SWECO UNIVERSITY OF TWENTE.

BIOBASED MATERIALS IN THE CONSTRUCTION INDUSTRY

A CASE STUDY INTO THE EFFECTS OF BIOBASED CONSTRUCTION MATERIALS ON LIFE CYCLE COSTS

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Preface

Dear reader,

In front of you lies the end product of my Master's thesis 'Biobased materials in the construction industry: a case study into the effects of biobased construction materials on the life cycle costs'. With this thesis, I officially graduate from my Master Construction Management and Engineering at the University of Twente. My graduation also marks the end of my time as a student. I want to express my gratitude towards a number of people who have helped me during the process of writing my thesis or made my time in Enschede so enjoyable.

First of all, I would like thank Hans Voordijk and Marc van den Berg for supervising my thesis on behalf of the University of Twente. Their feedback helped me bring my thesis to the next level and provided me with important lessons and insights, which I know will be helpful during my professional career as well.

Next, I would like to thank Sweco for the opportunity. Specifically, I would like to thank Christiaan Voorend and Jeanine Többen for their help during the process. I really enjoyed our discussions and appreciate all of the feedback during the past months, both on my thesis and on a personal level. You continued to challenge me and this has allowed me to grow immensely over the past couple of months. I would also like to thank all of my other colleagues at Sweco that contributed in any way.

In addition, I would like to thank all of the companies that contributed to my research for their trust. Allowing me to use their information has enabled me to conduct this research and reach a very valuable and interesting end result. I think this thesis is a perfect example of how we can all come together to work towards a brighter, and more sustainable future.

To everyone that has made my time in Enschede so very enjoyable, thank you. I have made friends for life and I will forever look back on these years with so many great memories.

Finally, I would like to thank my (own and chosen) family for their continued support. Your words of encouragement always help to motivate me to keep going, even if the task feels impossible at first. At last, I would like to thank my girlfriend Elles for always supporting me with her feedback, guidance, advice, and emotional support. Both graduating from our Master's made it a special journey and so much more enjoyable.

I look forward to the future, as I will start my professional career as a Project leader at Sweco in July. I hope you enjoy reading my thesis.

Sven Lanting

Utrecht, 19th of May 2023

Management Summary

Circular construction is one of the ways to comply with the Paris Climate Agreement that aims to limit the global warming to 1.5°C. Using more renewable materials, such as biobased materials, can help to achieve this goal, but these materials also come with uncertainties and risks. Especially, the higher initial investment costs for these materials and the short-term vision of clients with respect to the potential long-term benefits are barriers that hinder the construction industry to become more circular. To enable project managers to consult clients, it is important to clarify the Life Cycle Costs implications due to the use of biobased materials in relation to the circular performance of apartments, i.e. Level of Circularity. Thus, the objective of this research is to analyse how biobased materials affect the relationship between Life Cycle Costs and the Level of Circularity of newly constructed apartments.

This research focuses solely on biobased materials and is guided by the Layers of Brand. The research only considers the Structure, Skin and Space Plan of apartments. The Services within the apartment are not part of the research, because no common biobased alternatives exist and operational costs are highly dependent on the end-user. Moreover, the Stuff layer is excluded, since the client has limited influence on this aspect and thus is highly dependent on the end-user as well.

Through a quantitative single-case study, the effects on Life Cycle Costs and Level of Circularity of constructing a single building layer with biobased materials are analysed. Furthermore, these effects are assessed when building layers are combined. An assessment framework using Life Cycle Costing and the Building Circularity Indicator calculation assesses the Life Cycle Costs and Level of Circularity of different design alternatives for an apartment in project X. Project X is an apartment building containing 108 apartments and is located in Groningen. Ten design alternatives are made from biobased materials such as wood, flax or hemp. Wood is used in the structure of the building or to construct window frames and inner door sills. Flax is used as insulation material, and Hemp is used to construct hempcrete for inner walls.

Analysis shows that the Structure has the highest influence on both the Life Cycle Costs (+11% to +31%) and Level of Circularity (+34% to +42%). The increase in Life Cycle Costs is caused by the higher material costs and the additional materials that are required to comply with the Building Decree. However, the biobased structure allows for easier disassembly and results in an increase in Level of Circularity.

The use of a biobased Skin entails an increase of 3 to 4% in Life Cycle Costs and shows limited to no influence on the Level of Circularity (0% to +1%). The increase in Life Cycle Costs arises from the significantly higher operational costs due to increased maintenance of the biobased materials used in the Skin. The limited influence on the Level of Circularity is caused by the fact that it is expected wood is incinerated at the end of its life cycle, which has a negative impact on the Material Circularity Indicator. The limited influence is also explained through the fact that a biobased alternative does not exist for every product in the Skin.

A biobased Space Plan causes a 13% increase in Life Cycle Costs, but has a negative impact on the Level of Circularity (-17%). The hempcrete inner walls and wooden inner door sills display higher costs over the whole life cycle. Similar to the Skin, the negative impact on the Level of Circularity is explained via non-existent biobased alternatives and the fact that wood and hempcrete are expected to be incinerated at the end of their life cycle.

Combining building layers in a design results in accumulated results for both the Life Cycle Costs and the Level of Circularity. The combination of a biobased Skin and Space Plan for example results in 17%

higher Life Cycle Costs, i.e. +4% for a biobased Skin and +13% for a biobased Space Plan. A strengthening effect on the Level of Circularity can be seen in combination with a biobased Structure due to the absence of spray plaster on the ceiling. A combination between a biobased Structure and Skin results in an increase in Level of Circularity of 0.13, while separately causing an increase of 0.12 and 0.00.

Ultimately, it is concluded that the use of biobased materials entails both an increase in Life Cycle Costs and Level of Circularity. The design alternative that entails both the highest Life Cycle Costs (+31%) and increase in Level of Circularity (+42%) is the alternative with a biobased Structure with wooden modules. The design alternative that only uses a biobased Structure from wooden elements and the alternative that combines this structure with a biobased Skin are the most cost-effective alternatives. These alternatives display an increase of respectively 11% in Life Cycle Costs and 33% in Level of Circularity and 15% in Life Cycle Costs and 36% in Level of Circularity. The inclusion of a biobased Space Plan is a less cost-effective measure, due to the negative impact of the biobased Space Plan on the Level of Circularity.

Important to note is the fact the implications on the Life Cycle Costs can differ when assessed for an apartment building as a whole. Additional benefits of constructing with timber, such as a faster construction time, are not included in this research, but are part of the construction costs for an apartment building. Moreover, the exclusion of Services has a significant decreasing effect on the Life Cycle Costs, since the Services approximately add up to 52% of the operational costs.

Despite the fact that the assumptions and data are verified with multiple sources, recommendations for further research relate to the validation of the results. by suggesting research into the additional benefits from constructing with timber for a whole apartment building, assessing other cases in a similar way, and to further develop circularity assessments.

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List of Abbreviations

Abbreviation	Meaning	Description
BCI	Building Circularity Indicator	An indicator that scores a building on circularity on a scale from 0 (not circular) to 1 (completely circular).
CE	Circular Economy	An economy in which there is no resource depletion, environmental pollution, and ecosystem degradation.
CLT	Cross-Laminated Timber	Timber that is glued cross-wise to construct walls and floors.
DDF	Disassembly Determining Factors	Factors found by Durmisevic (2006) that affect the disassembly of building elements.
DI	Disassembly Index	An indicator that scores the disassembly potential on a scale from 0 (not able to disassemble) to 1 (fully able to disassemble).
ECI	Element Circularity Indicator	An indicator that scores a building element on circularity on a scale from 0 (not circular) to 1 (completely circular).
ECI	Environmental Cost Indicator	The environmental impact based on the Life Cycle Assessment of products or materials expressed in shadow costs.
EOL	End of Life	The last life cycle phase of a building.
EPD	Environmental Product Declarations	Declarations that contain the environmental impact based on a Life Cycle Analysis.
HSB	Houtskeletbouw	Type of timber construction that uses bars and beams to create trusses.
LCA	Life Cycle Analysis	An analysis of the environmental impact of products or materials during their life cycle.
LCC	Life Cycle Costs	The costs arising during the full life cycle of a product or asset.
LCCA	Life Cycle Costs Analysis	An analysis to determine the Life Cycle Costs.
LFI	Linear Flow Index	An index that indicates the relative amount of a material or product that has a linear waste or End of Life scenario.
LoC	Level of Circularity	The circular performance expressed on a scale from 0 (not circular) to 1 (fully circular).
MCI	Material Circularity Indicator	An indicator that scores a material on circularity on a scale from 0 (not circular) to 1 (completely circular).
MPG	Milieu Prestatie Gebouwen	An assessment method that determines the Environmental Cost Indicator of a building expressed in € per m2 Gross floor area per year.
NMD	Nationale Milieu Database	A database that contains and manages the Environmental Product Declarations of products that are the fundament for sustainability/circularity assessments.
NPV	Net Present Value	The aggregated present value of costs/expenses.
PCI	Product Circularity Indicator	An indicator that scores a product on circularity on a scale from 0 (not circular) to 1 (completely circular).

