10.537.002**	**€ 434.803**	**€ 29.454.743**	
Scenario 2	€ 16.431.246	€ 10.810.324	€ 456.432	€ 27.698.001	-2,1%
Scenario 2 – escalation rate	**€ 16.158.077**	**€ 10.509.819**	**€ 460.436**	**€ 27.128.333**	
Scenario 3	€16.096.237	€ 10.578.266	€516.590	€27.191.093	-0,5%
Scenario 3 – escalation rate	**€ 15.999.209**	**€ 10.528.319**	**€ 516.986**	**€ 27.044.515**	
Scenario 4	€16.750.672	€10.050.970	€ -8.873	€ 26.792.769	-1,9%
Scenario 4 – escalation rate	**€ 16.602.875**	**€ 9.693.385**	**€ -8.466**	**€ 26.287.795**	

In the base scenario, without biobased materials, the LCC remains stable. However, all four circular scenarios exhibit decreased LCCs when the price reduction is applied. This trend underscores the potential financial implications of material choices and costs in sustainable construction.

Scenario 1, which relies heavily on wood, experiences a noticeable LCC reduction. This suggests that the use of biobased materials, specifically in structural components, can be financially advantageous when cost reductions occur. It should be noted that the changes in LCC are directly influenced by the choice of materials and their respective costs, emphasizing the importance of effective resource management and strategic planning in construction.

In Scenario 2, characterized by extensive use of biobased materials, a decrease in LCC is observed, albeit less than in Scenario 1. This indicates that the distribution and application of biobased materials across different parts of a building could lead to varying degrees of financial benefits. Further research may be required to determine optimal strategies and configurations to maximize these benefits.

Scenario 3 sees a modest reduction, owing to the use of recycled, partly biobased products. This highlights the potential economic benefits of recycling and reusing materials in construction, demonstrating the viability of a circular economy in this context.

Finally, Scenario 4, emphasizing demountable products, shows the potential of design strategies targeting deconstruction and adaptability, particularly when these approaches are complemented by cost reductions in biobased materials. These trends, observed across the different scenarios, demonstrate the potential economic implications of market developments and pricing trends related to biobased materials. This underscores the importance of strategic planning, continual market observation, and adaptive construction practices to respond to evolving material costs and market conditions, with the aim of optimizing the economic and environmental aspects of sustainable construction.

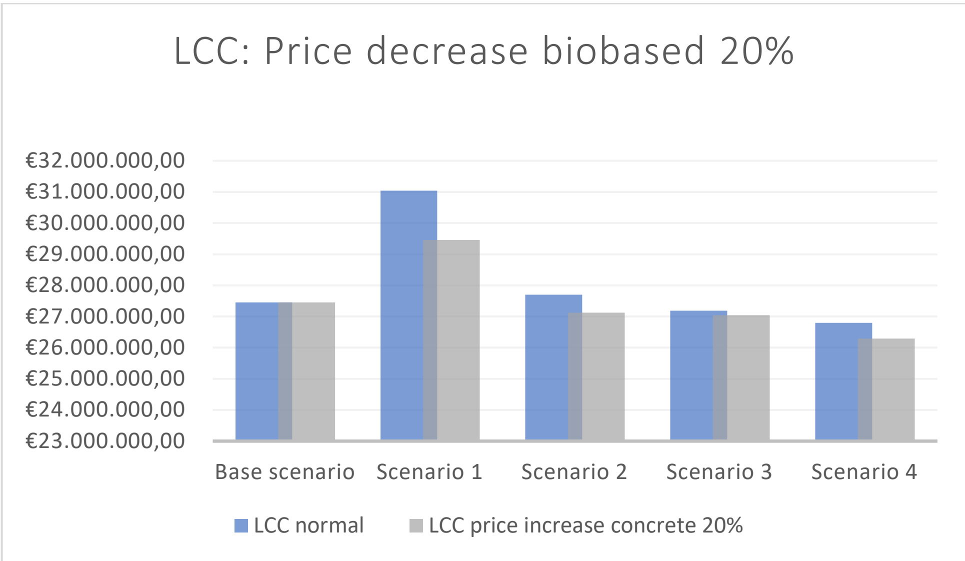

Figure 38 *LCC cost with a price decrease of biobased materials (author)*

7.4.6 LCC-analysis with fluctuating discount rates

In executing Life Cycle Cost (LCC) analyses for buildings, discount rates play a pivotal role. These variables provide the means to convert future costs and benefits into present values, thereby enabling a more accurate comparison and informed decision-making. However, discount rates vary and, consequently, can offer differing perspectives, especially with long-term investments such as buildings (Jawad & Ozbay, 2006). Therefore, working with varying discount rates in LCC calculations offers a deeper understanding, thereby enhancing our perception of LCC's sensitivity across diverse economic scenarios. This deeper understanding facilitates the development of robust strategies for building design and management.

The significance of the graph is underscored by the variance in the trendlines of the scenarios, rather than the absolute values conveyed by each trendline. With lower discount rates, the depreciation of a building's LCC occurs at a slower pace. This means that it would take a substantially longer time to reduce a building's LCC. In such cases, the application of circular strategies becomes necessary to expedite the LCC reduction over time. This implies a shift in focus towards future costs for buildings whose LCC discount at a slower rate. Conversely, at higher discount rates, the LCC of a building after certain years tends to be lower than in cases with a lower discount rate. In these instances, the relative savings provided by circularity are not as pronounced (Eisenberger et al., 1977).

Moreover, the graph elucidates different scenarios that can be adopted for the implementation of circularity. The difference in the trendlines, at a lower discount rate and also a higher rate, is relatively marginal. This suggests that, regardless of the chosen scenario, the LCC output generated would be almost identical. These findings are indicative and are a result of specific scenarios used for this study. Therefore, while they provide meaningful insights, they should not be generalized to all situations, given the variability in actual market conditions and potential shifts in economic factors over time.

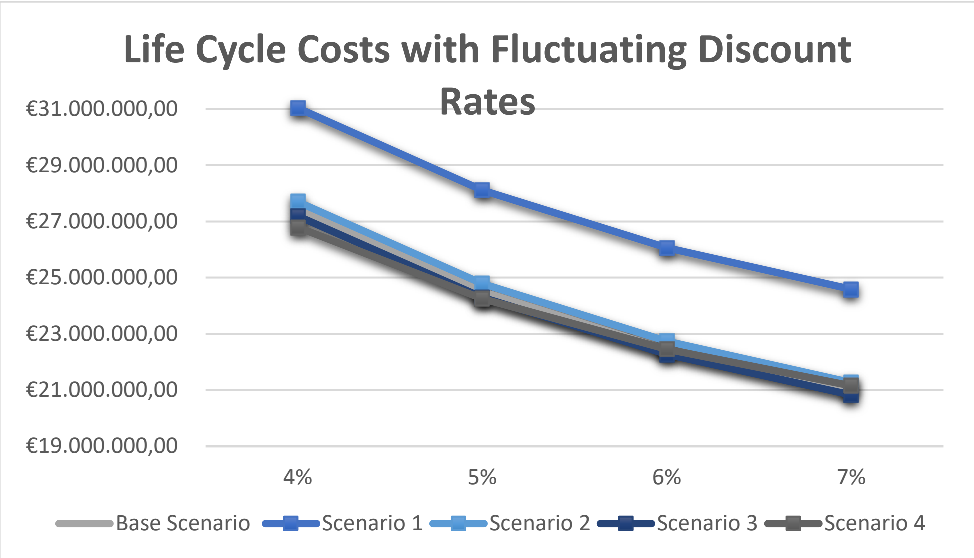

Figure 39 Life cycle cost with fluctuating discount rates (author)

7.4.7 LCC with different lifespan

In this sensitivity analysis, I modelled different building lifespans to investigate their impact on the life cycle costs (LCC). Initially, we performed the LCC calculation for a lifespan of 50 years. Additionally, we conducted calculations for lifespans of 20 and 35 years. The results are presented in the figures and table below.

Table 18 *LCC lifespan 20 years (author)*

	Initial	OMR	EoL	LCC
Base scenario	€ 16.167.163	€ 2.162.244	€ 408.246	€ 18.737.653
Scenario 1	€ 19.732.210	€ 2.162.244	€ 232.721	€ 22.127.176
Scenario 2	€ 16.431.246	€ 2.191.501	€ 247.041	€ 18.869.788
Scenario 3	€ 16.096.237	€ 2.171.337	€ 283.767	€ 18.551.341
Scenario 4	€ 16.750.672	€ 2.023.401	€ 99	€ 18.774.172

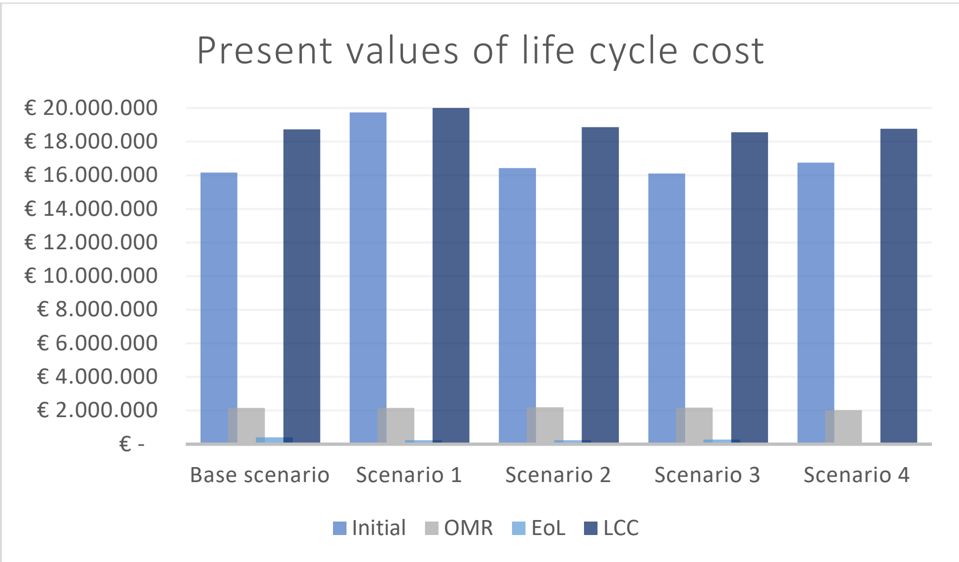

Figure 40 *LCC comparison time span 20 and 50 years (author)*

A gradual increase in the life cycle costs (LCC) was observed for all scenarios over time. This increase was primarily driven by the annual operation, maintenance, and repair costs (OMR). Notably, shorter building lifespans exhibited lower OMR costs, attributed to reduced requirements for prolonged maintenance and repairs. Consequently, the LCC demonstrated a slower rate of increase for shorter lifespans. Additionally, a decrease in end-of-life (EOL) costs was observed for shorter lifespans. This can be explained by the assumption that certain components would require replacement at longer building lifespans, either due to their longer technical lifespan or poor quality, resulting in higher EOL costs.

Remarkably, a pattern of a slight decrease in the incremental rate of life cycle costs as the building lifespan increased was evident, reflected in the less steep slope of the graph. One possible explanation for this pattern is the influence of the time value of money. By discounting the LCC to present value, the impact of future costs diminishes as they are further into the future. This contributes to the decrease in the incremental speed of life cycle costs for longer lifespans. On average, the modeled scenarios exhibited an increase of 2.9% from 20 to 35 years and 1.5% from 35 to 50 years. These findings suggest a trend of decreasing cost escalation with increasing lifespan. However, it is important to note that these conclusions are based on the specific modeling approach and assumptions employed in this study.

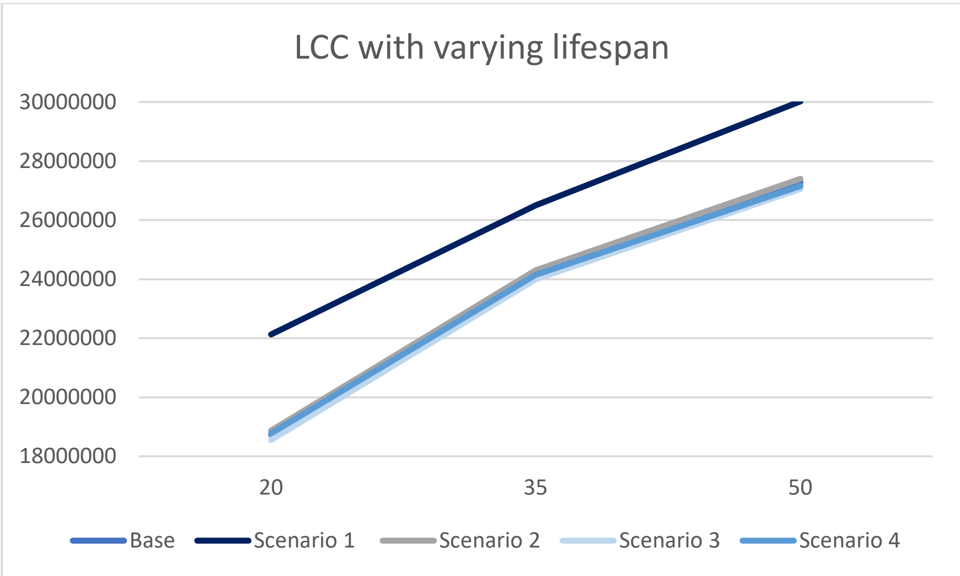

Figure 41 LCC with varying lifespan (author)

8. Discussion

This chapter engages in a detailed discussion concerning the conducted research, with its structure unfolding as follows. Initially, it delves into the literature study, beginning with a discourse on the principles of a circular economy and how these were incorporated into the research. This is followed by an exploration of the degree of circularity and how this concept was incorporated into the study. Then, it turns to discuss the financial aspects, examining how they were considered in the research and incorporated during the definition of the model. A brief discussion on how this theory translates and contributes to the tool's development follows. Further elaboration on the tool's construction forms a part of the discussion, where the contribution of interviews is also scrutinized. The chapter concludes with a comprehensive discussion, providing an overview of successful aspects, areas for improvement, limitations, and ultimately, recommendations for further research.

This study has identified a number of uncertainties and challenges in the development of the tool and the modeling of scenarios. It is important to acknowledge that the outcomes of the scenarios are presented in monetary values, specifically in euros. These values are derived from simulations conducted using the tool. However, it is crucial for readers to recognize that these results are based on simulations and therefore may not be considered 100% reliable.

8.1 Circular built environment

Chapter 2 discusses the theoretical background of the principles of a circular economy in the built environment and how this can be authentically translated into the construction sector. It clearly highlights that the design phase is crucial for achieving a circular building as it lays the foundation for the integration of circular principles and strategies throughout the building's lifecycle (Iyer-Raniga, 2019). This phase determines material choices, resource efficiency, the level of building flexibility, and crucially, the manner in which the building will be deconstructed at the end of its lifecycle to ensure the reuse and recycling of materials. This aligns with MacArthur's butterfly diagram principles (MacArthur, 2013). The model aims to provide deeper insights into how these elements affect a project's costs. It represents a projection of reality where uncertainties, barriers, and obstacles are minimized through a clear and structured model built upon circular principles.

While developing the tool designed to clarify what different degrees of circularity mean for a project's lifecycle costs, the construction and development stages, usage phase, and end-of-life phases were considered. The model is designed to clarify all costs and potential returns per degree of circularity at the beginning (design phase) of a project. Each element is evaluated in terms of its material, its flexibility (disassembly index), and potential for reuse and recycling. Defining these faced numerous challenges, especially in accurately estimating the potential for reuse and recycling. A module was used to offer more insight into this (discussed in the next paragraph). Input to the model also involved many uncertainties, requiring sufficient data for computation. This research utilized data available for the Coolbase project, which was quite extensive. All initial costs were defined based on hourly wage, material level, and equipment level, and quantities with corresponding dimensions/weights were available. However, incorporating all this data into the model was challenging. For instance, not all construction elements used the same units, and only the final costs were available for some construction products, lacking the hourly wage or specific subcontracting costs. Using data from sources like Madaster or ‘’bouwformatie” can reduce this uncertainty due to better and more structured and uniform data (Madaster, 2021).

The literature and interviews reveal that there are various scales at which a building can be deconstructed, such as product level, material level, scale level, etc. In the model, construction products are retained in their highest form for potential reuse; if reuse is not possible, it is analyzed at the material level for potential recycling.

Estimating these material values is challenging as many factors influence them. Furthermore, these values must be estimated since they will only be analyzed in the future, adding a degree of uncertainty. This uncertainty is minimized as much as possible through the model's justification, elaborated on in the following paragraph.

There are various circularity strategies contributing to the establishment of a circular economy. This study uses Kirchherr et al. (2017) R-strategies to develop different scenarios. Each scenario has different degrees of circularity, which are defined and applied to the case study. A building is highly complex and can be divided into different layers, as per Brand (1995). These layers have different life years, which affect their circularity. The model is built based on this structure, taking into account the lifespan of different materials and components. This can assist in determining how easy it is to repair or dismantle something, and what the technical lifespan of a component is. The next paragraph provides a more detailed discussion on how this is specifically implemented via the disassembly index (Chapter 8.4).

8.2 Assessment of circularity in building projects

This study investigates the degree of circularity and its influence on the Life Cycle Cost (LCC) of a building. Literature suggests that there is not yet a clear method of measurement that satisfies all the principles of a circular assessment model. Currently, no requirements are set for the degree of circularity of buildings, as is done for sustainability. The Netherlands has set a goal to have a circular economy by 2050; therefore, it is expected that a holistic assessment model/framework will emerge to evaluate and test circularity. At present, the evaluation is conducted in a subjective manner, which renders the evaluation qualitative. To improve the assessment process, clear criteria need to be established to make the evaluation more precise. This can be achieved by incorporating quantitative assessment methods, which will make the evaluation more measurable, quantifiable, and authoritative (Tokazhanov et al., 2022).

The focus of this study is to investigate the influence of the degree of circularity on the LCC of a building. The primary objective is to make specific costs and benefits transparent throughout the entire lifecycle. It was decided not to use a specific method of measurement to test the degree of circularity of a building, as there is no recognized assessment mechanism and this exploration is a separate study. The literature review, however, examined several methodologies for use in this study. From my knowledge accumulated from the literature and the insights gained during interviews, I chose not to use any of the discussed methods of measurement. This would be very interesting for a follow-up study.

In the paper by Zhang et al. (2021), a method of measurement is described that is more holistic than other methods and satisfies almost all the principles of a circular economy. The setup of this model could then be used in a follow-up study. Moreover, this model focuses on multiple value facets of a circular economy, such as the technical, economic, functional, and social values. These will be discussed later. To make the degree of circularity transparent, I chose to work with the various R-strategies (Potting et al., 2017). These strategies are defined from least circular to having the most influence on a circular economy. These strategies provide insight into the degree of circularity, but more broadly (qualitatively) and this value is not quantifiable. This is a lack in the research and would add value. Despite the less specific score, the R-strategies method provides a good picture of the degree of circularity of a construction project. There are 10 R-strategies in total, and this study uses the strategies of reduce, reuse, recycle, refurbish, and repair. This is because these strategies can be translated well into building elements. Furthermore, refurbish, recycle, and reuse are considered in achieving a circular construction environment (MacArthur, 2015). From the results of the interviews, these five strategies also emerged as the most important in realizing a circular construction environment. These five strategies have ultimately been translated into the four scenarios that are modeled by the LCC tool to map out the financial implications.

In a linear economy, value is usually defined in the form of monetary values. In a circular economy, social impact, functional value, and technical value are also considered. All these facets contribute to a circular economy. This study focuses on the technical and economic value because the social value is difficult to define and hard to translate into economic value (LCC). The technical value is closely linked to the functional value, where the technical value depends on its ability to meet current and future demand. In a report by CB23 (2020b), this has been translated into various criteria that define this technical value. These criteria are as follows: adaptability of the layers, distribution of the different construction layers, adaptability of the building elements/products, disassembly, sustainability of the chosen material, toxicity of the raw materials. Many of these elements are also discussed in the previous chapter. When developing and building the model, these criteria were taken into account. For instance, a distribution of different construction layers was included, using Brand's layers . This has been translated into an adaptability score (per layer of Brand) and impacts the adaptability of the building elements/products that are ultimately tested in the LCC. The adaptability is defined by the detachability index (discussed in the next chapter). The criteria of sustainability and toxicity are not included in the model. These two criteria are difficult to quantify in euros and hence do not add value at this point. It would, however, be highly interesting to include them, given that Europe aims to introduce the EU taxonomy (EuropeanCommision, 2023).

This EU taxonomy implies, for instance, that the embodied carbon of materials is quantified in euros and priced. This is very interesting for an LCC calculation since construction products like cement and steel will become significantly more expensive than bio-based materials, which are less harmful to the environment. This is something to consider in further research for implementation in the LCC calculation. The LCC calculations took this into account by running different modelling assuming a price increase of concrete and a price decrease of bio-based materials.

8.3 Evaluations of financials in circular projects

As we transition towards a circular economy, it becomes essential to have a circular cost model in place. Current real estate models are typically short-term oriented and do not take future value, benefits, and costs into account. Consequently, a traditional cost model fails to provide a fair comparison between traditional and circular alternatives (Jeroen Verberne et al., 2021). Although there are several initiatives to assess the economic value of circularity, there is currently no standardized method for attributing this value (Oppen et al., 2021). In this research, a circular cost model is developed that operates over long time horizons and incorporates multiple life cycles compared to linear business models.

This tool is based on a Life Cycle Cost (LCC) analysis, capturing all phases of a building's life: the initial, operation, maintenance, and repair (OMR), and end-of-life phase. The literature lacks a model that comprehensively maps these stages, often omitting the end-of-life phase or accounting only for potential costs while ignoring the benefits. However, a complete comparison can only be made by including all these factors. Potential sales revenues and rental income are not included in this calculation, but their consideration would add value in further studies.

When defining financial implications across all phases, various obstacles and barriers arise. It is challenging to estimate the potential residual value of a product at the end of its lifecycle and to determine what is suitable for recycling. This research discusses various methodologies aimed at defining potential residual value. The report from Alba Concepts on defining financial residual value was chosen as a guide in the model. Interviews and literature indicate that critical factors influencing potential residual value include dismantling time, potential quality, storage costs, and logistical expenses, all of which are included in the model.

Developing an LCC model requires consideration of the time value of money and the application of net present value. This ensures future cash inflows and outflows are discounted to reflect the current value of an investment, forming the basis of an LCC. Hence, the calculation method must account for the interest rate, which could vary in the future, adding uncertainty. Inflation also influences future costs and is included in the model. These two rates significantly impact a project's LCC. In this model, a 4% interest rate and 2% inflation are assumed, based on literature and estimates. This assumption is a significant uncertainty, as these values can differ in the future. However, these rates are adjustable in the model to model various scenarios.

Future prices may also vary due to factors such as scarcity. The model accommodates this by allowing the adjustment of the price escalation rate per material, catering for potential price changes in the future and modelling different scenarios. For instance, prices can be defined based on past trend lines to predict future values. When defining future costs, as in this model, a sensitivity analysis offers a solution for testing various scenarios. This could involve calculating with different interest rates or varying degrees of inflation. The next chapter will elaborate on the barriers and obstacles encountered during the actual development of the tool.

8.4 Development of C-LCC tool

The most significant challenge in developing the model was formulating the residual value, which was based on a model by Alba Concepts. The definition process differentiates between building products and material flows, aligning with previous knowledge gained from literature studies. Further differentiation occurs when defining the financial residual value, between reuse value and recycling value. This aspect is incorporated in the model, which examines the potential reuse and recycling value of each building element.

The potential reuse value is influenced by the purchase price, loss of product/material, quality reduction, dismantling costs, refurbishment costs, transport costs, and storage costs. Each of these factors is defined through justification and formulas to ensure consistency within the model. The calculation of loss is based on the purchase price and percentage of loss, defined based on assumptions about which layer the building product is in and its technical lifespan. Quality reduction is calculated in a similar way. The aging curve, translated into a default value by Alba Concepts, is used here. The quality is assessed on a scale of 1 to 6, which is subjectively dependent on user estimation. Quantifying quality is inherently challenging, so there will always be uncertainty when assessing a material's future quality. For comparison, other reuse models define this by simply linking factors to it.

The tool accounts for dismantling costs, which are crucial in defining LCC (Life Cycle Cost) costs as the reuse value is strongly dependent on the disassembly capability of a building product. The ease of disassembly is calculated using the disassembly index from Alba Concepts, which provides a good indication of a building product's disassemblability. It takes into account accessibility, connection type, edge confinement, and intersections. This remains an estimate based on user judgements. There is a lack of dataset in the built environment defining disassemblability of building products, hence this tool serves as the most accessible and best indicative tool.

Transport and storage costs are defined by a formula dependent on different rates. It considers factors such as how far the project's destination is in kilometers, hourly rate, call-out charges, weight of the products, and hours of work. In the calculations, these values are kept constant, as the end-of-life destination of products is unknown. Therefore, transport and storage costs depend on the weight or volume of the products. To better estimate these costs, the end-of-life destination of a building product should already be defined. This information is currently unavailable, and it doesn't make sense to make an estimate for each building element.

The potential reuse proportion of products is estimated based on which layer it is in, or the disassemblability of a product. These two factors have a significant influence on potential reuse as they clarify the adaptability of a building product. These remain estimates and no model or datasheet currently makes this clear. Furthermore, it heavily depends on the project, making it a good indicator in my view and according to interviews. Estimating the potential recycling value is somewhat easier. Once the proportion of reuse is known, the recycling proportion is calculated by looking at what remains. The formula to calculate the recycling value depends on the amount of material in kilograms and the demolition price. In this model, current demolition prices obtained from demolition companies like New Horizon are used (Horizon, 2023). These prices may vary in the future, but considering inflation and conducting a trend analysis for the price per material should allow us to reasonably predict the demolition price.

Defining various costs in a future LCC analysis is based on various assumptions and expectations. Therefore, the model cannot provide a uniform reality of future costs and benefits. However, it can provide an indication, making the degree of circularity and financial implications more visible. At the very least, it creates a better overview based on justifications rather than mere estimates.

8.5 Interpretations of the case study

Based on interviews, literature, and R-strategies, various scenarios have been developed. These scenarios depend on the strategies of reduction, reuse, recycling, repair, and refurbishment. In the interviews, these strategies were discussed and interventions for each strategy were identified for each Layer of Brand. The layers considered include: structure, skin, services, and space plan. This selection is based on the available data from FSD and the findings from the interviews, since these layers significantly influence the level of circularity in a construction project. The tool is applied to the available data from FSD, which originates from a contractor, thus is reliable. This data, derived from the definitive design, may in practice present higher values. However, this is a risk inherent to any project. Additionally, a risk margin has already been factored in by the contractor when defining the values. The same approach is applied to the construction products in the scenarios so that costs can be compared. Testing the various R-strategies has resulted in four scenarios. The first focuses on reducing concrete (reduce), the second on the use of as many biobased materials as possible, the third on second-hand and recycled products, and the last one on maximizing the reuse value of products.

To better illustrate the degree of circularity and associated costs, additional scenarios could be developed. However, this was not done in the study due to time constraints.

In the various scenarios, construction products were chosen based on their properties that align with the chosen scenario. The interviews generated a wide range of circular construction products from which a selection was made. This selection was based on my own interpretation, thus, it is not certain if these materials are the most suitable. Furthermore, whether certain constructions are possible is uncertain and not addressed in the study. However, the choices were discussed during interviews, and no odd findings arose.

Application of the tool led to different results, with each scenario having varying influences on costs during specific phases and the LCC. Scenario 1 minimizes the use of concrete and replaces it with wood as much as possible. Given a contractor had planned to deliver the Coolbase construction project in timber construction, this information is available, thus providing a realistic picture. The results show that the LCC of scenario one is significantly more expensive than the base scenario. This is largely due to the high initial costs caused by the higher costs of timber construction compared to concrete. These costs were obtained from various timber suppliers. I created the cost breakdown myself, but involving a cost specialist and a constructor could better define these costs. The OMR costs are also higher because timber construction requires more maintenance than concrete and has a shorter lifespan. Wooden structures are suitable for dismountable construction, and as this scenario primarily focuses on the structure layer, no account was taken of replacing the timber construction during the OMR. However, due to the dismountable structure of timber construction, there is substantial savings during the EoL phase due to its high reuse value compared to the base scenario.

Scenario 2 primarily applies biobased materials to the skin and space plan layers. These layers incur less cost than the structure, hence the differences here are less significant. The initial costs are slightly higher than the base scenario because biobased materials are on average more expensive than traditional products. As biobased materials require more maintenance and have a shorter lifespan, the OMR phase is more expensive than with traditional construction. The EoL phase is also somewhat more expensive because at the EoL stage, biobased materials are mainly suitable for recycling and not for reuse. Thus, overall this scenario is more costly than the base scenario. In this scenario, implementing environmental costs would be very interesting because biobased materials cause much less environmental damage than traditional construction products.

In Scenario 3, recycled and second hand products are used as much as possible. It is noticeable that second-hand products are significantly cheaper, while recycled products tend to be slightly more expensive, thus balancing each other out. This results in an initial investment roughly equivalent to the base scenario. The OMR costs in scenario 3 are also similar since it uses the same construction products as the base scenario. During the EoL phase, savings are seen because the chosen construction products are more suitable for dismountable construction and recycling. This scenario heavily relies on second-hand products, making it difficult to implement in the Coolbase project. For smaller projects, however, this could be a more feasible approach.

Scenario 4 deploys construction products that are highly suitable for reuse, resulting in an interesting LCC outcome. The initial costs are higher than the base scenario due to the often more expensive purchase price of the product, but the shorter dismountable construction process somewhat mitigates this difference due to resulting savings. The costs throughout the lifespan of the building are considerably lower since the chosen products adhere to circular principles, making them highly suitable for dismountable construction and very durable. The most significant savings are seen in the final scenario, with almost a 100% saving! This is attributable to the chosen products being suitable for dismountable construction, thus having a high reuse value.

8.6 Note results

This research underscores the significant role of circular alternatives in understanding the impact of circularity on building costs. It appears that the adoption of circular alternatives inevitably leads to an increase in initial investments. There is also a considerable variability in the Operations, Maintenance, and Repair (OMR) across scenarios, with factors like the degree of removability, durability of materials, and technical lifespan being influential. An interesting observation is that the End of Life (EoL) phase contracts with a gradual increase in circularity, aiding in reducing lifecycle costs that would otherwise be higher. Removability has been identified as a critical factor in determining a project's circularity and its potential reuse value.

Timber construction emerges as a viable alternative to conventional concrete, albeit with a higher initial investment. Biobased materials, despite currently being costlier, hold a promising future due to anticipated price reductions. A sensitivity analysis was conducted to understand the potential effects of a price increase in concrete and a price decrease in biobased materials. The results show that while a price rise in concrete consistently increases the Life-Cycle Cost (LCC) across scenarios, circular strategies show minimal LCC increase compared to the base scenario. Conversely, a price reduction in biobased materials could lead to LCC savings exceeding 1.5 million euros, a significant margin that shows the potential for biobased construction products and the adoption of circularity in the built environment.

Addressing investor apprehension regarding the economic viability of circular projects, this study presents a tool that provides clarity on the economic feasibility of such projects. By focusing on improving circularity in construction projects and carrying out an LCC analysis, this tool offers insights into economic viability and ecological impact.

The study successfully fills a research gap regarding the financial implications of circular interventions, by systematically comparing various circular alternatives. This approach aligns with the demand for alternative design solutions that account for the entire lifecycle of a process (Ghisellini et al., 2016). Though the initial investments for circular strategies are higher than for the base scenario, it's crucial to note the long-term LCC benefits these strategies offer. By highlighting the benefits of circularity, stakeholders are encouraged to embrace circular projects, aiding the slow but sure shift from a linear economy towards a circular one. This shift is made possible by applying circular interventions layer-by-layer in a building, linking these to financial outcomes, and comparing them to identify the most favourable scenario.

8.7 Value of the model

The primary objective of this research was to develop a tool that provides better insights into the level of circularity and its associated financial implications. Through various simulations of the model on defined scenarios, a wealth of results has been obtained. The model presents a project's life cycle cost throughout a building's entire lifespan in euros. This is particularly valuable as the literature review and expert interviews revealed a scarcity of models capable of expressing this information, indicating a limitation in the field. Ultimately, the tool is intended to serve as a resource for project developers and investors to substantiate circular investments better and recognize the value of circularity.

The literature review highlighted that one of the significant barriers to implementing circularity in the construction industry is the perceived higher costs compared to traditional building methods.

However, this research shows that such reasoning needs to be revised, as it is based on traditional business cases. A traditional business case for a developer or investor is typically based on the initial investment, revenue from sales and rentals, operating costs, and potential resale after a certain number of years. When applying this framework to a circular building, it is undeniable that the costs will be less favourable for stakeholders, given the higher initial investment (as evidenced by the model). However, a circular building holds potential residual value due to the ability to reuse construction products and materials at the end of its life cycle.
In contrast, a traditional building is usually demolished or redeveloped, incurring additional costs. Thus, at the end of the life cycle, a circular building has the potential for earnings instead of expenses. These end-of-life costs/benefits are characteristic of circular buildings and should be included in the business case for developers/investors to consider. This will be further explained in the following paragraph. Stakeholders need to change their mindset and business case models to grasp the potential of circularity fully. Without this shift, it becomes challenging to make accurate comparisons.

This study focused on exploring the relationship between circularity, performance, potential visible performance, and life cycle costs. Emphasis was placed on cost, as it is a crucial factor in decision-making within the built environment. However, it is essential to note that the cost discussion should be within the broader concept of value creation. A question that arises is why stakeholders should pay attention to costs. One possible explanation lies in the potential cost shifts resulting from factors such as stricter carbon accounting. In such a situation, costs represent more than just financial considerations; they reflect the new reality that stakeholders will face in the future.

While there may be a tendency to focus on initial costs, the value proposition extends beyond the initial investment. The costs at the end of the life cycle also play a significant role in determining the overall value of a project. However, investors may need to fully consider the long-term implications to primarily focus on initial costs. Understanding the importance of life cycle costs is crucial not only from the perspective of investors but also from the viewpoint of tenants and users. As awareness of sustainability and operational efficiency grows, users can pay more attention to operating costs and their potential impact on daily activities.

Ultimately, the primary value of the model is to provide insights into the level of circularity and its associated costs/benefits. However, the purpose of the model is not to provide the definitive answer but to demonstrate how to arrive at an answer and document the tool's development. This allows for future modifications and the inclusion of additional variables as clarity emerges, to facilitate the transition to a circular built environment.

8.8 Traditional business model vs circular

The previous section highlighted that it takes a mindset change to build circularly. This section compares the results of Chapter 7 with traditional business models. Appendix XIII explains how such a classic business case is constructed. Below its main findings are shown in the table below.

Table 19 Principles of traditional business model

	Development phase	OMR phase	End-of-life phase
Real estate developer	• Foundation costs • Sales proceeds		
Investor		• OMR costs • Rental income	• Demolition costs • Redevelopment costs • Residual value (circular)

This overview reveals that investors or developers primarily consider initial investments, operational costs (such as energy expenses) to maintain the building, rental income, and potential resale or demolition costs. The two key cost factors held side by side are the initial costs and potential revenues, upon which the business case is formulated (FSD, 2023). To demonstrate the potential of the developed model, a different approach must be taken when considering the business case. The crucial difference lies in better incorporating the End-of-Life (EOL) phase and the operation, maintenance, and replacement (OMR) phase, as they present variations compared to traditional calculations.
The results indicate that circular building designs offer significant potential in EOL costs. However, this impact is still relatively small compared to the initial costs incurred. Additionally, investors often do not plan for 50 years but instead focus on a timeframe of 15-25 years to sell the building again. This represents the standard approach for investment calculations. The developed model does not account for this perspective. Typically, an investor assumes selling the entire building at the end of the period (15-25 years). They make an initial investment, generate returns through rent, and aim for a value increase in the building, considering it as an investment object. This is how investors and funds view it. Subsequently, the next investor may encounter potential replacement costs and other expenses to maintain the building's condition.
The calculated model considers 50 years, encompassing reuse and replacement costs. It would be exciting to compare the outcomes of this model with those from a traditional investor calculation. The appendix contains gathered information on investor calculations from FSD, enabling a side-by-side comparison. The calculations of the traditional approach and the circular variant are juxtaposed for different time intervals: 20 years and 50 years. The analysis examines scenarios where the building is either demolished, resold, or potentially reused after 20 years. The same evaluation is conducted for 50 years.