1. Introduction

As is commonly known, the Paris Climate Agreement is set to limit the global warming to 1.5°C (UNFCCC, 2015). Research has shown that global warming is dependent on the accumulated CO_2 emissions. Therefore a carbon budget is introduced, which indicates the maximum amount of CO_2 that can be emitted to limit the global warming to 1.5°C (van Vuuren et al., 2016). To achieve the CO_2 reductions, the Dutch government aims to have a fully circular economy in the Netherlands by 2050 (Dutch Government, 2016, 2021).

The Dutch government has assigned five priorities in the transition to a circular economy, amongst which is the construction industry (Dutch Government, 2016), since the construction sector caused the highest amount of waste of all sectors in the Netherlands in 2016 (CBS, 2019). Furthermore, the construction sector is responsible for approximately one third of the waste generated in the world (Miller, 2021). To reduce CO_2 emissions within the construction industry and stay within the CO_2 budget, circular construction is a solution (Smit & Dirkse, 2023).

The material transition is an important aspect of creating a circular construction industry and seeks to use sustainable and 100% circular materials (Duurzaam-ondernemen.nl, 2021). Circular materials are materials that can be reused, renewed or given back to nature, all with the purpose to eliminate waste streams (GPR Software, n.d.-c). Biobased materials are an example of a circular materials and solve a tension between the current housing demand and the required reduction of CO_2 emissions in the upcoming decade (Studio Marco Vermeulen, 2020). Also, biobased materials can be a solution for the nitrogen emissions due to construction projects. The light weight of biobased materials results in lower emissions due to transport, and the production of these materials causes lower nitrogen emissions (Baggerman, 2022).

However, there are some uncertainties and preconceptions regarding the use of biobased materials such as high risks, unfamiliarity with the materials, unsupportive legislation, which results in a reluctance to use biobased materials within the construction industry (Studio Marco Vermeulen, 2020). These aspects can be translated back to the higher price of biobased materials (Studio Marco Vermeulen, 2020). Even though the potential benefits of biobased materials are evident (Dutch Government, n.d.-a; Quist, 2021b), the use of biobased materials remains behind. Therefore, this research aims to clarify the costs of using biobased materials, by analysing the relationship between the level of circularity and life cycle costs through using biobased materials.

1.1. Circular Economy

Ultimately, the Circular Economy (CE) is based on three principles, as is stated by the Ellen Macarthur Foundation (n.d.-e). These principles are: "[1] eliminating waste and pollution, [2] circulate products and materials (at their highest value), and [3] regenerate nature." (n.d.-e). The first principle, eliminating waste and pollution, arises from the fact that the current take-make-waste economy depletes the planet's resources. CE aims to eliminate the waste stream that occurs in a linear economy by ensuring that the materials are introduced into the economy again, see Figure 1 (Ellen MacArthur Foundation, n.d.-b).

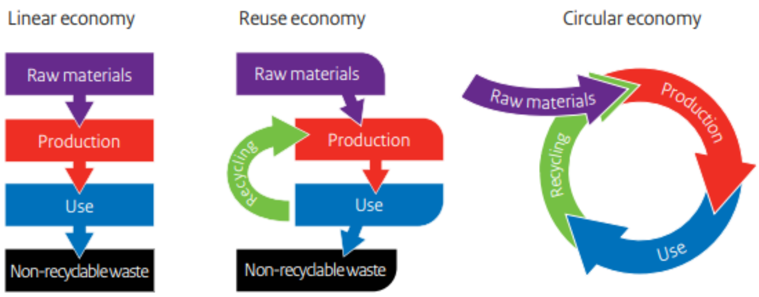


Figure 1: Models of a linear, reuse, and circular economy (Dutch Government, 2016, p. 15)

The second principle, circulate products and materials, concerns the process of: "… keeping materials in use, either as a product or, when they can no longer be used, as components or raw materials." (Ellen MacArthur Foundation, n.d.-a). This process is characterised by two types of cycles, namely the biological and the technical cycle (Ellen MacArthur Foundation, n.d.-a). Enabling biodegradable materials to return to Earth through natural processes such as extraction of biochemical feedstock or anaerobic digestion is part of the biological cycle. On the other hand, in the technical cycle products and materials are recycled, reused or remanufactured. The final principle of a circular economy stated by the Ellen Macarthur Foundation (Ellen MacArthur Foundation, n.d.-c) is regenerate nature, which is explained as supporting natural processes and allowing nature to thrive.

In addition to the principles and definitions defined by the Ellen MacArthur Foundation, Benachio et al. (2020) as well as Norouzi et al. (2021) found other definitions of CE that exist. The definition of Lacy and Rutqvist (2015) focuses more on the circular advantage caused by extended use of resources. Pomponi and Moncaster (2017, p. 711) identified six dimensions, which CE in the construction industry has to address such that a circular building is defined as: "… a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles.".

Ultimately, these principals and definitions of CE provide the basis for circular buildings, which means the building is "… developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation." (Kubbinga et al., 2018, p. 7).

1.1.1. CE in the construction industry

Current research of CE in the construction industry mainly focuses on the development of CE in the construction industry (Benachio et al., 2020), the reuse of sources/materials (Osobajo et al., 2022), and waste management (Hossain et al., 2020; Osobajo et al., 2022). The development of CE in the construction industry considers the barriers, challenges and opportunities to apply CE principles in the built environment (Benachio et al., 2020). Further exploration of the effects of material performance on material use and the reduction in CO_2 emissions, the appraisal of material components, and the economic and environmental benefits of reuse are focus points of research into the reuse of resources/materials (Osobajo et al., 2022). The contributions of CE to efficient waste management and the benefits of waste prevention through efficient use of construction materials are focus points of research into waste management (Osobajo et al., 2022).

Although a considerable amount of literature is available, the fields of standardization, the creation of building material passports, offsite construction and economics in relation to CE are unexplored (Benachio et al., 2020; Hossain et al., 2020; Osobajo et al., 2022). Especially, the economics of CE in the construction industry is currently unknown. According to Benachio et al. (2020), the business models related to the CE in the construction industry requires additional research as the current business models still focus on a linear philosophy. Furthermore, Osobajo et al. (2022) argues that a reduction of construction costs through CE is not considered in current research, as well as the concept of Whole Life Costing to assess the social, environmental and governmental costs in addition to construction costs is not investigated in considered literature. This is also mentioned by Hossain et al. (2020) as it was concluded that none of the considered literature critically reflected on the economic dimension of CE in the construction industry.

Platform CB’23 (2021a) compiled six circular design strategies to implement CE in the construction industry based on scientific literature and guidelines. The first strategy is ‘design for prevention’ and aims to prevent the use of resources. The second strategy is ‘design to reduce life cycle impact’ and focuses on the minimal environmental impact considering all life cycle phases. Third, ‘design for future resilience’ allows buildings to adapt to wishes and demands in the future. The fourth strategy considers ‘design with reused objects’ and relates to designing with reused building materials. Fifth, ‘design with secondary resources’ relates to the use of resources that are used before or are waste streams from other products. Finally, the last strategy considered by Platform CB’23 is ‘design with renewable materials’ and entails the use of resources that are replenished naturally on a human time scale.

1.2. Biobased materials

Biobased construction materials are made of renewable resources and (partly) consist of biological fibres (Quist, 2021b), which contributes to the material transition mentioned in the introduction. Biobased construction materials originate from regenerative cultivation that also protects the harvest location, are made from raw materials that grow back within 100 years, are not abiotic raw materials from geological formations, and subsequently reusable as raw material in a new construction material or nature (Dutch Government, n.d.-a). An example of a well-known (biobased) construction material is wood. Less common examples are flax wool or hemp isolation.

There are however lots of uncertainties regarding the use of biobased construction materials (TNO, n.d.-b). Even though, the use of biobased construction materials has several benefits over the use of traditional construction materials, such as the storage of CO_2, lightweight construction, or a healthier indoor climate (Dutch Government, n.d.-a; Quist, 2021b; Van der Hoeven, 2022a), some uncertainties and disadvantages arise with the use of biobased construction materials as well, such as the impact on farmers, higher price compared to tradition construction materials, and inappropriate building codes and regulations (Dutch Government, n.d.-b; Quist, 2021b; Van der Hoeven, 2022b).