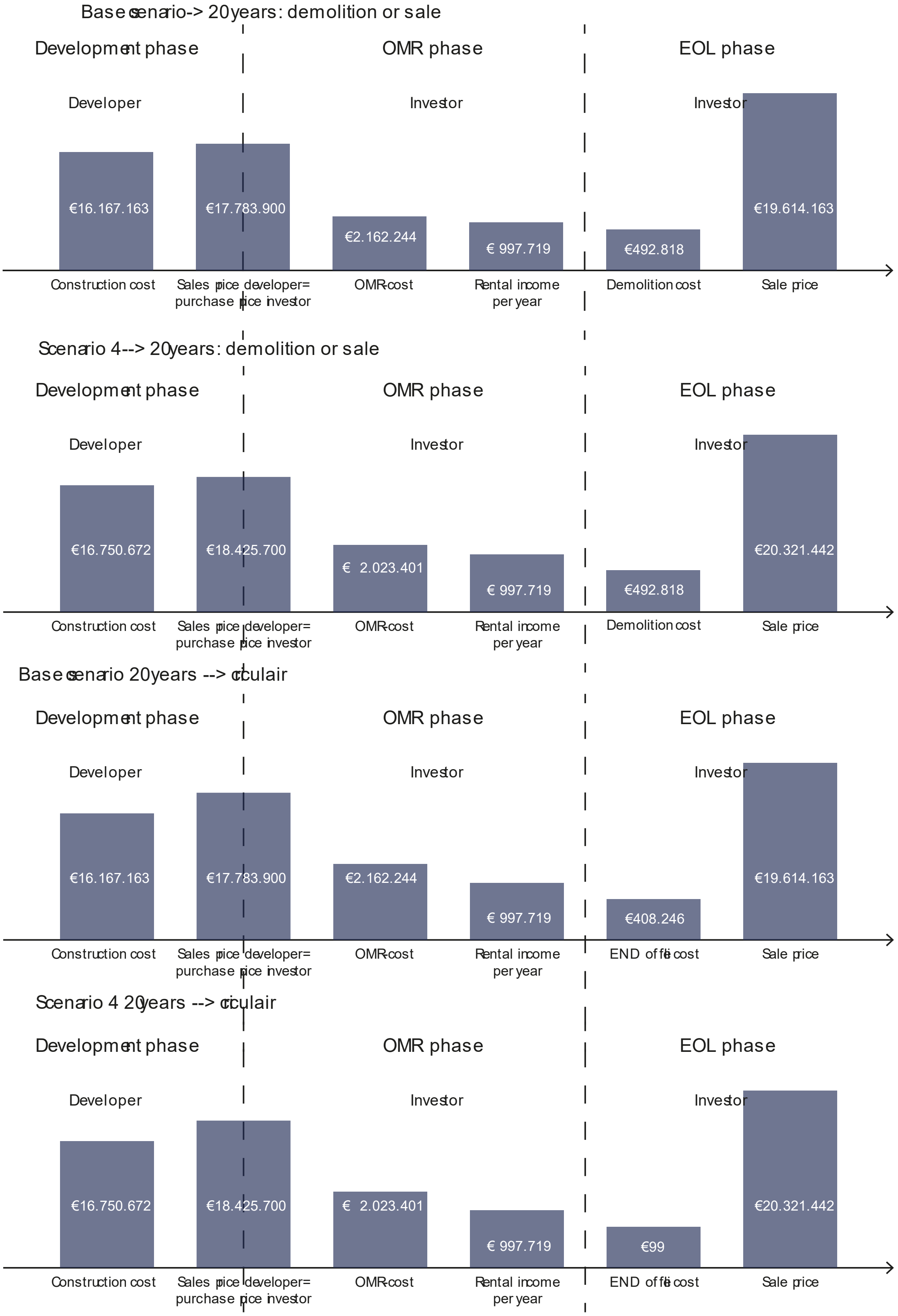

Figure 42 *Business case 20 years traditional vs circular (author)*

On the previous page, the outcomes of the Life Cycle Cost (LCC) were compared with traditional business models from the perspective of both the developer and the investor. In the initial analysis, the potential selling price and demolition costs after 20 years were examined. In the circular scenario, the potential selling price, potential residual value, and demolition costs were considered. It was assumed that a developer achieves a 10% return on his construction costs and that this can be passed on to the investor (assumption). The investor then incurs Operations, Maintenance, and Repair (OMR) costs over a period of 20 years and receives rental income. At the end of the building's lifecycle, it can be demolished, sold, or End of Life (EOL) costs can be incurred.

From the developer's perspective, a return of 10% is achieved. However, the residual/demolition value at the end of a building's lifecycle can be discounted in the selling price. Using the first scenario as a benchmark, the other alternatives can be calculated with a different EOL cost component. This would result in the following percentage increases:

- Base Scenario - 20 years: demolition or sale: 0.0%
- Scenario 4 - 20 years: demolition or sale: 0.1%
- Base Scenario - 20 years: circular: 0.6%
- Scenario 4 - 20 years: circular: 3.1%

A salient observation is that the potential selling prices of the property developer increase in the circular scenarios. This indicates that any increased costs in the initial phase can be covered. An assumption here, however, is that the investor should also be able to pass on these End of Life (EOL) costs, otherwise they would lack financial incentive. When comparing the Life Cycle Cost (LCC) calculation with only the traditional variant, the baseline scenario performs better. This is due to the costs in the initial phase being significantly lower compared to the circular alternatives and the costs/savings in the end of life phase not being included in this business case.

Yet, it is plausible that the investor could generate more rental income and have lower Operations, Maintenance, and Repair (OMR) costs throughout the lifespan of their investment. This would result in higher revenue, enabling them to cover the higher costs associated with a circular scenario, an aspect further explored below. As evident from the analyses, as circularity increases, the costs in the initial phase also increase. This makes a non-circular alternative more attractive in a traditional business case as these initial costs are lower. In this analysis, it has been assumed that rental income remains the same regardless of a building's degree of circularity and that potential selling prices are also not influenced by the degree of circularity. An alternate assumption could be that these increase as circularity escalates. In such a case, circular alternatives would perform better than the outcomes suggested above.

From the investor's perspective, there are various costs and benefits to consider. The investor purchases the building at a predetermined purchase price, following which they generate rental income and incur Operations, Maintenance, and Repair (OMR) costs. At the end of the building's lifecycle, the End of Life (EOL) costs are determined. These costs can be offset during the sale. The potential selling price is determined by the initial investment, discounted at an inflation rate of 4%. The 4% represents an average of the past 20 years (CBS, 2023). The interest rate used in the study has also been taken into account. The following results were calculated, using the Baseline Scenario - 20 years: demolition or sale as a benchmark (see appendix for data):

- Base Scenario - 20 years: demolition or sale: 0.0%
- Scenario 4 - 20 years: demolition or sale: 1.6%
- Base Scenario - 20 years: circular: 0.9%
- Scenario 4 - 20 years: circular: 5.4%

As evidenced by the calculations, the circular alternatives (scenario 4) significantly outperform the baseline scenario based on a traditional model in circular business cases. When the End of Life (EOL) costs are excluded and only investment costs, Operations, Maintenance, and Repair (OMR) costs, rental income, and potential sale (traditional business case) are considered, the difference is minimal and the circular alternatives perform slightly better. This is due to the lower OMR costs for these alternatives, despite the higher initial costs associated with circular alternatives. Executing the Life Cycle Cost (LCC) analysis and comparing it with a standard business case reveals the financial potential of circular investments to be more attractive. The above calculations were carried out using available data and certain assumptions. To gain a better understanding, further research needs to be conducted. The aforementioned analysis has also been performed for a lifespan of 50 years, as can be demonstrated.

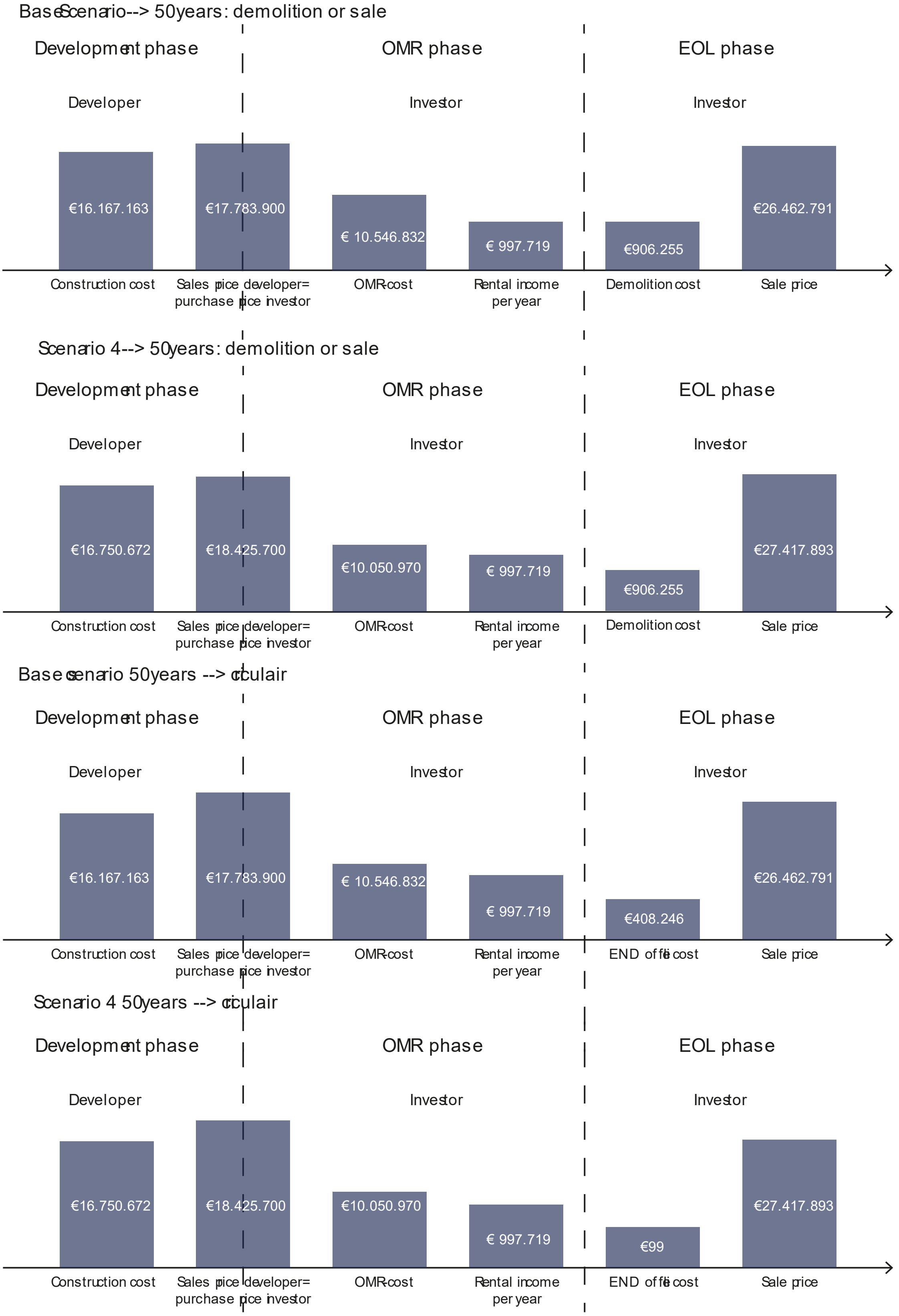

Figure 43 Business case 50 years traditional vs circular (author)

The same is now done for the 50-year scenario. Below are the results for the developer:

- Base Scenario - 20 years: demolition or sale: 0.0%
- Scenario 4 - 20 years: demolition or sale: 3,8%
- Base Scenario - 20 years: circular: 2,6%
- Scenario 4 - 20 years: circular: 9,2%

As can be seen, the percentages increase more than in previous 20-year calculations. What is striking is that the circular scenarios again score better than the traditional ones. This is due to EOL costs being higher. As observed, the percentages increase more significantly than in the earlier 20-year calculations. Notably, the circular scenarios once again perform better than traditional ones. This can be attributed to the higher End of Life (EOL) costs (benefits), as the technical life spans of various construction products have expired, necessitating more maintenance and repairs. This primarily applies to non-circular scenarios, whereas circular scenarios save costs through the residual value. As the time frame extends, the investment scenario from the developer's perspective becomes more favorable for circular scenarios, assuming the previously stated conditions and research assumptions remain applicable.

It's important to reiterate that these results are derived from a circular business case. In a traditional business case, EOL costs/benefits are not factored in, and the baseline scenario performs slightly better. The results are largely similar to the 20-year scenario, except the figures are even more advantageous for the developer compared to the 20-year scenario. Therefore, it is crucial to approach this from a circular business case perspective, indicating a necessary shift in mindset.

From the investor's perspective, there are various costs and benefits. The same analysis has also been conducted for a 50-year timeframe, as illustrated below. It's noteworthy that the benefits for the investor increase more than for 20 years, and furthermore, the circular alternatives also perform significantly better.

- Base Scenario - 20 years: demolition or sale: 0.0%
- Scenario 4 - 20 years: demolition or sale: 4%
- Base Scenario - 20 years: circular: 2,5%
- Scenario 4 - 20 years: circular: 9,8%

This analysis aimed to compare a traditional business case with a circular one. When End of Life (EOL) costs are not considered, the differences remain consistent and the traditional variant performs better due to lower initial costs. However, the business cases favor the circular variant when EOL costs are factored in, from both the investor's and developer's perspective. These scenarios assume a constant rental price, and the sale price is calculated based on the purchase price. A more realistic approach would be to adjust the rental price based on the scenarios. A higher rental price could justify a higher return. It could also be justified for a circular building, likely to be more energy-efficient than a traditional one. The selling price could also be higher than that of a traditional building. However, these considerations have not been included in this price calculation. It's notable that the percentage changes again increase more significantly than in the 20-year calculations. These insights indicate the financial potential of circularity, by comparing the outcomes with a traditional business case.

8.9 CO2 pricing for building products

A small analysis was conducted on the carbon pricing of construction products, examining the following scenarios: the base scenario and scenario 1, which focuses on timber construction. The life cycle costing (LCC) calculation revealed that these scenarios involved the highest and lowest amounts of concrete, respectively. This mini analysis examines the CO2 emissions associated with concrete and timber, specifically evaluating the replacement of all concrete in the base scenario with timber, resulting in the following outcomes:

Table 20 CO2 emissions (author)

Material	CO2 emission production	Embodied CO2	Total emission
Concrete	401 kg CO2/m3	408 kg CO2/m3	809 kg CO2/m3
CLT/timber	150 kg CO2/m3	-1000 kg CO2/m3	-850 kg CO2/m3

The results were obtained from Cobouw (2022), ICE (2023), and Rijksoverheid (2021). Currently, there are speculations that CO2 pricing may be implemented by 2030, according to Rijksoverheid. Two price levels have been identified, namely 40 euros per ton of CO2 emissions and 80 euros per ton of CO2 emissions. It is expected that the 80 euro price will have the most significant impact on achieving the climate goals of the Paris Agreement. In the base scenario, there is a substantial presence of 3,557 m3 of concrete, while scenario 1 requires 4,649 m3 of timber (more timber than concrete). These quantities result in the following CO2 emissions and pricing implications:

Table 21 CO2 prizing (author)

Scenario	CO2 emission	Pricing CO2 (40 euro)	Pricing CO2 (80 euro)
Base scenario	4652 ton CO2	€ 186.000,-	€ 372.160,-
Scenario 1	-3952 ton CO2	-€ 158.000,-	-€ 316.110,-

In the scenario with a price of 40 euros, the base scenario incurs an additional cost of €186,000, while at a CO2 price of 80 euros, the cost increases to €372,160. In scenario 1, the costs turn negative, indicating potential profit or the need to receive financial compensation. Currently, no agreements are in place, suggesting that they may not have to pay anything. These results are promising and will accelerate the transition towards a circular construction environment. The CO2 pricing is easily implementable in this model, offering potential for further development. The costs incurred contribute significantly to the potential of circular construction projects, although they are still relatively small compared to the initial investment, amounting to approximately 1 to 2 percent in additional costs. Nonetheless, these costs contribute to the feasibility of circular construction projects.

8.10 Discussion panel with stakeholders on outcomes model

In order to translate the results of the model and the thesis into potential value, a discussion panel was held to discuss these findings. This conversation took place with colleagues from FSD and investors. During this discussion, a critical evaluation was conducted to translate improvements, limitations, and interpretations into reality. The model was also validated, and the results were examined to ensure the quality of the thesis and the model.

During the conversation, the focus was primarily on the results of the LCC model, and they were compared to a traditional real estate feasibility study. Various assumptions and alternative scenarios were discussed to speculate further on the potential of the model and the outcome of the thesis. The results of the thesis were presented during this discussion. The key points that were addressed included the fact that the initial investments are indeed more expensive than the costs in the base scenario. The results indicate that savings can be achieved during the OMR and EOL phases, but these savings are minimal compared to the costs incurred in the initial phase. An interesting point raised in response to this was that these costs have the most significant impact on the investor and the developer's finances. This observation holds true if we approach it from a traditional way of thinking.

In response, I suggested considering the potential impact of the EOL phase by including it from the beginning (t=0). This could serve as an incentive for developers to embrace circular development, as it would help cover the increased foundation costs, which could then be passed on to the investor. The investor could then factor this into potential resale. Additionally, OMR costs decrease in circular scenarios compared to the base scenario, which directly affects the investor. The response to this suggestion acknowledged the significant potential and indicated openness to it. However, it was noted that translating this into practice is currently challenging due to the current market conditions. Rising construction prices, high interest rates, nitrogen regulations, and project delays make it difficult for developers to make their business cases feasible. Developers are currently striving to achieve their projects by minimizing costs. Given the increased prices and interest rates, it is challenging to incorporate additional investments in circularity or sustainability. Furthermore, there are currently no government regulations determining the level of circularity, which means the potential of circular development is not recognized, or it is currently challenging to make it feasible. This applies to both developers and investors.

From the perspective of the investor, these costs are also challenging. The investor is also facing increased interest rates, which reduces available funds. Moreover, investors often represent large funds and need to achieve a certain return on investment. Additional investments for a circular project entail higher risks, as they increase the likelihood of a project becoming unfeasible. In summary, investing in a circular project is currently challenging because both developers and investors have been facing difficulties lately. This conclusion is based on the results of the LCC model, as the initial costs are higher. If this were not the case, developers and investors would likely be more open to considering circular alternatives.

Building upon that, I discussed the scenario I ran considering price increases and decreases of certain materials. Specifically, I examined the price increase of concrete and the price decrease of biobased materials. As a result, the differences in initial investment between the different scenarios diminished. This modeling approach is particularly interesting because it reflects real-world dynamics. Last week, an article in the financial newspaper highlighted that concrete prices have risen by a significant 30% in recent years, while biobased materials are becoming increasingly affordable. This aligns well with the scenario I modeled and sparked reactions from the discussion panel, which agreed that building with wood instead of concrete is becoming more advantageous. This is an evolving trend that is becoming increasingly compelling. In the model, scenarios can be simulated to predict the necessary price decreases in concrete and wood to make circular scenarios financially viable. This allows for the prediction of the tipping point. However, currently, only the feasibility of the initial investment is considered in the model, without taking into account the potential savings in OMR and EOL costs. These developments offer great prospects for the entire industry and the model itself. The model truly has the potential to accurately predict this value.

Furthermore, it was suggested that it would be interesting to incorporate possible additional taxes on emission-intensive materials into the model, as this may happen in the future. In response, I acknowledged the significance of this suggestion and emphasized the need for further research. However, I was able to conduct a preliminary analysis that demonstrated potential savings of up to 80% in terms of CO2 emissions for both the base scenario and scenario 1. This reduction is equivalent to nearly 8000 tons of CO2. The model makes it easy to incorporate such factors and perform calculations. By visualizing these savings, circular alternatives with a smaller carbon footprint become even more financially attractive.

The last point raised by one of the attendees was that the investor/developer must have a strong motivation to invest in a circular manner. It is now possible, for example, that an investor wants to make their portfolio more sustainable or that a developer is willing to take the risk of investing in circular projects because they consider not only economic values but also ecological and social values. Another possible scenario is that large funds are required to invest more sustainably, perhaps due to government regulations in other countries. In response to this, I mentioned that it would be very interesting if the government provided discounts on loans for more sustainable projects compared to traditional projects. This means that lower interest rates would be charged for loans for circular construction projects, while higher interest rates would apply to traditional projects. This would make circular investing much more attractive. A response to this idea was that it is indeed very interesting, and they also see developments in this area. It was emphasized that the circular life cycle cost model is particularly interesting because it allows for accurate calculation of the end-of-life (EOL) and operation and maintenance (OMR) phases. This means that profits can also be generated at the end of the lifespan. However, there would need to be agreements on how these profits are calculated and distributed to the developer or investor. Finally, it was emphasized that the first circular investors would likely want to hold onto a project longer than usual, selling it after 40-50 years instead of 15-25 years. This is because the investments would become even more attractive due to the decreased OMR and potential profits in the EOL phase. Referring back to the results and outcome of the thesis, the reactions were very positive and hopeful. It was exciting to see that the potential of the model was recognized and that it can truly help investors and developers accelerate the transition to a circular construction economy. Everyone was also enthusiastic about how the model works and the amount of data available for calculations.