1.3. Problem analysis

Literature states there are barriers that hinder the transition to a CE. Each barrier can be categorised as a financial, sectoral, technological, regulatory, or organisational barrier. An overview of the barriers can be found in Figure 49 (enlarged in Appendix A). The different barriers are addressed in the following paragraphs.

The first type of barriers are the financial barriers, amongst which the costs of building materials (Campbell-Johnston et al., 2019; Çetin et al., 2021; Kok et al., 2013), the unclear business case (Adams et al., 2017; Campbell-Johnston et al., 2019; Çetin et al., 2021; Guerra & Leite, 2021), and a short-term focus (Campbell-Johnston et al., 2019; Springvloed, 2021). In general, the costs for circular and more innovative building materials are higher than the traditional alternatives. Combined with the fact that it is yet unknown how these materials add value in the supply chain results in an unclear business case. Furthermore, the focus on short-term costs and benefits contributes to the perception of an unclear business case.

The technological barriers arise from the implementation and use of (new) technologies. Some examples of technological barriers that limit the implementation of CE principles in the construction industry are the lack of information about materials (Campbell-Johnston et al., 2019; Charef et al., 2021; Salvador et al., 2020) or the mismatch between supply and demand of reused materials (Kanters, 2020; Salvador et al., 2020). The lack of information about for example the best use of circular materials results in a preference for traditional materials and limits the transition to a CE. The second barrier relates to current differences between demand and the available supply at a certain moment, which requires more careful planning.

Traditionally, the construction industry is a conservative (Charef et al., 2021; Guerra & Leite, 2021; Kanters, 2020; Springvloed, 2021) and risk averse industry (Ritzén & Sandström, 2017; Springvloed, 2021). This is translated back to the fact that the industry is hesitant in to be innovative, which hampers the use of innovative building materials such as biobased materials or building with reused materials. This is primarily linked to the risks involved with these innovative ways of working. These barriers are considered to be sectoral barriers that limit the implementation of CE principles. Sectoral barriers are caused by the nature of the industry itself. Another example of a sectoral barrier is the lack of awareness for sustainability and the urgency of it (Adams et al., 2017; Çetin et al., 2021; Guerra & Leite, 2021; Kok et al., 2013; Ritzén & Sandström, 2017; Springvloed, 2021). In addition to the aspects just mentioned, the industry also is not interested in these topics, which results in a lack of awareness of sustainability and the urgency of it.

Different priorities set by the management of companies within the industry (Çetin et al., 2021; Charef et al., 2021), lack of time and human resources (Çetin et al., 2021; Salvador et al., 2020; Springvloed, 2021), and operating in a linear system instead of a circular system (Campbell-Johnston et al., 2019; Çetin et al., 2021) are organisational barriers. The organisational barriers arise from the organisation, i.e. construction company, whereas barriers due to regulations and governmental policies are deemed regulatory barriers.

1.3.1. Opportunity for research

This research is focused on the financial barriers such as an unclear business case, surpluses seen as costs, and the lower profitability for clients. These focus points are identified as research gaps in the transition to a circular construction industry. Furthermore, it is deduced that the implementation of circularity within construction projects in practice is dependent upon the financial aspect. This also became apparent during exploratory conversations with project leaders and managers from Sweco consulting in the residential construction industry. They mention that often circular measures are excluded due to the higher costs and risks related to building with new materials.

High investment costs for biobased materials in combination with the unrecognised added value of implementation in the design also results in the client wondering: “Why do I have to pay more? What do I get in return?”. In addition, the conservative nature and risk averse behaviour of the construction industry further complicates the adoption of the unknown biobased materials within new construction projects.

It can also be seen that the focus of the construction industry is mainly short-term, where long-term benefits are deemed irrelevant for clients (Campbell-Johnston et al., 2019; Kanters, 2020). However, in a CE these long-term benefits are important to properly assess the added value of circularity principles within new construction projects. For, example, the End Of Life (EOL) phase of buildings becomes more important in a CE, because in this phase the building is deconstructed and elements are recycled. Neglecting these values during cost-benefit analyses results in an incomplete assessment of the added value.

It is important for project managers in the residential construction industry to properly advise clients on circular measures within their projects. Furthermore, they need to be able to clarify the influence of the use of biobased materials on the life cycle costs and the gains in terms of circular performance (Level of Circularity). Due to the Paris Climate Agreement, ultimately the construction industry has to become circular as well. So, the urge for implementing circular construction materials, such as biobased materials, is rising and is the motivation for this research.

1.4. Research objective

The motivation of this research leads to the following research objective. Clarifying the relation between LCC and LoC when using biobased construction materials helps to address the reluctance to use biobased materials within new apartment buildings. Ultimately, the goal of this thesis is:

"To analyse the effects of using biobased construction materials within new apartment buildings on the relation between life cycle costs and level of circularity by comparing the life cycle costs and the level of circularity of different design alternatives of an apartment."

1.5. Research strategy

This research is considered to be a single case study research with a quantitative focus on the relation between the Life Cycle Costs (LCC) and the Level of Circularity (LoC) using biobased construction materials in newly constructed apartment buildings. Generally, at least a double case study should be performed to allow for generalization of results (Flyvbjerg, 2006; Goodrick, 2014; Yin, 2003). However, Flyvbjerg (2006) argues that a single case study has indeed a scientific value and states that the power of example is undervalued in science. Consequently, the single case considered in this research allows for a deeper analysis and can therefore contribute scientifically. In addition, this research has a quantitative focus, since it analyses the numerical effects on the LCC in relation to the LoC.

1.6. Main research question

In this subsection, the main research question is discussed. The main research question is built upon the research objective, which is stated in Section 1.4, and focuses on predictive knowledge, since it aims to quantify the influence of biobased construction materials on the LCC and LoC. This objective translates to the following main research question:

"How does the use of biobased construction materials within newly constructed apartments affect the relationship between the life cycle costs and level of circularity?"

1.7. Subquestions

This subsection elaborates on the subquestions that contribute to answering the main research question.

1. "What is the theoretical relationship between the LCC and LoC of apartments using biobased construction materials?"
2. "Which biobased construction materials are currently used within the construction industry in the Netherlands?"
3. "What is the impact of applying biobased materials in one layer of the building based on the layers of Brand in terms of life cycle costs and level of circularity?"
4. "How do the life cycle costs of apartments (partly) constructed of biobased materials vary with the level of circularity?"

1.8. Research scope

To ensure the research is reproducible, achievable within the set timeframe and the outcomes are understandable it is important to demarcate the scope of the research (DiscoverPhDs, 2020). In addition, the scope clarifies which aspects are taken into account, and which aspects are neglected. The research characteristics important for demarcation of the scope are discussed below.

First, this research focuses on a single circular design strategy. Platform CB'23 (2021) has defined six different circular strategies, amongst which the strategy 'Design with renewable raw materials'. This type of strategy entails construction materials that are made of renewable sources, e.g. cultivation, natural replenishment, or natural purification (Platform CB'23, 2021b). As designing with renewable raw materials is the most common strategy within the research of W/E Adviseurs (2022), this strategy is the focus of this research. Additionally, it can be seen as the most tangible strategy, because it only entails a material change within projects and is more quantitative in comparison to other strategies such as future proof design.

Secondly, the research only aims to address the financial barriers for the lack of implementation of CE in the construction industry (see Figure 49 in Appendix A). Since finance is always an important aspect in a construction project, the focus will be on the Life Cycle Costs. This includes the costs made during the life cycle of a building, such as investment costs, maintenance costs, operating costs, but also disposal and demolition costs.

The third aspect is related to the type of building assessed in the research. Similar research by Braakman et al. (2021) focuses on a single-family house, which is based on a common building design for a Dutch single-family house. Within this research newly constructed apartments are taken into account. Since Sweco's daily operations consists of a high percentage of apartment buildings, a conscious choice is made to research this type of project.

Furthermore, this research focuses on three layers of the Brands Shearing layers model (see section 2.2). These layers include the Structure, Skin, and Space plan. The scope is limited to these layers as first of all, the Site is out of scope due to the nature and lifespan of that layer. Second, the Services layer is excluded from this research, because the energy costs are not taken into account, the utilisation of systems is very dependent on the client, and there are no biobased alternatives for this layer (NIBE, 2019). Lastly, the Stuff layer is also not part of the scope of this research, due to the fact that Sweco nor the client that owns the building, have an impact on the elements inherent to the Stuff layer. Concluding, only the layers Structure, Skin, and Space plan are part of the scope of this research.

Lastly, to restrict the extensiveness of the research, it focusses on a selection of building elements. These building elements are based upon the Layers of Brand, which categorises the building in different layers. As was just discussed, this research includes the Structure, Skin, and Space Plan layer. Table 1 (on the next page) shows an overview of the building elements taken into account per building layer. The Layers of Brand are further explained in section 2.2.