8.11 Limitations of the research

This study aims to forge a tool capable of discerning the intricate link between circularity levels and the financial ramifications in the context of real estate development projects. However, due to certain unavoidable limitations such as the crunch of time, hurdles in data gathering, and the ambiguity associated with cost definitions, the research is not without its constraints.

1. The scope of this study is restricted to the analysis of a single case study. Given the unique design and cost structure of every project, results extrapolated from this case study may not precisely align with other projects.
2. The research employs various R-strategies to ascertain the degree of circularity, which were subsequently adapted into scenarios specifically tailored for this case study. Therefore, the results might considerably deviate when applied to other projects.
3. The chosen case study for this research is a substantial 16-story residential tower, hence, the incurred costs are significantly high. The methodology utilized in this research may be more appropriate for projects of a similar scale.
4. The estimation of costs carries a level of uncertainty. While the research endeavors to constrain these uncertainties as much as practicable, their existence remains inevitable in any Life-Cycle Cost (LCC) analysis.
5. The calculation of end-of-life costs is based on expert inputs, Alba Concepts' financial residual value model, and insights derived from the study. However, these costs can fluctuate drastically in the real world, subject to myriad influencing factors such as price escalations, specific material taxes, etc.
6. The measurement of circularity degree is not quantified in this research. The R-strategies adopted to determine the degree of circularity merely hint at its position on the circularity ladder. Translating this degree into tangible figures remains a challenging endeavor.
7. The data inputs for the model were sourced from the contractor and suppliers, excluding the use of any universal data input. This factor may diminish the reliability of the model.
8. The study incorporates calculations premised on several assumptions, including interest rates, inflation, and material escalation rates. In the real world, these values may deviate, making the model a representation of a projected view rather than absolute reality.
9. This study does not take into account environmental costs, a factor that could profoundly influence future value and significantly affect the LCC of various scenarios.

8.12 Recommendations for further research

Through the authoring of this research and the analysis of discussions and limitations, several suggestions for future research have emerged.

1. The integration of a quantitative circularity assessment alongside a cost evaluation warrants further investigation. The steps to successfully implement these integrated methods could be assessed and validated.
2. Other economic incentives for circular construction projects should be explored to improve the execution of such projects.
3. A study focusing specifically on defining the financial residual value of products, and integrating this into a cost evaluation analysis, would be beneficial.
4. A study that targets multiple case studies could generate more data, thereby enabling a more robust comparison.
5. The inclusion of an environmental cost indicator in a cost analysis, especially when embodied carbon is priced, should be considered.
6. Creation of a uniform dataset of construction products, showcasing the principles of circularity (e.g., demountability, quality reduction, etc.), is recommended.

9. Conclusion

The primary objective of this research has been to investigate the intricate interconnections between building design, the degree of circularity, and the associated life cycle costs and benefits (LCC). A thorough understanding of the principles of a circular economy, specifically as they apply to the built environment, formed the bedrock of this inquiry. The circular economy, as examined in this study, proposes an economic system designed for resource efficiency, realized through an array of circularity strategies such as reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover. Reuse emerged as a standout strategy due to its efficacy in maintaining the primary function of building products.

A key revelation of the study is the substantial influence of design on both circularity and costs. Designing for adaptability and disassembly not only enhances circularity but also brings substantial cost savings. It's imperative to note, however, that the benefits extend beyond the economic realm, incorporating broader dimensions of value including social, technical, and functional facets. This research paid particular attention to both the technical and economic value, given their bearing on cost computations and alignment with circular principles.

While the study emphasizes the need for clear definitions and consensus in the application of circular strategies, it also acknowledges a prevailing lack of agreement on the interpretation of the circular economy in the context of the built environment. The study underscores the importance of differentiating between circularity strategies, such as the distinction between reuse and recycling. It further illuminates that the potential of reuse is largely determined by several factors including disassembly capability, the layer in which the product is situated, and the ability to uphold the product in its highest form rather than resorting to recycling.

In the endeavor to quantify the degree of circularity in buildings, the study explored various methodologies and assessment criteria. It employed circular strategies as indicators of a building's circularity, thereby accentuating the need for a universally accepted measure of circularity. In addition, these circularity strategies found application in defining different scenarios for the LCC model.

The financial implications of deploying circular strategies in real estate development projects formed a significant part of the investigation. An extensive analysis of cost factors in construction projects, particularly those adopting circular building design principles, shed light on the indispensable role of Life Cycle Costing (LCC). LCC, an encompassing tool accounting for all life cycle phases of a construction project, offers critical insights into various cost components and serves as a blueprint in the development of the research tool.

However, conducting a life cycle cost analysis of a circular building isn't without challenges. Notable among these are uncertainties in defining costs, the concept of residual value, and the lack of data for model input. A further significant uncertainty is the reliance on cost estimates based on assumptions and expectations, such as interest rates and inflation, underlining the necessity for more precise data and refined cost-estimation methodologies. This highlights the importance of conducting more case studies and performing sensitivity analyses through modeling, which would increase the accuracy of outcomes. Nonetheless, the tool developed in this study remains a projected representation of reality, offering insights into the impact of circularity on the financial costs and benefits of a project.

The study reveals that different scenarios, each characterized by varying degrees of circularity, have varying impacts on a project's LCC. Notably, the disassembly capability of building products exerts a strong influence on the LCC. Furthermore, while initial costs for circular alternatives may be higher, they could be recouped through the application of cost analyses such as LCC, as opposed to traditional cost analyses that solely consider the initial investment at t=0.

In conclusion, this research sheds light on the potential and intricacies of integrating life cycle costs and circularity metrics in real estate development. The findings suggest that further work is necessary to better define and apply circular strategies, develop robust tools for assessing circularity, and delve deeper into the financial implications of circular real estate development. This research therefore contributes to an ongoing dialogue, paving the way for a future where the built environment is sustainable, resource-efficient, and economically viable.

9.1 Summary of answers to research questions

To address the research gap, the main research question was formulated as follows:

> How can life cycle cost and circularity metrics be developed and framed for circular real estate development?

To gain sufficient knowledge to answer the main research question, several sub-questions will first be be answered first:

> SQ1: What are the principles of a circular economy in the built environment?
> SQ2 : What are methodologies and assessment criteria for quantifying the degree of circularity in a building?
> SQ3: What are the financial implications of applying circular strategies in real estate development projects?
> SQ4: What are the main challenges and obstacles when conducting a life cycle cost analysis of a circular building?

SQ1: What are the principles of a circular economy in the built environment?

The principles of a circular economy in the built environment are focused on facilitating sustainable value chains, reducing material usage, ensuring circular building operations, and promoting high-value material reuse. These principles closely align with the core circularity strategies proposed by Bocken et al. (2016), which involve limiting resource flows, slowing down resource consumption, and closing material loops. By applying these principles, the construction sector can contribute to a more sustainable and circular economy while minimizing waste and optimizing resource utilization. This can be achieved by taking into account the various 10-R principles during construction to ensure that a building contributes economically to human well-being and the biosphere. This involves selecting technical elements to be demountable and reusable while returning biological elements back to the biological cycle. Essential tools to achieve this include Design for Disassembly and Adaptability strategies.
Furthermore, it is crucial to recognize a building as a compilation of different layers rather than one building as a whole to understand its value. It is crucial to preserve the value of the building in its highest form by retaining building elements instead of breaking them down into raw materials. The R-framework mentioned above has been used to operationalize the level of circular economy activity in

the built environment, considering the different dimensions of a building. These principles encourage circularity in the built environment and provide better insight into the focal points during real estate development projects.

SQ2 : What are methodologies and assessment criteria for quantifying the degree of circularity in a building?

In order to accurately assess the degree of circularity within a building's construction, it is essential to comprehend the inherent relationship between circularity and its impact on the value of the built environment. In this context, "value" refers not only to economic aspects but also the technical and societal dimensions. Current assessments of circularity frequently resort to qualitative measures as they rely heavily on subjective evaluations (Tokazhanov et al., 2022). However, it is recommended to incorporate more quantitative methodologies to enhance the robustness and precision of these evaluations. These methods offer more measurable, authoritative, and quantifiable results, mitigating inherent subjectivity. Various studies have proposed different methodologies to quantify circularity. However, the field is yet to converge on a unified model that holistically represents all the principles and dimensions of value within circularity. The model by Zhang et al. (2021) presents a comprehensive approach by incorporating all value chains into the circularity assessment, but it requires further refinement to achieve completeness.

To facilitate a more comprehensive assessment of circularity, the values identified in section 3.1 were used, corresponding to specific assessment criteria. This study focuses mainly on the technical and economic aspects, as they affect the model. In this study, the "10-R" framework was used as a tool to provide a comprehensive picture of circularity levels. This framework ranks various factors according to their influence on circularity, from least influential to most influential Important contributors to circularity within the built environment in this context include the adaptability of building layers, the creation of clear separations within building layers, and the adaptability of individual building elements or products. The assessment also factors in the capacity for disassembly, the sustainability quotient of the selected materials and products, and the toxicity levels of the (raw) materials used.

SQ3: What are the financial implications of applying circular strategies in real estate development projects?

The application of circular strategies in real estate development projects carries various financial implications, as discovered through this research's extensive exploration into building design, the degree of circularity, and the associated lifecycle costs and benefits. One of the key insights is the significant influence of design on both circularity and costs. When buildings are designed with adaptability and disassembly in mind, it strengthens circularity and yields cost savings.

This research utilizes a circular life cycle cost model to map all phases of a construction project's lifecycle. This model aids in uncovering the financial implications of circular strategies and provides valuable insights into the various cost components linked to a building's different phases.

The different modelled scenarios, each characterised by a different degree of circularity, were found to have a different impact on a project's LCC. The study revealed that the disassembly capacity of building products significantly influences the LCC, particularly at the end-of-life phase. While the initial costs for circular alternatives might be higher, the research suggests these can be recouped through a comprehensive LCC analysis. This contrasts with traditional cost analyses that focus solely on the initial investment.

Modelling the various scenarios yielded mixed results. The initial costs are higher for circular strategies, as predicted in the literature. However, savings are visible in the operation, maintenance, and replacement (OMR) costs, and circularity substantially impacts the EOL phase, where significant savings can be realized. The analysis reveals that the most considerable influence on the financial feasibility of circularity can be achieved through savings in the initial phase, as it is the most cost-intensive. In conclusion, different circular strategies affect the LCC, with each scenario having its characteristic impact per lifecycle phase.

SQ4:What are the main challenges and obstacles when conducting a life cycle cost analysis of a circular building?

Conducting a circular life cycle cost analysis of a circular building presents a variety of challenges and obstacles. The most important of these is the uncertainty around determining costs. Fluctuations in material prices, labour costs and project-specific variables often make cost estimation a highly complex process. This study further underscored this complexity when data from FSD was occasionally inaccurate. This challenge is amplified when personal contact with producers becomes the primary data source, given that these inputs can still contain a degree of uncertainty.

An equally complex aspect is defining the residual value. This represents the remaining worth of an asset after full depreciation and its determination is notoriously complicated. The residual value is influenced by many factors such as the materials' lifespan, the degree of maintenance, and the potential for reuse or recycling of building components. This value's intrinsically futuristic nature necessitates a level of prediction which only increases the complexity. An attempt to address this within the study involved dividing the residual value into multiple variables to attain as accurate a definition as possible. These challenges are compounded by the limited data available for model input. The novelty of circular buildings as a focal point in property development means that there is often a need for more reliable data, which affects the accuracy of circular life cycle cost analysis.
more reliable data, which affects the accuracy of life-cycle cost analysis..

The complexity extends further when assumptions and expectations such as interest rates and inflation are incorporated into cost estimates. Erroneous assumptions can easily lead to inaccurate cost forecasts, amplifying the need for robust methodologies. To mitigate this, sensitivity analyses can serve as a valuable tool in enhancing the reliability of these estimates. In this study, uncertainties have been tackled as much as possible with justifications, often in the form of variables and factors. The main input for this is data; the more data available, the better the uncertainties can be tackled.

Main research question:

How can life cycle cost and circularity metrics be developed and framed for circular real estate development?

The formulation and contextualisation of life-cycle costing (LCC) and circularity metrics for circular real estate development necessitate an integrated approach. This approach converges in-depth research, cross-functional teamwork, and continuous metric refinement and verification cycles. At the heart of this undertaking lies the task of deciphering the complex ties between architectural design, the notion of circularity, and their economic ramifications.

One of the key findings of this investigation underscores the profound impact of architectural design on both circularity and cost variables. Architectural designs that prioritise adaptability and ease of disassembly can bolster circularity. This is achieved through the facilitated reuse and recycling of building materials, which can also yield substantial cost savings over the lifespan of a building. An essential stride towards creating LCC and circularity metrics is to assimilate these circularity-fostering design principles into the metrics. These principles were crucial in structuring the simulations and affected the various 'R-strategies' used due to the absence of a standardised circularity methodology.

Creating universally accepted and meaningful metrics necessitates a robust foundation. This can be achieved by unifying or standardising circular strategies, along with their definitions and impacts on the built environment. As revealed by the research, a potent circularity metric would need to factor in these diverse strategies and the variables that govern their implementation, as elucidated in the first subquestion.

Financially, the research reaffirms the vital role of Life Cycle Costing (LCC) in capturing the expenses of all life-cycle stages of a construction project. LCC emerges as a holistic tool, providing indispensable insights into the various cost elements. Therefore, it forms a crucial part of the framework for devising cost-centric metrics for circular real estate development. To align this tool with circular buildings, certain adjustments were necessitated. The model is built upon three distinct phases and considers Brand's layers for its formation.

The journey to develop these metrics presents certain challenges, such as uncertainties in cost definition, computation of residual value, and scarcity of data for model input, signaling the areas that demand further refinement. The dependency on cost estimates driven by assumptions and expectations accentuates the need for precision in data and advancement in cost-estimation techniques. In model development, this is achieved by associating as many variables as possible to the model to diminish uncertainty and conducting numerous sensitivity analyses to improve the definition and estimation of certain costs.

In summary, the development and alignment of life-cycle cost and circularity metrics for circular real estate development demand a methodical and iterative process. It necessitates understanding the dynamics between design, circularity, and cost variables, addressing the demand for standardisation and agreement in circular strategies, enhancing data gathering and analysis techniques, and consistently adjusting and validating these metrics against real-world cases. Through such a stringent, cooperative, and evolving process, these metrics can truly bolster the transition towards a built environment that epitomises sustainability, resource efficiency, and economic viability.

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10. Acknowledgement

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I Interview protocol

Interview protocol
Delft University of Technology
Management in the built Environment

Datum interview:

Naam van de geinterviewde:

Titel van het onderzoek: A Circular Life Cycle Cost model: Quantifying the Financial Implications of Circularity in Real Estate Development

Naam onderzoeker : Noah Zijlstra

Plaats:

Algemeen

- Waar houdt bedrijf zich mee bezig en hoe komen circulaire principes hierin terug?

- Wat zijn volgende u de definitie van circulaire economie en een circulair gebouw en wat zijn de fundamentele verschillen ten opzichte van een traditioneel gebouw? En wat betekent circulair bouwen?

Voor dat we verdergaan met de volgende vragen laat ik het conceptmodel zien dat ik heb gemaakt.

Circulariteit

- Waar liggen de knelpunten in het huidige ontwikkeltraject voor het realiseren van circulaire gebouwen?

- Hoe meet u de mate van circulariteit? Zijn er interne instrumenten?

- Welke criteria hanteert u momenteel bij het nemen van beslissingen over circulaire bouwprojecten?

- Bent u op de hoogte van het 10R-kader? Zo ja, Welke strategieën binnen het 10R-kader hebben de grootste impact op het realiseren van circulaire gebouwen?

- Wat zijn de bouwkundige ingrepen en welke activiteiten kunnen worden uitgevoerd om de circulariteit van een gebouw te vergroten (gerelateerd aan deze strategieën)

- Bij het ontwikkelen van circulaire gebouwen, wordt er speciale aandacht besteed aan verschillende lagen, zoals de schil, structuur en locatie? Indien ja, op welke laag ligt de grootste focus?

Financiën

- Wat is de belangrijkste drijfveer voor uw organisatie om te investeren in circulaire bouwprojecten?

- Wordt circulariteit al meegenomen in kostencalculaties bij jullie bedrijf?

- Zo ja, waar loop je dan tegenaan als je dit soort dingen wil gaan calculeren?

- Zo nee, hoe zou zo'n model er dan voor u uitzien?

- Welke factoren hebben invloed op financiële restwaarde?

- Hoe zou financiele restwaarde gedefinieerd kunnen worden? (denk aan recyclingwaarde, restwaarde, kwaliteitsreductie, reviseerkosten)

- Wat zijn dingen die jullie graag in het circulaire life cycle costing model terug willen zien?

- Hoe zou u de kosten gedurende de levensduur van een gebouw inschatten en de kosten aan het einde van de levenscyclus bepalen?

II Informed consent participation in research on circularity in the built environment.

Betreft: Geïnformeerde toestemming deelname onderzoek naar Circulariteit in de gebouwde omgeving

Geachte heer/mevrouw,
Dit onderzoeksproject heeft als doel een uitgebreid Circular Life Cycle Cost (CLCC) model te ontwikkelen dat alle levenskosten van bouwprojecten omvat en evolueert over verschillende niveaus van circulariteit. Het CLCC-model zal actoren in de bouwsector voorzien van informatie over de financiële gevolgen van circulaire ingrepen in de bouwsector en hen in staat stellen weloverwogen beslissingen te nemen over investeringen in circulaire projecten. Het is van cruciaal belang dat de gehele levenscyclus van een gebouw in aanmerking wordt genomen, van sloop tot recycling en hergebruik, om het aandeel van circulariteit in de gebouwde omgeving te vergroten.
Momenteel is er in de bouwsector aarzeling om te investeren in circulair bouwen vanwege financiële belemmeringen en het ontbreken van inzicht in de kosten en baten van circulair bouwen. Door het CLCC-model te ontwikkelen, zullen hopelijk de financiële en circulaire uitdagingen waarmee de bouwsector wordt geconfronteerd worden aangepakt. Dit zal helpen bij het realiseren van de doelstelling van de overheid om tegen 2050 circulair te worden en nieuwe zakelijke kansen te creëren, terwijl duurzaamheid wordt bevorderd en hulpbronnen worden behouden. Het verkrijgen van inzicht in mogelijke circulaire interventiestrategieën en hun bijdrage aan levenscycluskosten en circulariteit is essentieel voor de ontwikkeling naar een circulaire economie in de bouwsector.

Mijn onderzoek richt zich op het vergelijken van verschillende circulaire strategieën met betrekking tot de totale kosten van een project (life cycle cost analyse). Het niveau van circulariteit van een project wordt bepaald aan de hand van het 10R-kader (zie bijlage: 10R-strategien), waarbij de 10 circulaire strategieën worden getest op een bouwproject om de relatie tussen de mate van circulariteit en de totale kosten van een project te begrijpen. Het doel van het onderzoek is om besluitvorming over circulaire praktijken in bouwprojecten te verbeteren door te kijken naar de totale kosten van een project.
Ik wil graag meer inzicht krijgen in de haalbaarheid van circulaire strategieën in bouwprojecten en welke trends we kunnen verwachten in de komende jaren. Ik zou graag willen horen welke manieren er zijn om de mate van circulariteit in de gebouwde omgeving te vergroten (bij voorkeur op basis van het 10R-kader). Verder wil ik meer begrijpen welke problemen er momenteel bestaan bij het implementeren van circulaire praktijken en wat de drijfveren en obstakels zijn. Bovendien ben ik geïnteresseerd in uw visie op het model. Welke aspecten moeten bijvoorbeeld worden opgenomen in het model en op welke criteria baseren jullie de besluitvorming?

Ik zal het interview afnemen als interviewer, mijn naam is Noah Zijlstra. Het interview duurt ca. 45 tot 60 minuten en ik zou het graag opnemen om het achteraf uit te kunnen werken. Ik wil graag leren van uw ervaringen. Vanuit de universiteit ben ik gewend om nog eens apart te vragen of u wilt deelnemen aan het onderzoek en of u het goed vindt om het interview op te nemen. U mag ook nu aangeven dat u liever niet wilt deelnemen. U kunt zich op elk moment bedenken en uw deelname intrekken zonder opgave van reden. U mag ook weigeren om bepaalde vragen te beantwoorden.
Als u besluit om deel te nemen, vraag ik u om uw handtekening onderaan deze brief te zetten en deze als pdf naar mij terug te sturen. Ik zal ook mijn handtekening zetten. Dit doen we om ervoor te zorgen dat u er zeker van bent dat we vertrouwelijk omgaan met uw gegevens en antwoorden. Uw organisatie

zal het interviewverslag niet te zien of te horen krijgen. We maken een algemeen en anoniem verslag van de ervaringen van meerdere werknemers binnen uw organisatie. Als we uw woorden citeren, beloven we om uw naam niet te gebruiken en ervoor te zorgen dat het niet duidelijk is wie dit heeft gezegd. We zullen uw naam- en contactgegevens meteen na afloop van het onderzoek vernietigen.
Als u vragen heeft over dit onderzoek, kunt u contact met mij opnemen: Noah Zijlstra, T.N.Zijlstra@student.tudelft.nl, 0648527729. U kunt ook contact opnemen met mijn docent: Paul Chan (email: P.W.C.Chan@tudelft.nl), of Vincent Gruis (email: V.H.Gruis@tudelft.nl).
Als u mee wilt doen aan dit interview, wilt u dan de onderstaande verklaring invullen en ondertekenen?
Met vriendelijke groet,
Noah Zijlstra

In te vullen door de medewerker & studenten

Ik verklaar op een voor mij duidelijke wijze te zijn ingelicht over de aard, methode, doel en belasting van het onderzoek.
Mijn vragen zijn naar tevredenheid beantwoord.
Ik begrijp dat het geluids- en/of beeldmateriaal (of de bewerking daarvan) en de overige verzamelde gegevens uitsluitend voor analyse en wetenschappelijke presentatie en publicaties zal worden gebruikt.
Ik behoud me daarbij het recht voor om op elk moment zonder opgaaf van redenen mijn deelname aan dit onderzoek te beëindigen.
Ik heb dit formulier gelezen of het formulier is mij voorgelezen en ik stem in met deelname aan het onderzoek.

- ☐ **Graag ontvang ik aan het eind van het onderzoek een korte samenvatting van de resultaten van het onderzoek. Om deze reden verleen ik toestemming om mijn naam- en adresgegevens tot het eind van het onderzoek te bewaren.**

Plaats:

Datum:

_ _
(Volledige naam, in blokletters)

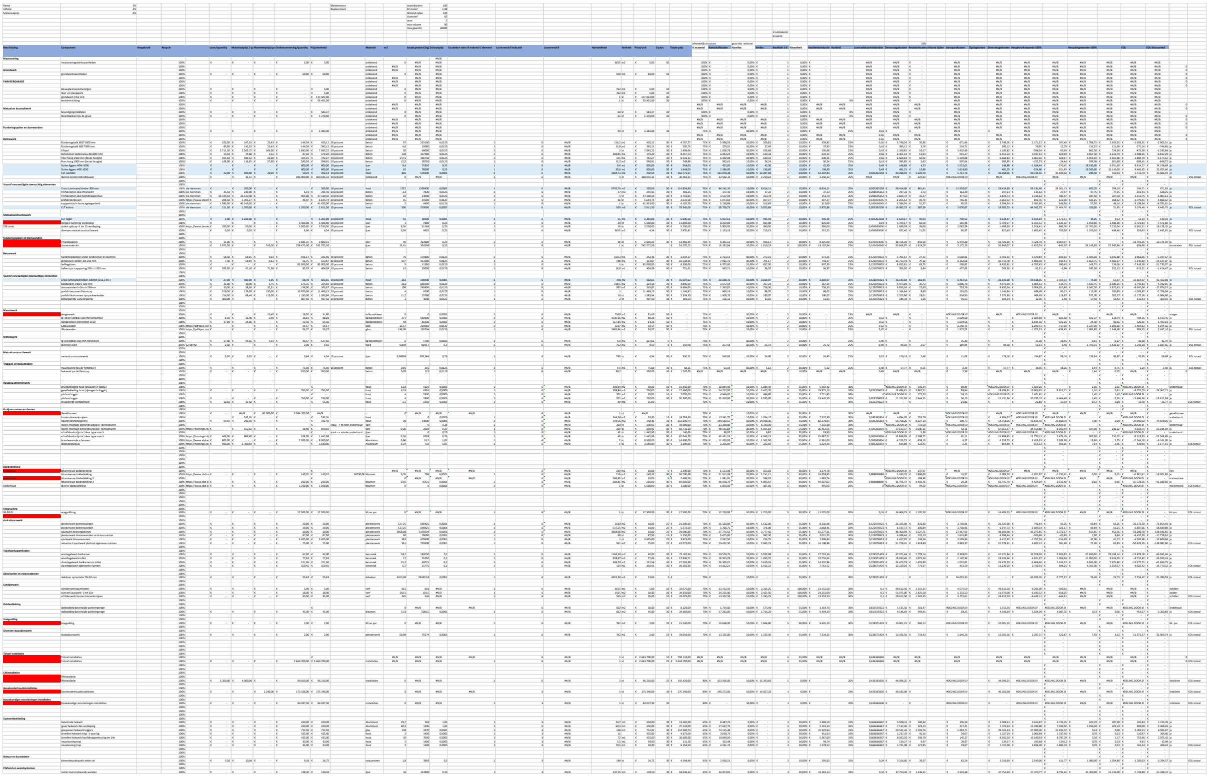
_ _
(Handtekening deelnemer)

‘Ik heb toelichting gegeven op het onderzoek en verklaar mij bereid nog opkomende vragen over het onderzoek naar vermogen te beantwoorden.’

Noah Zijlstra

_ _
(Handtekening student)

III Excel sheet model



IV EoL phase data sheet

Type verbinding		Toegankelijkheid		Randopsluiting		Doorkruizingen	
Droge verbinding	1	Vrij toegankelijk zonder extra handelingen	1				
'Verbinding met toegevoegde elementen	0,8	Toegankelijk met extra handelingen die geen schade veroorzaken	0,8	Randopsluiting		Doorkruizingen	
'Directe integrale verbinding	0,6	Toegankelijk met extra handelingen met volledig herstelbare schade	0,6	Open, geen belemmering voor het (tussentijds) uitnemen van producten of elementen	1	'Geen doorkruisingen - modulaire zonering van producten of elementen uit verschillende lagen	1
'Zachte chemische verbinding	0,2	Toegankelijk met extra handelingen met gedeeltelijk herstelbare schade	0,4	Overlapping, gedeeltelijke belemmering voor het (tussentijds) uitnemen van producten of elementen	0,4	Incidentele doorkruisingen van producten of elementen uit verschillende lagen	0,4
Harde chemische verbinding	0,1	Niet toegankelijk - onherstelbare schade aan het product of omliggende producten	0,1	Gesloten, volledige belemmering voor het (tussentijds) uitnemen van producten of elementen	0,1	Volledige integratie van producten of elementen uit verschillende lagen	0,1

Prijs/eenheid		Material	m3	totaal gewicht [kg	Schootprijs	Escalation rate of material / element	Loonverschil indicatie	Loonverschil	Hoeveelheid	Eenheid	Price/unit	Cyclus	Totale prijs	% material
		onbekend	#N/B	#N/B	#N/B									#N/B
		onbekend	#N/B	#N/B	#N/B									#N/B
€ 420,12	10 procent	beton	97	223100	0,0125	1	6	#N/B	114,2	m1	€ 420,12	30	€ 4.797,77	75%
€ 395,12	10 procent	beton	4,6	10580	0,0125	1	6	#N/B	12,8	m1	€ 395,12	30	€ 505,75	75%
€ 7.045,22	10 procent	beton	30	69000	0,0125	1	6	#N/B	2	st	€ 7.045,22	30	€ 1.409,04	75%
€ 179,20	10 procent	beton	138	317400	0,0125	1	6	#N/B	460,81	m2	€ 179,20	30	€ 8.257,72	75%
€ 742,27	10 procent	beton	172,5	396750	0,0125	1	6	#N/B	115	m2	€ 742,27	30	€ 8.536,11	75%
€ 599,91	10 procent	beton	12,5	28750	0,0125	1	6	#N/B	12,5	m2	€ 599,91	30	€ 749,89	75%
€ 600,00	10 procent	ijzer	9,4	73320	0,25	1	6	#N/B	9,4	m1	€ 600,00	30	€ 564,00	75%
€ 600,00	10 procent	ijzer	10	78000	0,25	1	6	#N/B	30,8	m1	€ 600,00	30	€ 1.848,00	75%
€ 492,54	10 procent	hout	826	578200	0,0005	1	6	#N/B	3304,73	m2	€ 492,54	30	€ 162.771,17	75%
€ 300.031,11	10 procent	onbekend	0	#N/B	#N/B	1	6	#N/B	1	st	€ 300.031,11	30	€ 30.003,11	75%
€ 200,00	10 procent	hout	1722	1205400	0,0005	1	6	#N/B	5742,74	m2	€ 200,00	30	€ 114.854,80	75%
€ 291,91	10 procent	beton	3,4	7820	0,0125	1	6	#N/B	17	m2	€ 291,91	30	€ 496,25	75%
€ 47.160,50	10 procent	beton	10	23000	0,0125	1	6	#N/B	1	st	€ 47.160,50	30	€ 4.716,05	75%
€ 1.644,74	10 procent	beton	15	34500	0,0125	1	6	#N/B	16	st	€ 1.644,74	30	€ 2.631,58	75%
€ 41.825,00	10 procent	beton	2	4600	0,0125	1	6	#N/B	1	st	€ 41.825,00	30	€ 4.182,50	75%
€ 2.611,50	10 procent	hout	300	210000	0,0005	1	6	#N/B	300	m3	€ 2.611,50	30	€ 78.345,00	75%
€ 1.201,00	10 procent	hout	55	38500	0,0005	1	6	#N/B	55	m3	€ 1.201,00	30	€ 6.605,50	75%
€ 5.500,00	10 procent	ijzer	1	7800	0,25	1	6	#N/B	20	st	€ 5.500,00	30	€ 11.000,00	75%
€ 3.250,00	10 procent	ijzer	6,56	51168	0,25	1	6	#N/B	16	st	€ 3.250,00	30	€ 5.200,00	75%
€ 4,34	10 procent	ijzer	0,59	4602	0,25	1	6	#N/B	6615	m2	€ 4,34	30	€ 2.870,91	75%

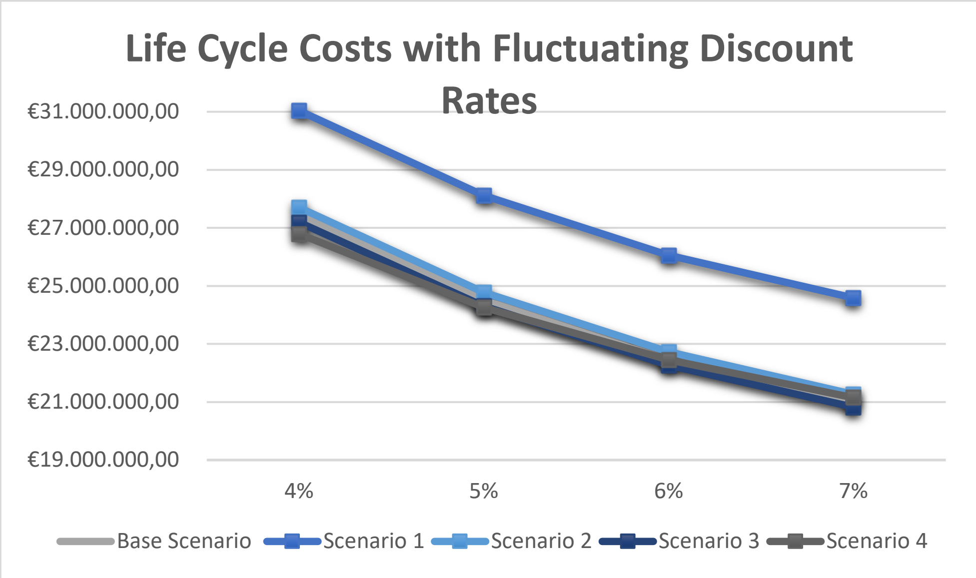
Prijs/eenheid		Material	m3	totaal gewicht [kg	Schootprijs	Escalation rate of material / element	Loonverschil indicatie	Loonverschil	Hoeveelheid	Eenheid	Price/unit	Cyclus	Totale prijs	% material	Aansch
		onbekend	#N/B	#N/B	#N/B									#N/B	
		onbekend	#N/B	#N/B	#N/B									#N/B	
€ 420,12	10 procent	beton	97	223100	0,0125	1	6	#N/B	114,2	m1	€ 420,12	30	€ 4.797,77	75%	€
€ 395,12	10 procent	beton	4,6	10580	0,0125	1	6	#N/B	12,8	m1	€ 395,12	30	€ 505,75	75%	€
€ 7.045,22	10 procent	beton	30	69000	0,0125	1	6	#N/B	2	st	€ 7.045,22	30	€ 1.409,04	75%	€
€ 179,20	10 procent	beton	138	317400	0,0125	1	6	#N/B	460,81	m2	€ 179,20	30	€ 8.257,72	75%	€
€ 742,27	10 procent	beton	172,5	396750	0,0125	1	6	#N/B	115	m2	€ 742,27	30	€ 8.536,11	75%	€
€ 599,91	10 procent	beton	12,5	28750	0,0125	1	6	#N/B	12,5	m2	€ 599,91	30	€ 749,89	75%	€
€ 600,00	10 procent	ijzer	9,4	73320	0,25	1	6	#N/B	9,4	m1	€ 600,00	30	€ 564,00	75%	€
€ 600,00	10 procent	ijzer	10	78000	0,25	1	6	#N/B	30,8	m1	€ 600,00	30	€ 1.848,00	75%	€
€ 492,54	10 procent	hout	826	578200	0,0005	1	6	#N/B	3304,73	m2	€ 492,54	30	€ 162.771,17	75%	€ 1
€ 300.031,11	10 procent	onbekend	0	#N/B	#N/B	1	6	#N/B	1	st	€ 300.031,11	30	€ 30.003,11	75%	€
€ 200,00	10 procent	hout	1722	1205400	0,0005	1	6	#N/B	5742,74	m2	€ 200,00	30	€ 114.854,80	75%	€
€ 291,91	10 procent	beton	3,4	7820	0,0125	1	6	#N/B	17	m2	€ 291,91	30	€ 496,25	75%	€
€ 47.160,50	10 procent	beton	10	23000	0,0125	1	6	#N/B	1	st	€ 47.160,50	30	€ 4.716,05	75%	€
€ 1.644,74	10 procent	beton	15	34500	0,0125	1	6	#N/B	16	st	€ 1.644,74	30	€ 2.631,58	75%	€
€ 41.825,00	10 procent	beton	2	4600	0,0125	1	6	#N/B	1	st	€ 41.825,00	30	€ 4.182,50	75%	€
€ 2.611,50	10 procent	hout	300	210000	0,0005	1	6	#N/B	300	m3	€ 2.611,50	30	€ 78.345,00	75%	€
€ 1.201,00	10 procent	hout	55	38500	0,0005	1	6	#N/B	55	m3	€ 1.201,00	30	€ 6.605,50	75%	€
€ 5.500,00	10 procent	ijzer	1	7800	0,25	1	6	#N/B	20	st	€ 5.500,00	30	€ 11.000,00	75%	€
€ 3.250,00	10 procent	ijzer	6,56	51168	0,25	1	6	#N/B	16	st	€ 3.250,00	30	€ 5.200,00	75%	€
€ 4,34	10 procent	ijzer	0,59	4602	0,25	1	6	#N/B	6615	m2	€ 4,34	30	€ 2.870,91	75%	€