Table 1: Overview of building elements in scope based on the Layers of Brand.

Structure
Lead-bearing structure
Floors
Skin
Inner cavity leaf
Cavity insulation
Outer cavity leaf
Window frames
Glazing
Space Plan
Inner walls
Door sills
Doors
Floor finishing
Wall finishing
Ceiling finishing

2. Literature review

This chapter describes the current state in literature regarding (i) the relationship between LCC and LoC when using biobased materials, (ii) LoC assessments (iii) LCC assessments, and (iv) biobased materials used in the construction industry.

2.1. Relationship LCC and LoC

This section further elaborates on the literature study on the relationship between LCC and LoC when using biobased construction materials. As discussed by Braakman et al. (2021), the design has an influence on both the LCC and LoC, due to the material choices, construction methods or connection types. This relation is schematised in Figure 2, by arrows A and B.

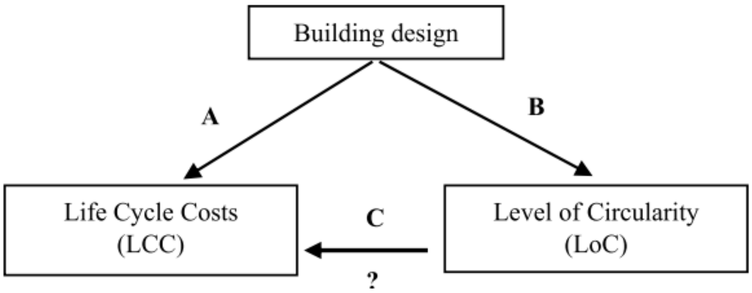


Figure 2: Relationship between building design, LCC and LoC (Braakman et al., 2021, p. 2)

The relation between the LoC and LCC contributes to the implementation of biobased construction materials. This is also expressed by Wang et al. (2017), because a solid financial case for involved stakeholders guides the development of material circularity (Wang et al., 2017). Kambanou & Sakao (2020) furthermore display that circular alternatives should provide at least the same functional value or value perceived by the owner, due to the unwillingness to pay for lower value alternatives.

However, apart from the research of Braakman et al. (2021), in which the influence of LoC on LCC was investigated by researching a single-family house, the relation between LoC and LCC (arrow C in Figure 2) is rather unexplored. Braakman et al. (2021) concluded that a doubling of the LoC through using alternative materials had no influence on the LCC. A further increase of the LoC with various alternative materials resulted in higher LCC in comparison to the baseline (Braakman et al., 2021).

Especially, the use of biobased materials in the context of this relation is unexplored, apart from small scale research into biobased elements. Braakman et al. (2021) focuses on replacing materials with circular alternatives, which also include reused or recycled materials. Di Biccari et al. (2019) performed a research into a visual BIM-based framework to assess LCC and LoC and therefore assessed an alternative of traditional walls and window frames, that contained biobased materials. Specific research into biobased materials is performed by Barrio et al. (2021) and Schulte et al. (2021), who respectively researched the LCC of biobased multilayer panels and insulation materials.

The latter two researches conclude that the LCC of the biobased alternatives is very similar to traditional materials. However, Barrio et al. (2021) point out that the current LCC is caused by higher costs for the novel processes involved with biobased materials due to the lack of optimisation. The expectation is that the costs for biobased materials will reduce after optimisation cycles (Arias et al., 2020; Barrio et al., 2021; TNO, n.d.-a). Additionally, Krasny et al. (2017) and Rudraraju (2020) investigated the LCC of circular buildings (partly) made from biobased materials. Rudraraju (2020) concluded that the LCC lowers with a gradual increasing LoC of the building. Krasny et al. (2017) discovered that the LCC of a biobased house is lower in comparison to a concrete house, where the biobased version is more economical in construction and maintenance. In addition, it became evident that the energy demand is lower in case of the biobased design.

Concluding, it was found that biobased materials show promising results in terms of lowering the LCC of buildings and increasing the LoC. Even though a scarce amount of literature is available, a reduction in LCC when using biobased materials in buildings is displayed due to lower maintenance costs. The construction or purchasing costs fluctuate around the price of traditional materials, but it is likely these costs will decrease over time as a result of optimisation and upscaling of the biobased industry.

An important note is the fact that quantifying the impact on the LCC by using biobased materials based on this literature study is hard, since the performed research only considers single cases. In addition, it is hard to compare due to differences in assumptions and methods used. This contributes to the urge to research the impact of biobased materials on the LCC.

2.2. Layers of Brand

To understand the principles of circularity within buildings, the shearing layers of change defined by Stewart Brand are explained. Brand (1994, as cited in BCI Gebouw, 2022) defined that a building cannot be seen as one component but consists of six separated layers, each with their own lifespan (see Figure 3) and impact. Each layer contains specific components, which are further specified in Table 22.

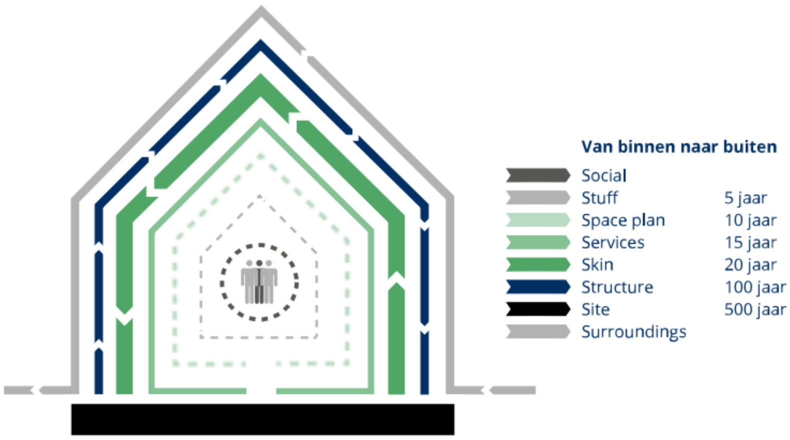


Figure 3: Shearing Layers model of Brand (BCI Gebouw, 2022a)

Table 2: Overview of components per building layer based on Brand (1994, as cited in TU Delft OCW, n.d.)

Layer	Components
Stuff	The stuff within a building, such as: chairs, desks, phones, pictures, kitchen appliances, lamps, hairbrushes … all the things that are around daily to monthly
Space Plan	The interior layout of walls, ceilings, floors and doors
Services	The so-called working guts: communication wiring, electrical wiring, plumbing, fire sprinkler systems, HVAC (heating, ventilation, and air conditioning), and moving parts like elevators and escalators
Skin	Façade of the building
Structure	The foundation and load-bearing elements
Site	The geographical setting in which the building is positioned

As will be discussed in section 2.3.3, the BCI uses functional lifespan to determine the utility factor. The shearing layers model defined by Brand (1994, as cited in BCI Gebouw, 2022) forms the basis for this lifespan. However, in literature there are various perceptions on these life spans. The BCI calculation uses the life spans originally defined by Brand (1994). An important note, is the fact that Brand defined these lifespans for buildings with an industrial function rather than a housing function. Table 3 provides an illustration of the differences in literature between the life spans.

Table 3: Overview of different life spans shearing layers model of Brand in literature

Layers/Source	(Brand, 1994 as cited in Crowther, 2001)	(Crowther, 2001)	(Tsolaki & Menzies, 2016)	(BCI Gebouw, 2022a)
Stuff	1 day – 1 month	1-5 years	<5 years	5 years
Space plan	3 years	10 years	5-10 years	10 years
Services	7-15 years	15 years	15-20 years	15 years
Skin	20 years	25 years	-	20 years
Structure	30-300 years	50 years	50-70 years	100 years
Site	∞	-	-	500 years

All in all, it can be concluded that various perceptions exist on the functional lifespan of building layers. It can be concluded that the life spans considered for the layers Structure, Skin, and Space Plan respectively range between 30-300 years, 20-25 years, and 3-10 years.

2.3. Circularity assessment

In order to compare, the circular performance of various design alternatives has to be quantified. Several methods exist to assess (amongst other) the circular performance of buildings. Some of these methods are focused on material or building sustainability in general instead of circularity such as the GPR and BREEAM-NL, however these methods also include subthemes that address material circularity. The eligible methods for assessing the circular performance are discussed in the following paragraphs. The methods are ranked in terms of extensiveness, so that first MPG and GPR are discussed, followed by the BCI. After the BCI, the Platform CB'23 guideline and the BREEAM-NL assessment are discussed. As the BCI method is used in this research, this method is explained in a more extensive manner, such that the method is properly understood.