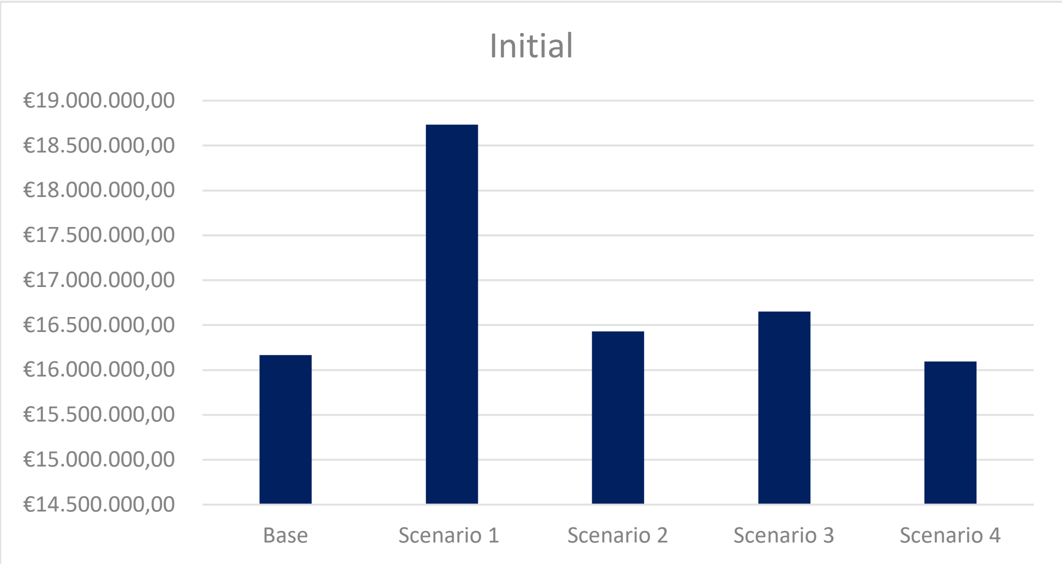
Cyclus	Totale prijs	% material	Aanschafkosten	%verlies	Verlies	Kwaliteit 1-6	%kwaliteit	Kwaliteitsreductie	%arbeid	Losmaakbaarheidsindex	Demontagekosten	Reviseerkoste	afstand rijden	transportkosten	Opslagkosten	Demontagekosten	Hergebruikswaarde 100%		R
		#N/B	#N/B	#N/B	#N/B	1	0,00%	#N/B	#N/B	0,16	#N/B	#N/B		#N/B		#N/B	#N/B	#N/B	
		#N/B	#N/B	#N/B	#N/B	1	0,00%	#N/B	#N/B	0,16	#N/B	#N/B		#N/B		#N/B	#N/B	#N/B	
30	€ 4.797,77	75%	€ 3.598,33	10,00%	€ 359,83	2	10,00%	€ 359,83	25%	0,16	€ 3.748,26	€ 35,98		€ 671,46		€ 3.748,26	€ 2.171,22	€ 347,40	€
30	€ 505,75	75%	€ 379,32	10,00%	€ 37,93	2	10,00%	€ 37,93	25%	0,16	€ 395,12	€ 3,79		€ 219,71		€ 395,12	€ 79,95	€ 12,79	€
30	€ 1.409,04	75%	€ 1.056,78	10,00%	€ 105,68	2	10,00%	€ 105,68	25%	0,16	€ 1.100,82	€ 10,57		€ 1.432,90		€ 1.100,82	€ -598,04	€ -95,69	€
30	€ 8.257,72	75%	€ 6.193,29	10,00%	€ 619,33	2	10,00%	€ 619,33	25%	0,16	€ 6.451,34	€ 61,93		€ 955,27		€ 6.451,34	€ 3.937,43	€ 629,99	€
30	€ 8.536,11	75%	€ 6.402,08	10,00%	€ 640,21	2	10,00%	€ 640,21	25%	0,16	€ 6.668,83	€ 64,02		€ 1.194,08		€ 6.668,83	€ 3.863,56	€ 618,17	€
30	€ 749,89	75%	€ 562,42	10,00%	€ 56,24	2	10,00%	€ 56,24	25%	0,16	€ 585,85	€ 5,62		€ 597,04		€ 585,85	€ -152,73	€ -24,44	€
30	€ 564,00	75%	€ 423,00	10,00%	€ 42,30	2	10,00%	€ 42,30	25%	0,48	€ 146,88	€ 4,23		€ 1.522,61		€ 146,88	€ -1.188,44	€ -570,45	€
30	€ 1.848,00	75%	€ 1.386,00	10,00%	€ 138,60	2	10,00%	€ 138,60	25%	0,48	€ 481,25	€ 13,86		€ 1.619,80		€ 481,25	€ -524,86	€ -251,93	€
30	€ 162.771,17	75%	€ 122.078,38	10,00%	##########	2	10,00%	€ 12.207,84	25%	0,505263158	€ 40.268,91	€ 1.220,78		€ 5.717,76		€ 40.268,91	€ 90.724,16	€ 45.839,58	€
30	€ 30.003,11	75%	€ 22.502,33	10,00%	€ 2.250,23	2	10,00%	€ 2.250,23	25%	#N/B	#N/B	€ 225,02		#DELING.DOOR.0!		#N/B	#DELING.DOOR.0!	#N/B	
																		€ -	
																		€ -	
30	€ 114.854,80	75%	€ 86.141,10	10,00%	€ 8.614,11	2	10,00%	€ 8.614,11	25%	0,505263158	€ 28.414,60	€ 861,41		€ 11.920,07		€ 28.414,60	€ 56.131,40	€ 28.361,13	€
30	€ 496,25	75%	€ 372,19	10,00%	€ 37,22	2	10,00%	€ 37,22	25%	0,208695652	€ 297,23	€ 3,72		€ 162,40		€ 297,23	€ 131,63	€ 27,47	€
30	€ 4.716,05	75%	€ 3.537,04	10,00%	€ 353,70	2	10,00%	€ 353,70	25%	0,208695652	€ 2.824,72	€ 35,37		€ 477,63		€ 2.824,72	€ 2.316,63	€ 483,47	€
30	€ 2.631,58	75%	€ 1.973,69	10,00%	€ 197,37	2	10,00%	€ 197,37	25%	0,145454545	€ 2.261,52	€ 19,74		€ 716,45		€ 2.261,52	€ 842,76	€ 122,58	€
30	€ 4.182,50	75%	€ 3.136,88	10,00%	€ 313,69	2	10,00%	€ 313,69	25%	0,145454545	€ 3.594,34	€ 31,37		€ 95,53		€ 3.594,34	€ 2.382,60	€ 346,56	€
30	€ 78.345,00	75%	€ 58.758,75	10,00%	€ 5.875,88	2	10,00%	€ 5.875,88	25%	0,505263158	€ 19.382,23	€ 587,59		€ 2.076,67		€ 19.382,23	€ 44.342,75	€ 22.404,76	€
																		€ -	
																		€ -	
30	€ 6.605,50	75%	€ 4.954,13	10,00%	€ 495,41	2	10,00%	€ 495,41	25%	0,505263158	€ 1.634,17	€ 49,54		€ 799,52		€ 1.634,17	€ 3.114,24	€ 1.573,51	€
30	€ 11.000,00	75%	€ 8.250,00	10,00%	€ 825,00	2	10,00%	€ 825,00	25%	0,24	€ 5.729,17	€ 82,50		€ 161,98		€ 5.729,17	€ 6.355,52	€ 1.525,32	€
30	€ 5.200,00	75%	€ 3.900,00	10,00%	€ 390,00	2	10,00%	€ 390,00	25%	0,436363636	€ 1.489,58	€ 39,00		€ 1.062,59		€ 1.489,58	€ 2.018,41	€ 880,76	€
30	€ 2.870,91	75%	€ 2.153,18	10,00%	€ 215,32	2	10,00%	€ 215,32	25%	0,436363636	€ 822,40	€ 21,53		€ 95,57		€ 822,40	€ 1.605,45	€ 700,56	€
																		€ -	

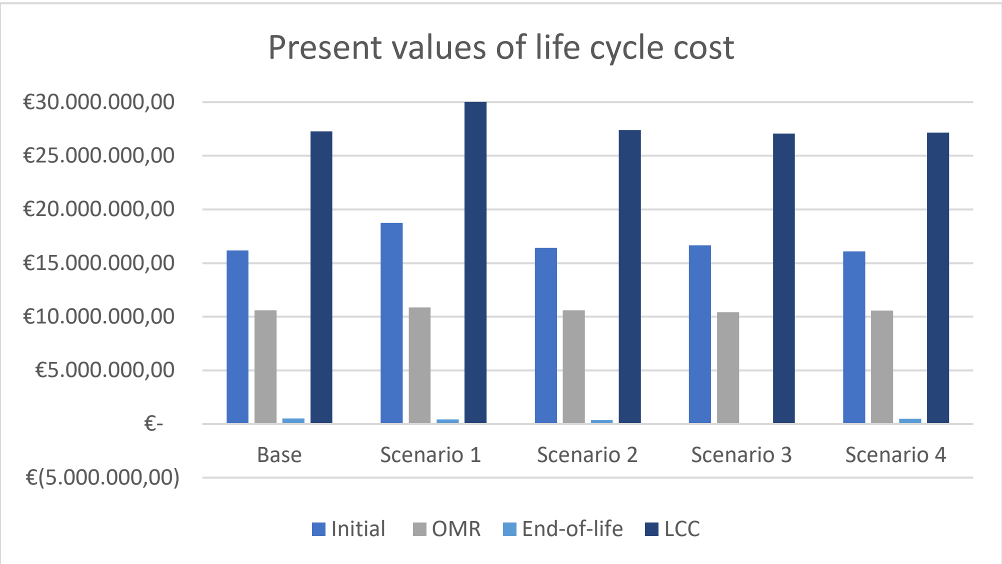
Recyclingswaarde 100%		EOL	EOL discounted			
€ 4.959,38	€ 4.165,88	€ -1.884,79	€ -5.174,53	ja		
€ 359,38	€ 301,88	€ -308,41	€ -846,72	ja		
€ 18.330,00	€ 9.531,60	€ 8.814,27	€ 24.198,88	ja		
€ 19.500,00	€ 10.140,00	€ 9.406,82	€ 25.825,66	ja		
€ 289,10	€ 143,03	€ 5.713,70	€ 15.686,49	ja		
#N/B	#N/B	#N/B	€ -	ja	EOL totaal	€ 37.336,21
	€ -	€ -	€ -			
	€ -	€ -	€ -			
€ 602,70	€ 298,18	€ 244,71	€ 671,83	ja		
€ 97,75	€ 77,35	€ -192,41	€ -528,25	ja		
€ 287,50	€ 227,50	€ -2.113,75	€ -5.803,12	ja		
€ 431,25	€ 368,52	€ -1.770,41	€ -4.860,52	ja		
€ 57,50	€ 49,14	€ -3.198,64	€ -8.781,61	ja		
€ 105,00	€ 51,95	€ 3.074,48	€ 8.440,73	ja	EOL totaal	€ -8.463,68
	€ -	€ -	€ -			
	€ -	€ -	€ -			
€ 19,25	€ 9,52	€ -51,14	€ -140,39	ja		

Layers		Code	Beschrijving	Component	Hergebruik	Recycle		Loon/quantity	Materiaalprijs / q	Materieelprijs/q	Onderaanneming/quantity
						100%					
		21	**Betonwerk**			100%					
Structure	ja	21.10		Funderingsbalk 850*1000 mm		100%		€ 105,00	€ 147,10	€ 23,43	€ 144,59
Structure	ja	21.11		Funderingsbalk 600 *600 mm		100%		€ 85,00	€ 142,10	€ 23,43	€ 144,59
Structure	ja	21.20		Liftput		100%		€ 2.711,50	€ 2.305,72	€ 345,00	€ 1.683,00
Structure	ja	21.21		Betonvloer kadeniveau dik(300 mm)		100%		€ 15,50	€ 74,88	€ 1,52	€ 87,30
Structure	ja	21.25		Poer hoog 1500 mm (bruto hoogte)		100%		€ 101,50	€ 189,52	€ 26,00	€ 425,25
Structure	ja	21.26		Poer hoog 1000 mm (bruto hoogte)		100%		€ 169,00	€ 119,81	€ 27,60	€ 283,50
Structure	ja	21.48		Stalen liggers HEM 1000		100%		€ -	€ -	€ -	€ 600,00
Structure	ja	21.49		Stalen liggers HEB 1000		100%		€ -	€ -	€ -	€ 600,00
Structure	ja	21.50		CLT wanden		100%		€ 22,00	€ 400,00	€ 20,30	€ 50,24
Structure	ja	21.51		diverse kosten betonbouwer		100%		€ -	€ 31,11	€ -	€ 300.000,00
						100%					
		23	**Vooraf vervaardigde steenachtig elementen**			100%					
Structure	ja	23.05		Cross Laminated timber 300 mm		100%	zie niersman	€ -	€ 200,00	€ -	€ -
Structure	ja	23.42		Prefab beton dak liftschacht		100%	zie niersman	€ 45,50	€ 240,00	€ -	€ 6,41
Structure	ja	23.61		Prefab beton dak hoofdtrappenhuis		100%	zie niersman	€ 10.144,50	€ 36.122,00	€ -	€ 894,00
Structure	ja	23.67		prefab bordessen		100%	https://www.steen	€ 208,50	€ 1.395,27	€ -	€ 40,97
Structure	ja	23.68		trappenhuis in horecagelegenheid		100%	zie niersman	€ 1.580,00	€ 40.245,00	€ -	€ -
Structure	ja	23.70		CLT kolom		100%	zie niersman	€ 211,50	€ 1.200,00	€ -	€ 1.200,00
						100%					
		25	**Metaalconstructiewerk**			100%					
Structure	ja	25.31		CLT ligger		100%		€ 1,00	€ 1.200,00	€ -	€ -

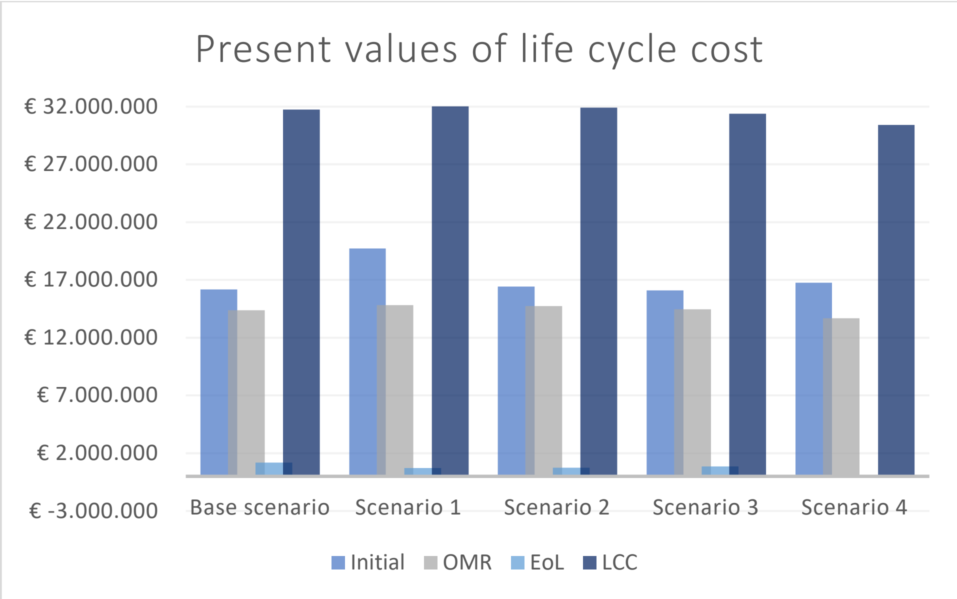
V First modelling

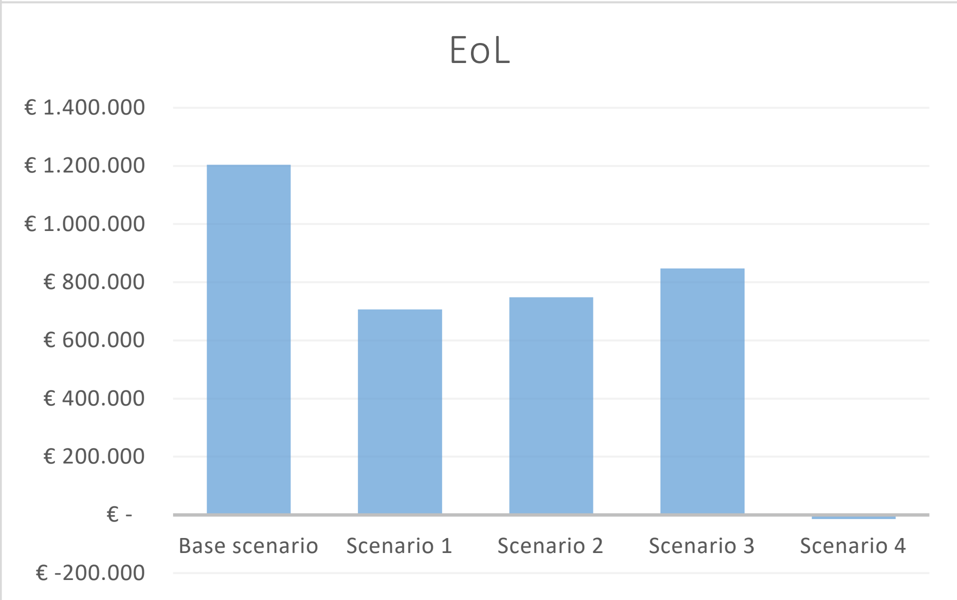


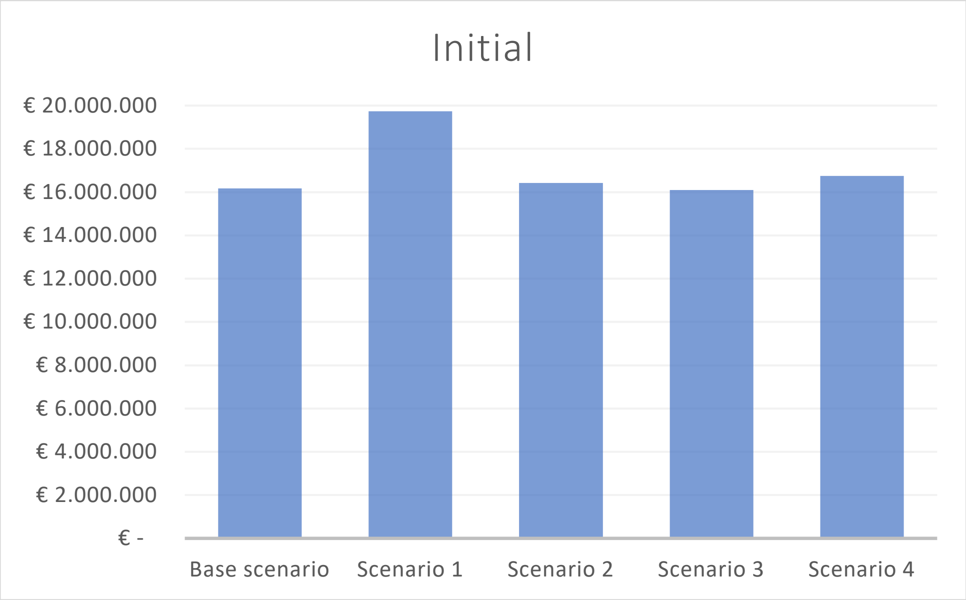




VI Second modelling






Initial
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€ 16.000.000
€ 14.000.000
€ 12.000.000
€ 10.000.000
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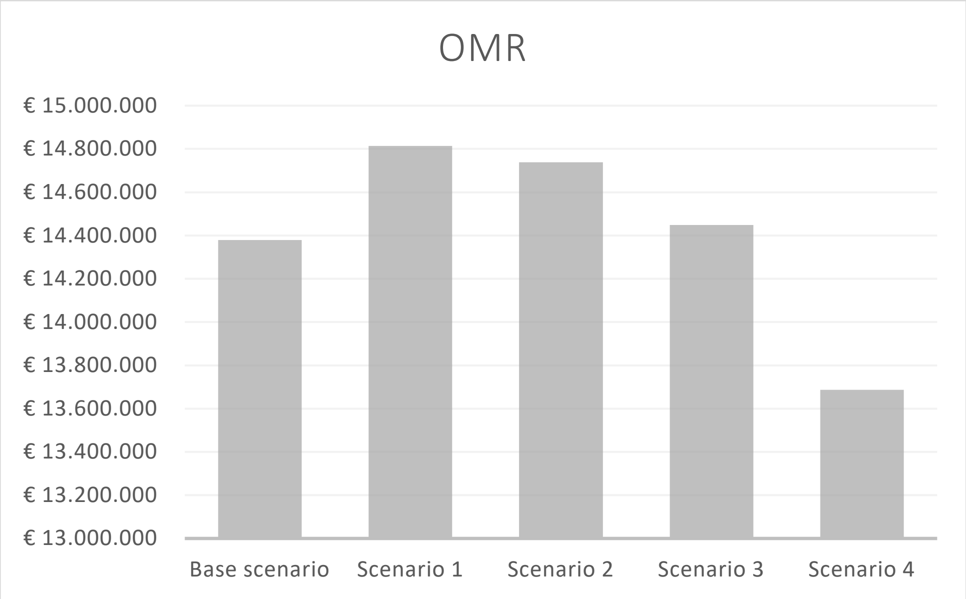
€ 6.000.000
€ 4.000.000
€ 2.000.000
€ -
Base scenario
Scenario 1
Scenario 2
Scenario 3
Scenario 4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€ 14.000.000
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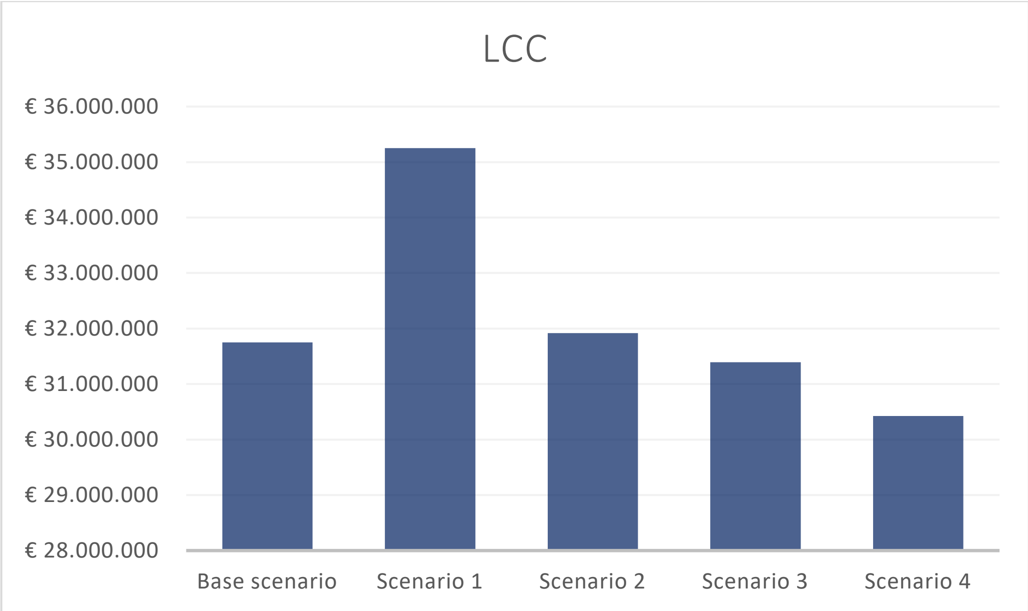
€ 13.000.000
Base scenario
Scenario 1
Scenario 2
Scenario 3
Scenario 4