2.3.1. MPG

The first method solely focuses on the material sustainability of the materials used in the building by determining the environmental impact of the building and is mandatory for the application of an environmental permit, namely the MPG or 'Milieu Prestatie Gebouwen' (RVO, 2017). The MPG uses the Environmental Cost Indicator (ECI, MKI in Dutch) to express the results in shadow costs per m^2 per year (Hillege, 2019). The shadow costs are based on a LCA, which is then divided over the gross floor area of the building to result in the MPG score (Hillege, 2019). As of the first of July 2021, the MPG score has to be lower than 0.8 to be eligible for an environmental permit (RVO, 2017). Ultimately, the goal of the Dutch government to lower the maximum MPG score to 0.5 (RVO, 2017).

The LCA assesses 11 impact categories, with a weighting factor in €/unit, to determine the environmental impact of materials (RVO, 2017). Ultimately, the environmental impact resulting from the LCA can be monetized in the ECI using the weighting factors. However, as from July 2022 the new LCA standard EN15804/A2 is enforced, which assesses 19 impact classes instead of the old 11 (MRPI, n.d.; Quist, 2021a). One of the new categories called 'Climate Change – Biogenic' entails a better insight into the environmental impact of biobased materials (EuGeos, 2020; Quist, 2021a). Nevertheless, the ECI calculation method has not yet defined a weighting factor for this category and can therefore not be calculated in the ECI (Quist, 2021a). Because the old LCAs are still used within the MPG, the CO_2 storage in the material is currently not taken into account in the MPG, which means that wood is undervalued.

The LCA data is stored via Environmental Product Declarations (EPD) in the "Nationale Milieu Database" (NMD), which can be categorised in three different categories depending on the quality of the data, shown in Table 4.

Table 4: Types of Environmental Product Declarations (derived from: (Stichting Nationale Milieudatabase, 2022))

Category	Source	Validated
1	Proprietary data from manufacturers and suppliers	Independent and qualified third party
2	Non-proprietary data from groups of manufacturers and/or suppliers and branches	Independent and qualified third party
3	Non-proprietary data from NMD. Due to genericity and inaccuracy of data an additional 30% is applied to the environmental impact.	-

Several different software suppliers developed software to calculate the MPG. Exclusively software acknowledged by the SBK ('Stichting BouwKwaliteit') can provide official calculations to apply for an environmental permit. These acknowledged software applications use the EPDs from NMD, which ensures validity of the calculations.

Ultimately, an overview is provided containing the amount of material eligible for recycling and reuse as well as the amount of secondary material, illustrating the possibility to roughly assess the circular performance of the building. However, it does not provide the amount of biobased material or a clear score so that the circular performance is understandable in one glance.

2.3.2. GPR

The GPR (Gemeentelijke Praktijk Richtlijn) developed by W/E Adviseurs is another method that measures the sustainability of buildings and that can quantify the circular performance. The method that considers five themes and rates these on a scale of one to ten to ultimately provide an overall score in terms of stars (GPR Software, n.d.-a; Vonk, 2021). The minimum requirements dictated in the Building Decree are met when a score of 6 is achieved (Agentschap NL, 2011). The result of the GPR is acknowledged by the Dutch government and can therefore be used for example to apply for subsidy regulations such as the MIA/VAMIL (GPR Software, n.d.-b).

The themes Energy, Water, Health, User quality and Future value are considered within the GPR, as is shown in Figure 4. Compared to the MPG, the GPR considers a wider scope which not only focuses on environmental impact of the materials but also on other sustainability aspects such as energy performance, climate adaptivity, acoustic comfort and air quality.

The GPR method allows for a quick analysis on the sustainability of the complete building and its surroundings. Part of the GPR is an MPG calculation to assess the materials used in the building. Additionally, the GPR focuses on very detailed aspects to calculate the sustainability score such as the type of shower head or the capacity of the toilet water reservoir. Also, some elements cannot be directly influenced are included in the GPR score, such as the air quality on location, the presence of public transport stops and the proximity of public amenities.

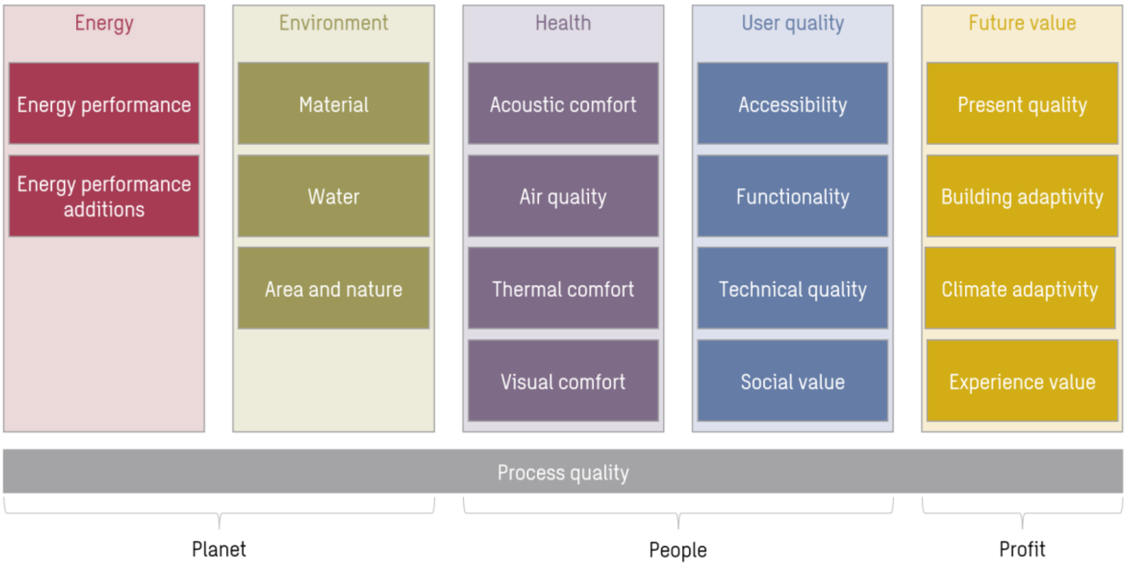


Figure 4: Categories GPR translated from GPR Gebouw (n.d.-a)

To assess the circular performance of buildings using the GPR the aspect Material can be used, because the resulting grade could be used to compare the circular performance of different alternatives. In addition to the MPG calculation, the GPR also focuses on the reuse of materials, the use of biobased materials, construction method, and the decoupling of building layers. However, the other focus points are superficial compared to the MPG, which allows for a quick but not so thorough analysis.

2.3.3. BCI

Another method specifically developed to encapsulate the circular performance of a building is called the Building Circularity Indicator or BCI. The BCI is originally defined by Verberne (2016) and further developed by Van Vliet (2018). Ultimately, a collaboration between Alba Concepts and the University of Eindhoven resulted in the software 'BCI Gebouw', which expresses the circular performance in the of level of circularity (BCI Gebouw, 2022a). The BCI score is expressed in Level of Circularity (LoC), which ranges from 0 (not circular/completely linear) to 1 (completely circular). The BCI focuses on the building materials as well as the disassembly index to calculate the LoC.

In order to determine the BCI score, several other indicators play a role in the calculation of the LoC as can be seen in the overview in Figure 5. It shows the stepwise calculation of the BCI using the Material Circularity Indicator (MCI), the Product circularity Indicator (PCI), and the Element Circularity Indicator (ECI). The first step is to determine the MCI, which focuses on the material origin and future scenario to assess the circularity of the material itself, including the fraction of biobased materials. These fractions are used to compile the Linear Flow Index (LFI), which indicates the amount of material that has a linear origin or waste scenario. The formula is derived from Ellen Macarthur Foundation & ANYS Granta (2019). The MCI also incorporates the principle that long-lasting products develop less waste per year than products with a shorter life span. With the help of the technical and actual lifespan, which respectively reflect the industry average life span and the expected life span of the product in the building, the utility factor can be calculated.

After compiling the MCI, the PCI can be calculated using the MCI and Disassembly Index (DI). The DI of BCI Gebouw is based on the DI of Van Vliet (2018) and assesses the disassembly potential based on four indicators, namely: Type of Connection, Accessibility of Connection, Independency, and Assembly shape. These indicators are further elaborated in following subsection. Ultimately, the DI results in a score between 0,10 and 1,00.

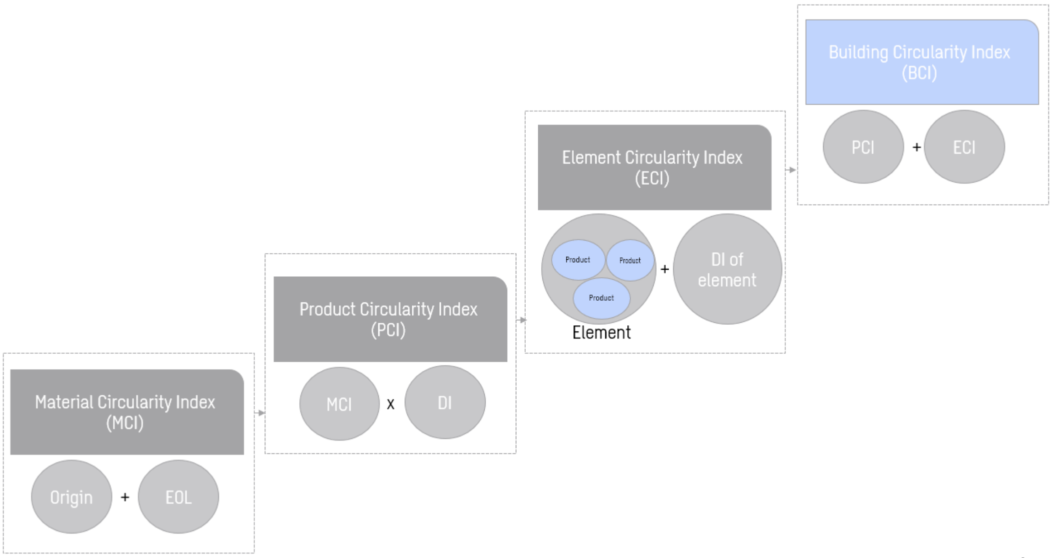


Figure 5: Stepwise calculation of Building Circularity Index deduced from (BCI Gebouw, 2022a)

The next step in the BCI assessment is the calculation of the ECI, which only applies when multiple products are seen as elements. In case a set of products arrives on the construction site pre-assembled and the score on the Accessibility of Connection is higher than 0,6 multiple products are identified as an element. For elements different calculation rules apply, such as the minimum of the technical and actual life span of all products to calculate the utility factor for the element. Furthermore, the DI is determined for the element instead of the products.

Finally, the BCI is calculated using the PCI and Element Circularity Indicator weighted with the Environmental Cost Indicator. A high Environmental Cost Indicator results in a higher contribution to the BCI score. The Environmental Cost Indicator incorporates the replacements required for products with a short life span and is used to result in an one point score. However, the Environmental Cost Indicator used within the BCI calculation is normalised for the chosen product/element and therefore is indicative (BCI Gebouw, n.d.).

The resulting BCI score indicates the LoC of the building based on all the products and elements used within building. This score ranges from 0 standing for completely linear to 1 standing for a completely circular building. Such a scoring scale allows for easy comparison between different alternatives and direct insight into the overall circular performance.

Concluding, the BCI method is very detailed and extensive in terms of material and disassembly potential, but it only focuses on the materials in the building. Furthermore, the database used to calculate the BCI is from NIBE, which also contains unofficial and unvalidated data. On the other hand, the amount of products and elements documented in the database is much larger in comparison to the database from NMD, which allows for a wider exploration of potential product alternatives.

Disassembly index

As was just mentioned the DI is based on Van Vliet (2018) and uses some of the Disassembly Determining Factors found by Durmisevic (2006). The following paragraph further elaborates on the different DI factors defined for implementation in the BCI method by Van Vliet (2018).

The first DI factor considered is Independency (Ind), which is related to the way in which products from different building layers are combined. Ideally, the products can be disassembled without affecting other products, but when multiple products from different layers are integrated this becomes much harder. See Figure 6 for a schematic overview of the different gradations of independency.

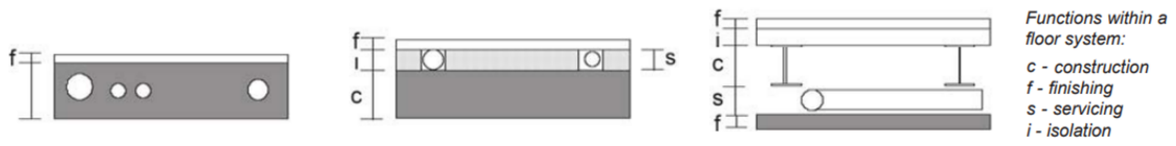


Figure 6: Overview of different types of independency f.l.t.r. Total integration, Incidental integration, Modular zoning copied from (Durmisevic, 2006)

Second, the type of relational pattern (PoR) influences the disassembly potential of products. This factor focuses on the amount of connections a product has with other products and/or elements. The higher the amount of connections the harder it is going to be to disassemble is the guiding principle for assessing this factor.

As third factor in the DI, the Assembly Sequence (Asq) is taken into account, which relates to the disassembly order of products. It can be dictated by the assembly order, which means the disassembly order is similar to the assembly order (Low level/High level). In this instance there is no other possibility to disassemble the element in another sequence. Ideally, two products/elements can be disassembled parallel to each other (Same level/Same level). In case a product can be disassembled before another product which was earlier in the assembly sequence and therefore requires fewer components to be disassembled this is considered to be High level/Low level.

The fourth DI factor is Assembly Shape (Ash) and addresses the obstruction for taking out products, which is dictated by the shape of the products (see Figure 7). The assessment is based on the interface of the products edge and the adjacent product/element. In case there is an open product edge it is possible to disassemble the product from one side without removing other products/elements, hence without obstruction. The Assembly Shape can also regarded as overlapping, which means the product edge is partly enclosed and at least one product edge has overlapping with another product edge. Ultimately this creates a partly obstruction for disassembly and requires to disassemble other products before disassembly of the targeted product is possible. In case the product is fully enclosed by other products/elements and at least two product edges are enclosed, this DI factor is considered to be closed.

Figure 7: Overview of Assembly Shape types copied from (Dutch Green Building Council, 2021a)

Fifth, the Method of Fabrication (MoF) is considered in the DI, and relates to the to the fact whether a product is constructed on the construction site or in a factory on forehand. In case a product is pre-fabricated it is argued that this ensures easier disassembly due to standardization of connections (Durmisevic, 2006), easier accessible connections (Rios et al., 2015) and the ability to disassemble complete components on-site and further separation of components off-site (Ciarimboli & Guy, 2005). Between pre-fabrication and construction at site, the product geometry can be considered to be half-standardised, which means that pre-fabricated products are constructed on site. An example for half-standardised products are bricks.

The Type of Connection (ToC) is the sixth indicator in the DI and relates to how a connection between products is made. A connection via nuts and bolts is easier to disassemble compared to a cement mortar connection between bricks for example. Table 5 shows an overview of commonly used connection types including the corresponding score in the DI.

Table 5: Overview of different types of connection and corresponding scores copied from (Dutch Green Building Council, 2021a, p. 13)

Type of Connection		Score
Dry connection	Loose	1,0
	Click connection	
	Velcro connection	
	Magnetic connection	
Connection with added elements	Bolt and nut connection	0,8
	Spring connection	
	Corner connection	
	Screw connection	
	Connections with added connection elements	
Direct integral connection	Pin connections	0,6
	Nail connection	
Soft chemical connection	Caulking connection	0,2
	Foam connection (PUR)	
Hard chemical connection	Adhesive connection	0,1
	Dump connection	
	Weld connection	
	Cementitious connection	
	Chemical anchors	
	Hard chemical connection	

Lastly, the Accessibility of the Connection (AoC) dictates the disassembly potential, since hard to reach connections are much harder to disassemble and are therefore probably neglected. This factor also incorporates the damage that occurs when accessing or disassembling the connection. Otherwise, a product can be disassembled, but cannot be reused after disassembly.

2.3.4. Platform CB’23 Guideline

The fourth method consists of a guideline to measure building circularity and is developed by Platform CB’23. Even though the guideline is still in development, Platform CB’23 (2022) indicates it can already be used. The guideline focuses on the protection of material resources, the protection of the environment, and the protection of the existing value, which can be traced back to the CE principles defined by EMF (n.d.-d). Table 6, shows an overview of the indicators used within the guideline to measure circularity. Similar to the BCI, the guideline from CB’23 addresses the origin and future scenarios of the materials which also takes a biobased origin into account to assess the circularity of the materials used.

The second goal of the guideline is aimed to protect the environment. Within the guideline this is expressed using the ECI as explained in section 2.3.1. The calculation is performed according to the newly introduced NEN 15804+A2 and therefore takes 19 impact categories into account.