LCC
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€ 31.000.000
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€ 29.000.000
€ 28.000.000
Base scenario
Scenario 1
Scenario 2
Scenario 3
Scenario 4

VIII Overview of results base scenario

Layer	Code	**Omschrijving**	**Initial**	**Operational**	**EOL**
Site	5	Maatvoering	€ 33.075,00	€ 0,00	
Site	12	Grondwerk	€ 30.000,00	€ 0,00	
Site	1	PARKEERGARAGE	€ 178.093,00	€ 0,00	
Site	43	Metaal en kunstofwerk	€ 112.472,20	€ 0,00	
Structure	20	Funderingspalen en damwanden	€ 235.917,00	€ 0,00	
Structure	21	Betonwerk	€ 977.722,42	€ 98.906,70	€ -15.448,17
Structure	23	Vooraf vervaardigde steenachtig elementen	€ 1.332.390,29	€ 28.735,91	€ -45.624,37
Structure	25	Metaalconstructiewerk	€ 320.747,40	€ 334,55	€ 4.810,62
Structure	20	funderingspalen en damwanden	€ 362.155,38	€ 0,00	€ -10.480,18
Structure	21	Betonwerk	€ 977.722,42	€ 23.716,77	€ -15.838,66
Structure	23	Vooraf vervaardigde steenachtige elementen	€ 284.063,09	€ 134.785,01	€ -11.941,31
Structure	22	Metselwerk	€ 537.969,54	€ 0,00	€ 16.376,34
Structure	22	Metselwerk	€ 3.977,94	€ 0,00	€ 2.731,77
Structure	25	Metaalconstructiewerk	€ 3.307,08	€ 32.446,90	€ 4,24
Structure	32	Trappen en ballustraden	€ 13.352,50	€ 1.350,74	€ -44,85
Skin	24	Ruwbouwtimmerwerk	€ 132.855,00	€ 243.565,35	€ -25.563,64
Skin	30	Kozijnen ramen en deuren	€ 5.517.503,79	€ 781.722,59	€ -38.288,53
Skin	33	Dakbedekking	€ 102.131,08	€ 152.620,50	€ -17.227,33
Skin	36	Voegvulling	€ 17.500,00	€ 35.406,37	€ -
Skin	40	stukadoorswerk	€ 117.603,30	€ 243.905,97	€ -124.960,25
Skin	41	Tegelwerkzaamheden	€ 157.575,76	€ 159.404,12	€ -89.349,31
Skin	42	Dekvloeren en vloersystemen	€ 116.150,43	€ 0,00	€ 31.868,91
Skin	46	Schilderwerk	€ 86.800,00	€ 439.042,21	€ -
Skin	33	Dakbeddeking	€ 36.990,00	€ 66.523,63	€ -4.469,16
Skin	36	Voegvulling	€ 1.524,00	€ 30.833,89	€ -
Skin	40	Diversen stucadorswerk	€ 1.524,00	€ 38.653,84	€ -4.469,16
Services	50-77	Totaal installaties	€ 2.643.700,00	€ 9.375.882,05	€ -
Services	80	Liftinstallaties	€ 192.420,00	€ 487.668,52	€ -
Services	84	Gevelonderhoudsinstallaties	€ 175.340,00	€ 886.885,50	€ -
Services	88	bouwkundige voorzieningen installaties	€ 84.037,50	€ 0,00	€ -
Space plan	32	Systeembekleding	€ 195.343,74	€ 0,00	€ -42.128,90
Space plan	35	Natuur en kunststeen	€ 4.548,48	€ 0,00	€ -1.363,07
Space plan	44	Plafond en wandsystemen	€ 95.496,63	€ 0,00	€ -2.648,66
Space plan	45	Afbouwtimmerwerk	€ 27.853,30	€ 28.176,49	€ -6.490,15
Space plan	47	Binneninrichting	€ 988.200,00	€ 999.666,13	€ -
Space plan	48	Bhangwerk vloerbedekking en stoffering	€ 18.108,30	€ 36.637,09	€ -4.206,26
Space plan	30	Kozijnen ramen deuren	€ 47.734,64	€ 48.288,51	€ 3.280,84
Space plan	45	afbouwtimmerwerk	€ 3.257,98	€ 3.295,78	€ 76,05
			€ 16.167.163,19	€ 14.378.455,10	€ 1.204.179,59
					7%
		Coolbase houtbouw	€ 19.732.210,17	€ 10.873.503,59	€ 430.826,89
			22%	-24%	-64,22%
		Biobased materials	€ 16.431.246,02	€ 10.810.323,52	€ 456.431,75
			2%	-25%	-62%
		Herbruikbaar	€ 16.750.672,11	€ 10.814.512,37	€ -8.873,21
			4%	-25%	-101%
		Recycelde materialen	€ 16.096.237,07	€ 10.578.266,26	€ 520.909,04
			-0,4%	-26,4%	-56,7%

IX Overview of results scenario 1

Layer	Code	Omschrijving	Initial	Operational	EOL
Site	5	Maatvoering	€ 33.075,00	€ 0,00	
Site	12	Grondwerk	€ 30.000,00	€ 0,00	
Site	1	PARKEERGARAGE	€ 178.093,00	€ 0,00	
Site	43	Metaal en kunstofwerk	€ 112.472,20	€ 0,00	
Structure	20	Funderingspalen en damwanden	€ 235.917,00	€ 0,00	
Structure	21	Betonwerk	€ 2.194.425,58	€ 221.988,76	€ 37.336,21
Structure	23	Vooraf vervaardigde steenachtig elementen	€ 2.266.535,81	€ 54.657,88	€ -8.463,68
Structure	25	Metaalconstructiewerk	€ 256.764,10	€ 334,55	€ 9.316,97
Structure	20	funderingspalen en damwanden	€ 367.387,38	€ 0,00	€ -25.226,69
Structure	21	Betonwerk	€ 2.194.425,58	€ 221.988,76	€ -33.253,90
Structure	23	Vooraf vervaardigde steenachtige elementen	€ 540.309,53	€ 229.283,45	€ -89.381,88
Structure	22	Metselwerk	€ 537.969,54	€ 0,00	€ 2.489,70
Structure	22	Metselwerk	€ 3.977,94	€ 0,00	€ 2.838,02
Structure	25	Metaalconstructiewerk	€ 3.307,08	€ 25.974,33	€ 44,17
Structure	32	Trappen en ballustraden	€ 13.352,50	€ 1.350,74	€ 3,40
Skin	24	Ruwbouwtimmerwerk	€ 132.855,00	€ 243.565,35	€ -30.856,60
Skin	30	Kozijnen ramen en deuren	€ 5.517.503,79	€ 781.722,59	€ -42.800,07
Skin	33	Dakbedekking	€ 102.131,08	€ 152.620,50	€ -48.457,43
Skin	36	Voegvulling	€ 17.500,00	€ 35.406,37	€ -
Skin	40	stukadoorswerk	€ 117.603,30	€ 243.905,97	€ -310.079,94
Skin	41	Tegelwerkzaamheden	€ 157.575,76	€ 159.404,12	€ -104.259,54
Skin	42	Dekvloeren en vloersystemen	€ 116.150,43	€ 0,00	€ -16.590,24
Skin	46	Schilderwerk	€ 86.800,00	€ 439.042,21	€ -
Skin	33	Dakbeddeking	€ 36.990,00	€ 66.523,63	€ -982,58
Skin	36	Voegvulling	€ 1.524,00	€ 30.833,89	€ -
Skin	40	Diversen stucadorswerk	€ 1.524,00	€ 38.653,84	€ -982,58
Services	50-77	Totaal installaties	€ 2.643.700,00	€ 9.375.882,05	€ -
Services	80	Liftinstallaties	€ 192.420,00	€ 487.668,52	€ -
Services	84	Gevelonderhoudsinstallaties	€ 175.340,00	€ 886.885,50	€ -
Services	88	bouwkundige voorzieningen installaties	€ 84.037,50	€ 0,00	€ -
Space plan	32	Systeembekleding	€ 195.343,74	€ 0,00	€ 10.204,03
Space plan	35	Natuur en kunststeen	€ 4.548,48	€ 0,00	€ -2.567,38
Space plan	44	Plafond en wandsystemen	€ 95.496,63	€ 0,00	€ -13.882,35
Space plan	45	Afbouwtimmerwerk	€ 27.853,30	€ 28.176,49	€ -13.011,76
Space plan	47	Binneninrichting	€ 988.200,00	€ 999.666,13	€ -
Space plan	48	Bhangwerk vloerbedekking en stoffering	€ 18.108,30	€ 36.637,09	€ -5.660,58
Space plan	30	Kozijnen ramen deuren	€ 47.734,64	€ 48.288,51	€ -22.643,05
Space plan	45	afbouwtimmerwerk	€ 3.257,98	€ 3.295,78	€ -10,84
			€ 19.732.210,17	€ 14.813.757,00	€ 706.878,61

X Overview of results scenario 2

Layer	Code	**Omschrijving**	**Initial**	**Operational**	**EOL**
Site	5	Maatvoering	€ 33.075,00	€ 0,00	
Site	12	Grondwerk	€ 30.000,00	€ 0,00	
Site	1	PARKEERGARAGE	€ 178.093,00	€ 0,00	
Site	43	Metaal en kunstofwerk	€ 112.472,20	€ 0,00	
Structure	20	Funderingspalen en damwanden	€ 235.917,00	€ 0,00	
Structure	21	Betonwerk	€ 977.722,42	€ 98.906,70	€ -35.851,66
Structure	23	Vooraf vervaardigde steenachtig elementen	€ 1.332.390,29	€ 28.735,91	€ -88.820,89
Structure	25	Metaalconstructiewerk	€ 259.851,40	€ 334,55	€ -3.811,07
Structure	20	funderingspalen en damwanden	€ 367.387,38	€ 0,00	€ -25.226,69
Structure	21	Betonwerk	€ 977.722,42	€ 98.906,70	€ -33.253,90
Structure	23	Vooraf vervaardigde steenachtige elementen	€ 284.063,09	€ 134.785,01	€ -26.404,90
Structure	22	Metselwerk	€ 700.624,72	€ 0,00	€ 12.287,27
Structure	22	Metselwerk	€ 42.121,11	€ 0,00	€ 301,84
Structure	25	Metaalconstructiewerk	€ 3.307,08	€ 26.286,65	€ 44,17
Structure	32	Trappen en ballustraden	€ 6.398,53	€ 11.234,56	€ 2,10
Skin	24	Ruwbouwtimmerwerk	€ 132.855,00	€ 243.565,35	€ -26.248,34
Skin	30	Kozijnen ramen en deuren	€ 5.526.630,09	€ 813.188,07	€ -46.045,89
Skin	33	Dakbedekking	€ 112.194,19	€ 162.800,37	€ -53.254,03
Skin	36	Voegvulling	€ 19.250,00	€ 38.947,01	€ -
Skin	40	stukadoorswerk	€ 191.426,60	€ 394.453,16	€ -224.079,14
Skin	41	Tegelwerkzaamheden	€ 192.457,37	€ 194.690,46	€ -201.754,69
Skin	42	Dekvloeren en vloersystemen	€ 133.572,99	€ 0,00	€ 15.869,47
Skin	46	Schilderwerk	€ 95.480,00	€ 482.946,43	€ -
Skin	33	Dakbeddeking	€ 40.689,00	€ 66.523,63	€ 729,45
Skin	36	Voegvulling	€ 1.676,40	€ 30.833,89	€ -
Skin	40	Diversen stucadorswerk	€ 1.676,40	€ 38.653,84	€ 729,45
Services	50-77	Totaal installaties	€ 2.643.700,00	€ 9.375.882,05	€ -
Services	80	Liftinstallaties	€ 192.420,00	€ 487.668,52	€ -
Services	84	Gevelonderhoudsinstallaties	€ 175.340,00	€ 886.885,50	€ -
Services	88	bouwkundige voorzieningen installaties	€ 84.037,50	€ 0,00	€ -
Space plan	32	Systeembekleding	€ 165.794,74	€ 0,00	€ 22.425,71
Space plan	35	Natuur en kunststeen	€ 4.548,48	€ 0,00	€ -2.567,38
Space plan	44	Plafond en wandsystemen	€ 88.243,75	€ 0,00	€ -21.386,45
Space plan	45	Afbouwtimmerwerk	€ 27.853,30	€ 28.176,49	€ -9.539,32
Space plan	47	Binneninrichting	€ 988.200,00	€ 999.666,13	€ -
Space plan	48	Bhangwerk vloerbedekking en stoffering	€ 21.061,95	€ 42.612,98	€ -3.323,50
Space plan	30	Kozijnen ramen deuren	€ 47.734,64	€ 48.288,51	€ 182,09
Space plan	45	afbouwtimmerwerk	€ 3.257,98	€ 3.295,78	€ 107,53
			€ 16.431.246,02	€ 14.738.268,22	€ 748.888,79

XI Overview of results scenario 3

Layer	Code	Omschrijving	Initial	Operational	EOL
Site	5	Maatvoering	€ 33.075,00	€ 0,00	
Site	12	Grondwerk	€ 30.000,00	€ 0,00	
Site	1	PARKEERGARAGE	€ 178.093,00	€ 0,00	
Site	43	Metaal en kunstofwerk	€ 112.472,20	€ 0,00	
Structure	20	Funderingspalen en damwanden	€ 235.917,00	€ 0,00	
Structure	21	Betonwerk	€ 977.722,42	€ 98.906,70	€ -35.851,66
Structure	23	Vooraf vervaardigde steenachtig elementen	€ 1.332.390,29	€ 29.169,24	€ -88.820,89
Structure	25	Metaalconstructiewerk	€ 274.125,30	€ 334,55	€ -212.634,41
Structure	20	funderingspalen en damwanden	€ 362.155,38	€ 0,00	€ -24.253,76
Structure	21	Betonwerk	€ 977.722,42	€ 98.906,70	€ -24.429,65
Structure	23	Vooraf vervaardigde steenachtige elementen	€ 288.346,71	€ 134.785,01	€ -30.401,04
Structure	22	Metselwerk	€ 594.459,27	€ 0,00	€ 29.713,73
Structure	22	Metselwerk	€ 3.977,94	€ 0,00	€ 2.865,82
Structure	25	Metaalconstructiewerk	€ 3.307,08	€ 183.734,84	€ 44,17
Structure	32	Trappen en ballustraden	€ 3.756,50	€ 380,01	€ 34,92
Skin	24	Ruwbouwtimmerwerk	€ 92.455,00	€ 140.009,57	€ -1.741,59
Skin	30	Kozijnen ramen en deuren	€ 5.486.926,22	€ 716.538,97	€ -45.468,43
Skin	33	Dakbedekking	€ 102.131,08	€ 152.620,50	€ -48.436,38
Skin	36	Voegvulling	€ 19.250,00	€ 38.947,01	€ -
Skin	40	stukadoorswerk	€ 100.489,98	€ 208.729,19	€ -223.818,40
Skin	41	Tegelwerkzaamheden	€ 157.575,76	€ 159.404,12	€ -182.464,98
Skin	42	Dekvloeren en vloersystemen	€ 122.884,50	€ 0,00	€ 50.729,55
Skin	46	Schilderwerk	€ 95.480,00	€ 482.946,43	€ -
Skin	33	Dakbeddeking	€ 36.990,00	€ 66.523,63	€ -917,17
Skin	36	Voegvulling	€ 1.676,40	€ 30.833,89	€ -
Skin	40	Diversen stucadorswerk	€ 1.524,00	€ 38.653,84	€ -917,17
Services	50-77	Totaal installaties	€ 2.643.700,00	€ 9.375.882,05	€ -
Services	80	Liftinstallaties	€ 192.420,00	€ 487.668,52	€ -
Services	84	Gevelonderhoudsinstallaties	€ 175.340,00	€ 886.885,50	€ -
Services	88	bouwkundige voorzieningen installaties	€ 84.037,50	€ 0,00	€ -
Space plan	32	Systeembekleding	€ 190.311,31	€ 0,00	€ 15.660,28
Space plan	35	Natuur en kunststeen	€ 4.548,48	€ 0,00	€ -2.567,38
Space plan	44	Plafond en wandsystemen	€ 95.496,63	€ 0,00	€ -13.882,35
Space plan	45	Afbouwtimmerwerk	€ 26.955,38	€ 27.268,15	€ -9.123,17
Space plan	47	Binneninrichting	€ 988.200,00	€ 999.666,13	€ -
Space plan	48	Bhangwerk vloerbedekking en stoffering	€ 18.981,30	€ 38.403,37	€ -1.293,90
Space plan	30	Kozijnen ramen deuren	€ 48.085,04	€ 48.642,97	€ -41,23
Space plan	45	afbouwtimmerwerk	€ 3.257,98	€ 3.295,78	€ 401,46
			€ 16.096.237,07	€ 14.449.136,64	€ 847.613,63