Table 6: Overview of indicators of Platform CB'23 guideline (adapted from: (Platform CB'23, 2022, pp. 9–10))

1. Input material	1.1 Of which secondary materials	1.1.1. Of which from reuse
		1.1.2. Of which from recycling
	1.2 Of which primary materials	1.2.1. Of which renewable
		1.2.2 Of which non-renewable materials
	1.3 Physical scarce material	1.3.1 Of which Physical non-scarce
		1.3.2 Of which physical scarce
	1.4 Socio-economical scarce raw materials	1.4.1 Of which socio-economical non-scarce
		1.4.2 Of which socio-economical scarce
2. Retain output materials	2.1 Of which for reuse	
	2.2 Of which for recycling	
3. Lost output material	3.1 Of which for energy production	
	3.2 Of which for disposal	
4. ECI/MPG	4.1 Climate change – Total	
	4.2 Climate change - Fossil	
	4.3 Climate change – Biogenic	
	4.4 Climate change – Land-use and change in land-use	
	4.5 Ozone layer depletion	
	4.6 Acidification	
	4.7 Eutrophication of fresh water	
	4.8 Eutrophication of salt water	
	4.9 Eutrophication land	
	4.10 Smog formation	
	4.11 Depletion of abiotic resources – minerals and metals	
	4.12 Depletion of abiotic resources – fossil energy carriers	
	4.13 Water usage	
	4.14 Fine dust emission	
	4.15 Ionising radiation	
	4.16 Ecotoxicity	
	4.17 Humane toxicity - carcinogen	
	4.18 Humane toxicity – non-carcinogen	
	4.19 Land-use related impact/soil quality	
5. Functional-Technical value at End of Life	5.1 Functional quality	
	5.2 Technical quality	
	5.3 Degradation	
	5.4 Reuse potential	
6. Economical value at End of Life		

The last goal refers to the protection of the existing value. The guideline focuses on the functional-technical value and the economic value at the end of life. Four indicators define the functional-technical value, namely: Functional quality, Technical quality, Degradation, and Reuse potential. These indicators are scored in a similar way as in the BCI, with a score between 0 and 1 based on NEN2767-1 and the 3DR-scale (O'Grady et al., 2021; Platform CB'23, 2022).

Ultimately, the result of the guideline from Platform CB'23 are presented per indicator in an extensive manner, which allows for thorough analysis of the circular performance, but can also be hard to understand when unfamiliar with these indicators. Furthermore, it makes comparing alternatives difficult, due to the many comparisons to be made for each indicator, and thus less suitable for this research.

2.3.5. BREEAM-NL

The last method that can be used to measure circularity of a building is called BREEAM-NL New Construction. BREEAM is an abbreviation for Building Research Establishment Environmental Assessment Method and is originally developed by the Building Research Establishment (BRE) to assess the sustainability performance of a building (BREEAM NL, n.d.-a). BREEAM was originally introduced in the UK, but is currently being used in over 80 countries.

BREEAM-NL relates to the Dutch version of the BREEAM framework, which is managed by the Dutch Green Building Council (DGBC) (Dutch Green Building Council, n.d.). The biggest difference between the original BREEAM framework from the UK and the BREEAM-NL label is the use of Dutch Building Decree guidelines in the assessment. Part of the BREEAM-NL label are four BREEAM-NL certifications specifically focused on New Construction, In-Use, Spatial Development, and Demolition & Disassembly.

BREEAM-NL New construction is an assessment method specifically developed for new construction projects in the Netherlands, which focuses on the nine categories shown in Figure 8 and uses stars to express the sustainability performance of the building (BREEAM NL, n.d.-b). In addition to the nine categories, the innovation category awards credits if sustainability measures are taken on top of the standard framework to stimulate the creation of more sustainable buildings (Dutch Green Building Council, 2020a, p. 31). This category focuses Within the framework credits can be obtained, which ultimately lead to a BREEAM-NL certification. For each category there are indicators that have criteria. When these criteria are met credits are achieved. The framework guideline explaining BREEAM-NL, its framework, and requirements, is very extensive and states the requirements for obtaining credits clearly including the mandatory burden of proof.

Figure 8: Overview of all categories BREEAM-NL New Construction and number of achievable credits per category
(Ongreening, n.d.)

Part of the BREEAM-NL assessment also allows to measure circular performance of buildings (Dutch Green Building Council, 2021b). Figure 9 shows the indicators of the BREEAM-NL framework that contribute to assessing the circular performance. Credits for these indicators can be achieved when a material passport is used, a plan is made for sustainable procurement, category 1 NMD data is used for more than 40% of the materials or when the disassembly index is higher than 0,40 (Dutch Green

Building Council, 2020a, 2021b). Ultimately, the achieved credits can be compared to the achievable credits, which provides a circular performance assessment.

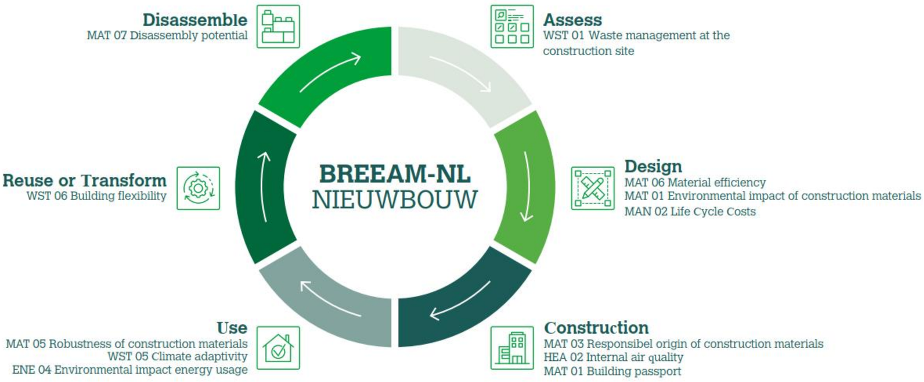


Figure 9: Overview of categories and indicators of BREEAM-NL New Construction to assess circular performance (source: Dutch Green Building Council, 2021)

2.3.6. Sub conclusion

Concluding, there are five methods that try to encapsulate the circular performance in various gradations. An overview of all these methods can be found in Table 7.

Reviewing the methods shows that the MPG, GPR, and BREEAM-NL are less suited to measure the circular performance of buildings. Although the MPG is mandatory for applying for an environmental permit, it is not focused on assessing the circular performance of buildings. The MPG only assesses the materials used within the building and provides an overview the environmental impact of these materials not specifically taking the biobased materials into account, which makes comparison difficult. Although, the GPR provides comparable results and includes biobased materials in the assessment, the focus is still solely on material circularity. Even though the GPR takes additional aspects into account regarding circularity, these aspects are rather superficial. BREEAM-NL on the other hand is a very extensive assessment framework that focuses on all aspects of circularity. Additionally, the results could be made comparable. However, the extensiveness of the framework entails time and feasibility limitations within this research.

To adequately grasp the circular performance of buildings and different alternatives the BCI and CB'23 guideline are best suited for this research. Since they focus on multiple principles of circularity and take biobased materials into account. The biggest difference between the two methods lies in resulting score on circularity. The BCI produces an one point scale to quantify the circular performance, whereas the guideline from CB'23 shows the value of each indicator including justification and assumptions. Consequently, the BCI allows for easier comparison while the guideline shows more insight during analysis. Another difference concerns the information used to calculate the circular performance. The BCI uses a database filled with own data and data from NIBE that can be accessed within the software of BCI Gebouw. On the other hand, the guideline from Platform CB'23 does not contain a database, which requires one to autonomously gather the required data.

All in all, it is concluded that the BCI method is best suited to quantify the circular performance in this research due to various reasons. First of all, the one point scale of BCI allows for easy comparison of the circular performance of the different alternatives. In addition, the CB'23 guideline is still in development, which means there are still uncertainties when using this method. Furthermore, the BCI software contains a large database of (biobased) products and elements, which can be used within this research. Whereas the NMD database contains a rather limited number of biobased EPDs.

Table 7: Overview of circularity assessment methods

	MPG	GPR	BREEAM-NL	BCI	CB'23
Focus	Material sustainability	Building sustainability	Building/Project sustainability	Building circularity	Building circularity
Result	€/m^2	Grade (0-10)	Stars (0-5)	LoC (0-1)	A score sheet containing scores for each indicator separately
Biobased included	No	Yes	Yes	Yes	Yes
Pros	-Software is widely available -Quick analysis -Results are comparable -Uses NMD database filled with certified data	-Software is available -Quick analysis -Comprehensible assessment	-Extensive assessment framework -Clear framework with requirements -Results are comparable and easy to interpret	-Quick analysis -Extensive database of biobased products -Single point scale, so easy to compare -Focuses on circularity and disassembly	-Requires more time -Comprehensive overview of scores on indicators
Cons	-Disassembly is not taken into account -No clear-cut result regarding biobased materials and/or circularity due to focus on environmental impact -LCA for wood in NMD database does not include carbon sequestration	-Very detailed on one hand, such that is sometimes defeats its purpose -Superficial on the other hand, the reality is not so straightforward as ticking a box	-Qualified assessors required -Requires a lot of time -Extensiveness requires a lot and different input data -Focuses on more than only circularity	-Database also contains unofficial and unvalidated data	-Still in development -Hard to compare results -Input data should be gathered
Applicability in research	MPG is easy to use but requires additional steps to be properly used within this research.	The GPR has a wider scope than MPG, and allows for quick analysis, but the level of detail makes this method less suited	BREEAM-NL is a high quality framework, but is too extensive for this research.	BCI is suited for this research due to the extensive database and comparability of the results. Also, the results are easy to interpret.	Even though the guideline is suited it is still in development and the results are harder to interpret. Which makes this guideline inapplicable in this research.