XII Overview of results scenario 4

Layer	Code	**Omschrijving**	**Initial**	**Operational**	**EOL**
Site	5	Maatvoering	€ 33.075,00	€ 0,00	
Site	12	Grondwerk	€ 30.000,00	€ 0,00	
Site	1	PARKEERGARAGE	€ 178.093,00	€ 0,00	
Site	43	Metaal en kunstofwerk	€ 112.472,20	€ 0,00	
Structure	20	Funderingspalen en damwanden	€ 235.917,00	€ 0,00	
Structure	21	Betonwerk	€ 1.001.415,87	€ 100.090,77	€ 33.095,44
Structure	23	Vooraf vervaardigde steenachtig elementen	€ 1.478.377,96	€ 29.161,76	€ 189.414,32
Structure	25	Metaalconstructiewerk	€ 329.017,10	€ 376,63	€ 13.347,35
Structure	20	funderingspalen en damwanden	€ 362.155,38	€ 0,00	€ -24.253,76
Structure	21	Betonwerk	€ 1.001.415,87	€ 100.090,77	€ -33.253,90
Structure	23	Vooraf vervaardigde steenachtige elementen	€ 288.272,78	€ 143.855,49	€ -4.199,98
Structure	22	Metselwerk	€ 630.864,92	€ 0,00	€ -13.923,08
Structure	22	Metselwerk	€ 3.977,94	€ 0,00	€ 2.865,82
Structure	25	Metaalconstructiewerk	€ 3.723,13	€ 33.283,47	€ 332,88
Structure	32	Trappen en ballustraden	€ 13.352,50	€ 1.350,74	€ 3,40
Skin	24	Ruwbouwtimmerwerk	€ 158.447,00	€ 253.920,93	€ 12.383,74
Skin	30	Kozijnen ramen en deuren	€ 5.542.997,80	€ 762.327,22	€ 5.898,06
Skin	33	Dakbedekking	€ 102.131,08	€ 142.440,63	€ -45.936,52
Skin	36	Voegvulling	€ 17.500,00	€ 35.406,37	€ -
Skin	40	stukadoorswerk	€ 117.603,30	€ 243.905,97	€ -258.744,99
Skin	41	Tegelwerkzaamheden	€ 189.090,91	€ 182.522,19	€ 8.821,87
Skin	42	Dekvloeren en vloersystemen	€ 139.380,52	€ 0,00	€ -3.702,42
Skin	46	Schilderwerk	€ 86.800,00	€ 439.042,21	€ -
Skin	33	Dakbeddeking	€ 36.990,00	€ 66.523,63	€ 2.834,85
Skin	36	Voegvulling	€ 1.524,00	€ 30.833,89	€ -
Skin	40	Diversen stucadorswerk	€ 1.524,00	€ 38.653,84	€ 2.834,85
Services	50-77	Totaal installaties	€ 2.643.700,00	€ 8.438.293,84	€ -
Services	80	Liftinstallaties	€ 192.420,00	€ 487.668,52	€ -
Services	84	Gevelonderhoudsinstallaties	€ 175.340,00	€ 886.885,50	€ -
Services	88	bouwkundige voorzieningen installaties	€ 84.037,50	€ 0,00	€ -
Space plan	32	Systeembekleding	€ 214.171,31	€ 0,00	€ 113.113,46
Space plan	35	Natuur en kunststeen	€ 4.548,48	€ 0,00	€ -2.567,38
Space plan	44	Plafond en wandsystemen	€ 105.865,29	€ 0,00	€ 48.666,63
Space plan	45	Afbouwtimmerwerk	€ 27.853,30	€ 28.176,49	€ -9.539,32
Space plan	47	Binneninrichting	€ 1.134.000,00	€ 1.147.157,85	€ -
Space plan	48	Bhangwerk vloerbedekking en stoffering	€ 21.600,57	€ 43.702,73	€ -576,12
Space plan	30	Kozijnen ramen deuren	€ 47.758,43	€ 48.312,57	€ -22.466,21
Space plan	45	afbouwtimmerwerk	€ 3.257,98	€ 3.295,78	€ 107,53
			€ 16.750.672,11	€ 13.687.279,79	€ -14.556,49

XIII Contemporary business case real estate development

The contemporary business case for property development entails the assemblage of property products by a property developer for marketing purposes. An essential characteristic of property development is that the developer assumes the project's risks and expenses. The property developer takes the lead in the development process, collaborating with various professionals such as architects, engineers, legal advisors, and brokers who offer specialized services and receive compensation for their involvement.

Funding for property development projects typically originates from sales or rental income generated by the project or from investors. It is the property developer's responsibility to ensure that the development costs, including consultant services, can be covered by the projected revenues. The ultimate objective of the property development process is to achieve a positive financial outcome contributing to the organization's profits. This necessitates that the sales or rental income surpass the costs and investments required for project realization. The contemporary business case for property development emphasizes the analysis of financial viability, identification of potential risks, and evaluation of the expected return on investment. Based on this analysis, investors and stakeholders can make informed decisions regarding the progression of the property development project.

Property developers create real estate products comprising land and structures. Real estate exhibits an extended economic lifespan and serves as a repository of diverse housing services. The real estate process can be categorized into three phases: (1) redevelopment, involving planning and construction; (2) operation, encompassing leasing or selling activities; and (3) end-of-life, comprising redevelopment, demolition, or sale to maximize value. Understanding these phases is crucial for comprehending the life cycle and management of real estate projects.

To elucidate the complex cash flows within a real estate process, the figure below illustrates the costs and benefits for both the developer and investor.

	Development phase	OMR phase	End-of-life phase
Real estate developer	• Foundation costs • Sales proceeds		
Investor		• OMR costs • Rental income	• Demolition costs • Redevelopment costs • Residual value (circular)

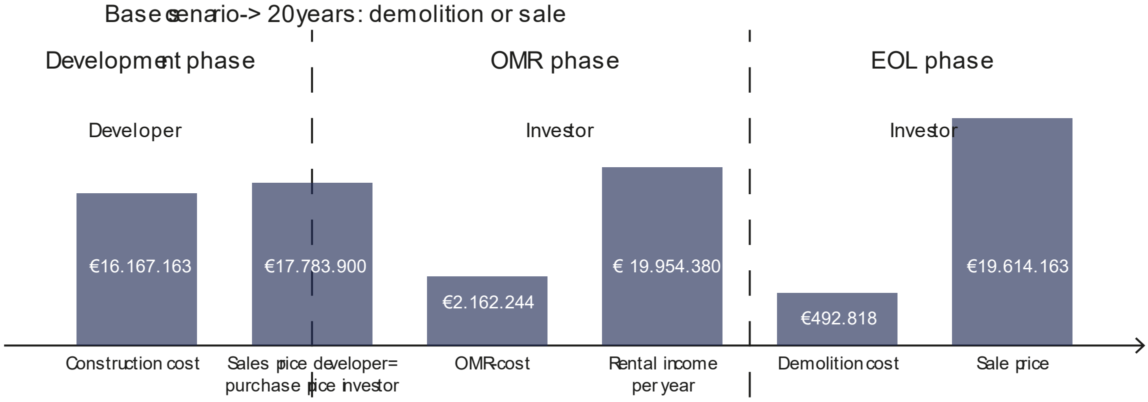
XV Potential rental income and demolition costs

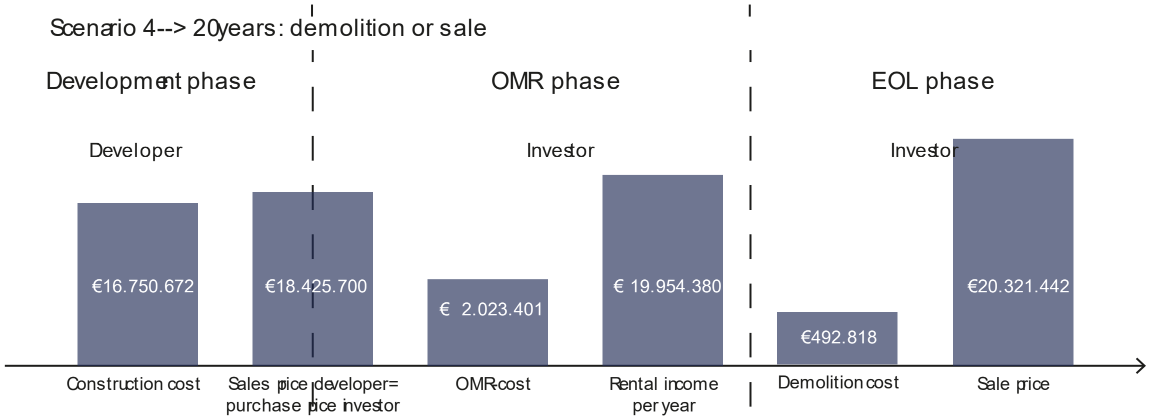
From FSD's budget, the following data were obtained regarding rental income. The Coolbase building will house 60 flats, 1 commercial space and 19 paid parking spaces. Below is an overview of Coolbase's potential rental income.

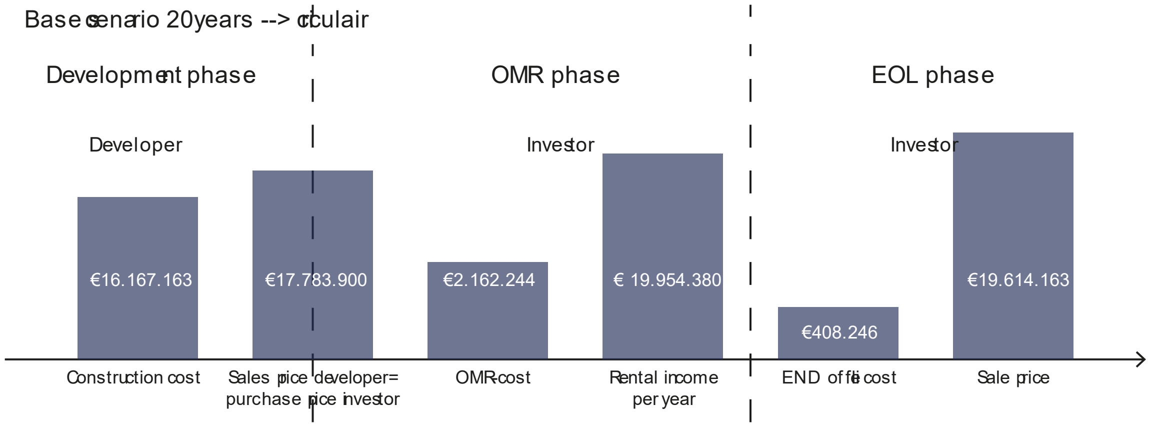
	Medium rental sector	Free rental sector	Commercial	Parking
Quantity	45	15	1	19
Rent per month (incl. VAT)	€998,65	€1909,60	6235,00	175
Total rental income per month	€44939,25	€28644	€6235,00	€3325
Total rental income (t=1)	€539271	€343728	€74820	€39900

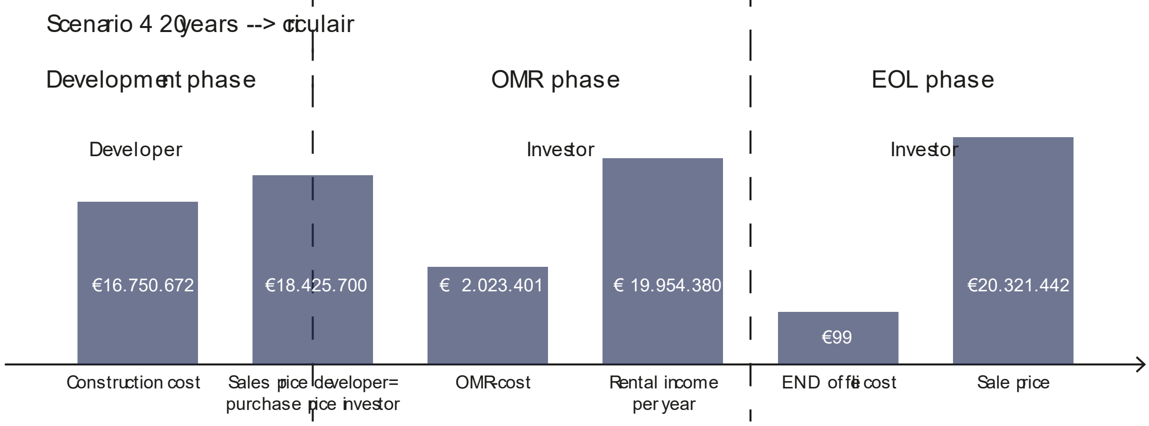
The total rental income per year is €997719 that can be generated when rented out.
For demolition costs, demolition costs per GLA of a building project in Amsterdam were used. These costs amount to €50 per m2 GLA. In the Coolbase project, potential demolition costs of the entire building would amount to 6615 GLA m2 * 50 = €330750. This amounts at t=1, when taking these costs into account any price increases should be taken into account.

XVI Business case 20 years

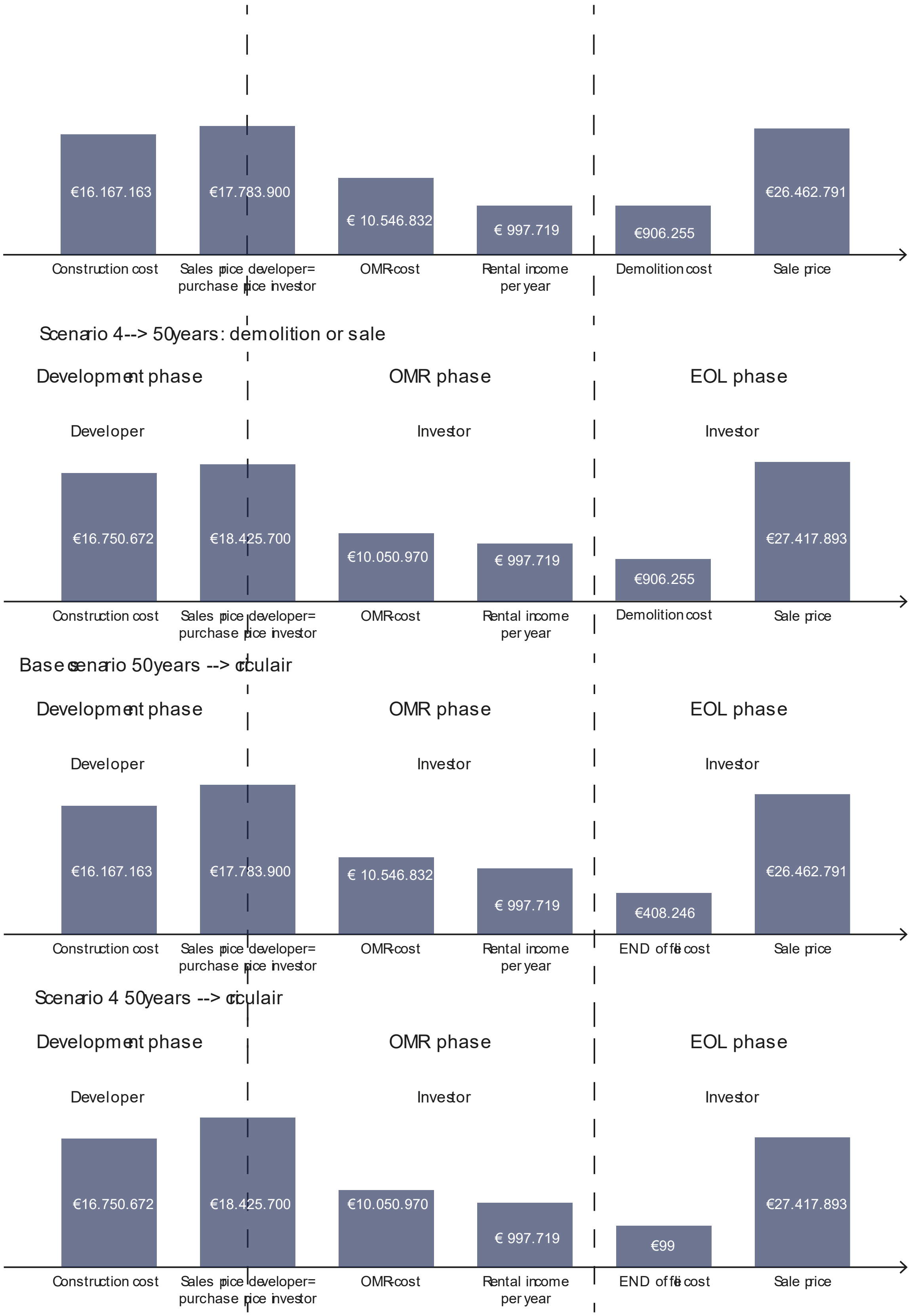








XVI Business case 50 years



XVI Scenarios business case

Sales price	OMR cost	Rent income	EOL cost	Sale price	Investor benefit
17783879,5	2162244	13690622,14	492818	19614163	12865843,2
18425700	2023401	13690622,14	492818	20321442	13070145,1
17783900	2162244	13690622,14	409246	19614163	12949395,1
18425700	2023401	13690622,14	99	20321442	13562864,1

Scenario 20 years

Sales price	OMR cost	Rent income	EOL cost	Sale price	Investor benefit
17783879,5	10546832	20258956,84	906255	26462791	17484781,3
18425700	10050970	20258956,84	906255	27417893	18293924,8
17783900	10546832	20258956,84	458246	26462791	17932769,8
18425700	10050970	20258956,84	-8.873	27417893	19209052,8

Scenario 50 years

Reflection

Reflecting on the journey undertaken during the development of this thesis, several key experiences and lessons learned stand out, offering a personal account of the challenges, rewards, and overall growth as a researcher.

Choosing a relevant and captivating thesis topic presented the initial challenge in my academic journey. The quest for an impactful topic was time-consuming and, at times, created a sense of lagging behind the set schedule. Nevertheless, I eventually chose the circular economy, aligning with my profound interest in sustainability, a theme consistently present throughout my undergraduate degree. It seemed a natural progression to consider the circular economy as the next phase towards a more sustainable world.

Recognizing the circular economy as a nascent field with no universally accepted definition, my initial goal was to address this ambiguity by creating a new methodology to measure circularity. However, as I delved deeper into the literature and discussions with various cost calculators in the construction sector, the focus shifted towards exploring the financial implications of the circular economy. This topic was under-explored and held significant potential to catalyze the transition towards a circular economy once brought to light.

As part of my exploratory study, I began collecting data and conducting interviews with construction professionals. These interviews, although challenging at times, were extremely insightful and enjoyable, providing unique knowledge and insight into the construction sector. Each interview highlighted the complexity of the field and the challenges I had taken on, contributing greatly to my understanding and development of the tool.

However, the path to graduation was not without its hurdles. From the struggle of not initially passing the P2 stage to recurrent health issues earlier in the year, these challenges tested my perseverance but also offered valuable learning opportunities and instilled resilience. My struggles extended to maintaining structure while tackling uncertainties, such as defining the financial residual value and implementing it in the model, a task I had underestimated and found more complex than anticipated, especially given my limited familiarity with Excel.

Throughout the research, I faced difficulties in defining the right research questions and setup. Valuable feedback from my supervisors helped immensely during this process. The final phase of the thesis, though demanding, was enlightening, shedding light on the core essence of circularity in the built environment and the potential of the tool I developed.

Reflecting on the academic journey, the MBE program's encouragement to foster creativity was pivotal. My research was a fusion of different aspects: conducting interviews, reviewing literature, and ultimately, creating and testing a tool using and apply it to case studies. This multidisciplinary approach helped foster a deeper understanding of the subject matter and nurtured skills valuable beyond the academic environment.

Ultimately, this research has taught me to think more critically, tested my perseverance, and enriched my understanding of sustainability and circular economy. Despite the challenges, it was a journey of immense personal and academic growth, culminating in a tool that I believe can contribute significantly to the transition towards a circular economy in the construction sector.