2.4. Life Cycle Cost Analysis (LCCA)

Depending on the scope one can assess solely the purchasing costs, operating costs and end of life costs of an asset, but to fully assess the financial impact of a design choice it is important to conduct an analysis that includes all life cycle phases. The use of biobased construction materials in buildings does not only impact the construction costs due to their higher price but also require different maintenance schemes and thus operating costs. Consequently, the materials are worth more or cost less to dispose than traditional materials, since they are more eligible for recycle. To create a holistic view of what design choices entail it is useful to execute a cost analysis.

One can opt for different methods to assess costs depending on the scope of the analysis as is also displayed in Figure 10. The method with the smallest scope is called life-cycle costing, which is also known as Total Cost of Ownership depending on the perspective (Koninklijk Nederlands Normalisatie-instituut, 2017; Rapaccini et al., 2012; Van Osch, 2020), and includes direct- and indirect costs, where the construction costs are categorised as direct costs and the operation costs are categorised as indirect costs. Total cost accounting (TCA) takes cost into account outside of the scope of life-cycle costing (Sterner, 2002). Whereas, Full cost counting (FCA) also includes the external costs and benefits and is also called Whole Life Costing (WLC) (RICS, 2016; Sterner, 2002; Willmott Dixon, 2016). For instance rent earned from tenants of the building are part of the larger scope and are thus taken into account in TCA and FCA/WLC (Koninklijk Nederlands Normalisatie-instituut, 2017). Externalities however, are related to costs and benefits for society such as additional costs due to waste from tenants, and therefore are only included within FCA/WLC (Koninklijk Nederlands Normalisatie-instituut, 2017). The corresponding scope appropriate for the different cost assessment frameworks are shown Figure 10. Figure 48 in Appendix C shows an overview of what costs these elements entail.

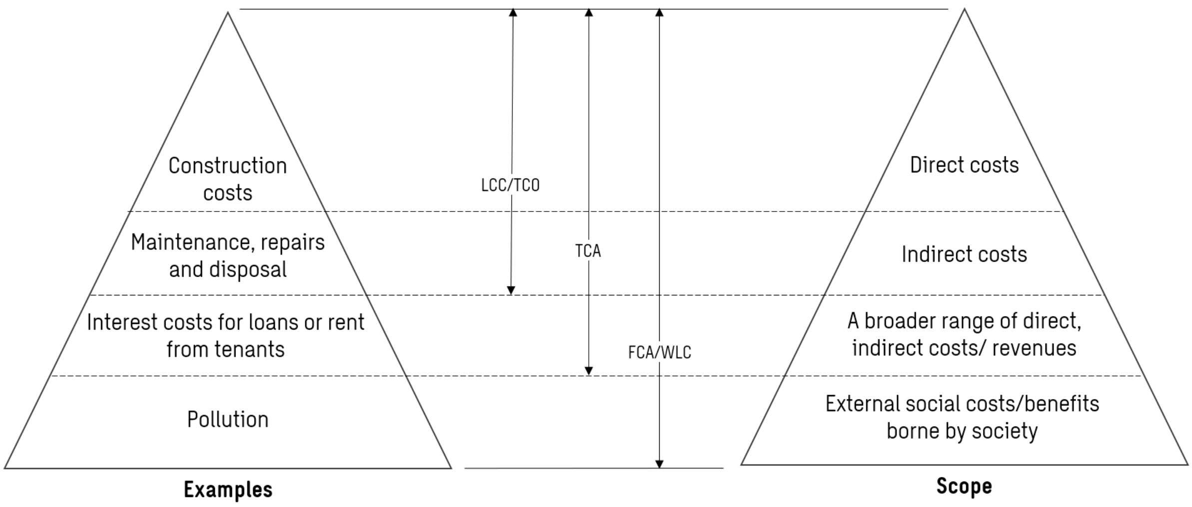


Figure 10: Overview of scope various cost assessment methods (derived from: (Koninklijk Nederlands Normalisatie-instituut, 2017, p. 8; Sterner, 2002, p. 39))

The framework for LCC and WLC assessments are laid down in the NEN – ISO 15686-5:2017 standard and focusses on the life cycle phases Construction, Operation, and End of Life (Koninklijk Nederlands Normalisatie-instituut, 2017). It is required to set a scope appropriate for the purpose/client and to define which elements are included and excluded in the LCCA (Koninklijk Nederlands Normalisatie-instituut, 2017). There is no pre-defined set of elements that are required to include within the analysis. Therefore the elements that are taken into account within this research are discussed in the section 3.2.2. Usually the assessment focuses on the total investment costs, which also includes annual operation, maintenance, and disposal costs of the building (Islam et al., 2015).

Within LCC and WLC the future costs often discounted to their ‘present value’, due to the uncertainty of future value caused by inflation or rate of return on the investment also known as the Time Value of Money (Fernando, 2022a, 2022b; Koninklijk Nederlands Normalisatie-instituut, 2017; Werkgroep discontovoet 2020, 2020). The government compiles a workgroup to determine the general discount ate every few years, which for 2020 is appreciated (Werkgroep discontovoet 2020, 2020). Therefore, the NEN – ISO 15686-5:2017 uses the Present Value (PV) of future transactions to determine the Net Present Value (NPV) of the building with equations 1 to 3.

$$NPV = \sum_{n=1}^{p} \frac{Cn}{(1+d)^n} \qquad (1)$$

In equation 1, *C* is the cost in year n, *d* is the expected real discount rate per annum, *n* is the number of years between the base data and the occurrence of the cost, *p* is the period of analysis, and *q* is the discount factor.

$$PV = Cn \times q \qquad (2)$$

In equation 2, *C* is the cost in year n, *n* is the number of years between the base data and the occurrence of the cost, *q* is the discount factor.

$$q_d = \frac{1}{(1+d)^n} \qquad (3)$$

In equation 3, *d* is the expected real discount rate per annum, *n* is the number of years between the base data and the occurrence of the cost.

There are two types of cost depending on whether or not the costs are corrected with the expected inflation rate. In case the current values are not corrected with the expected inflation rate, this is called real costs, the previous formula is used to calculate the present value of future transactions. However, it is generally required to use real costs within the LCC/WLC assessment. Therefore, the equation 4 is used to convert current monetary values are adjusted with the expected inflation rate, this is called the nominal costs, into real costs that can be used within the assessment.

$$q_{i,d} = (1+a)^n \qquad (4)$$

In equation 4, *a* is the escalation rate per annum, *n* is the number of years between the base data and the occurrence of the cost.

Ultimately, the result of LCC/WLC is the cost over the life cycle for a certain investment or asset. The purpose of performing such an investment can differ. To compare the economical effects of different materialisations for buildings a LCCA can be used. As described in the NEN-ISO 15686-5:2017 standard: “Life-cycle costing is a valuable technique that is used for predicting and assessing the cost performance of constructed assets.” (Koninklijk Nederlands Normalisatie-instituut, 2017, p. 6). A paper review by Islam et al. (2015) shows that LCCAs can have different purposes, either they inform designers and clients about different investment scenarios, assess financial benefits of energy efficiency measures, or optimize house design and aid decision-making. It is argued by Sterner (2002) that a LCCA is most useful as comparing instrument to rank different alternatives, which was also used within other research from Bhochhibhoya et al. (2017), Braakman et al. (2021), Di Biccari et al. (2019), Gluch & Baumann (2004), and Ristimäki et al. (2013).

2.4.1. Results of LCCA

The result of the investment appraisal can be expressed in a single monetary value that represents the life cycle costs. Additionally, other indicators aid the ranking of different alternatives, such as Equivalent Annual Cost (EAC), Discounted Payback Period (DPP), Internal Rate of Return (IRR), Net

Savings (NS), or Savings to investment Ratio (SIR) (Khisk et al., 2003). Although these indicators provide more insight into the investment appraisal, only the EAC is applicable in this research. Due to the fact that the other indicators suggest profitability of the asset, which is realistically speaking not the case with buildings. Therefore, merely the indicator EAC is further explained in the following paragraph.

EAC represents the annual cost of an alternative instead of a single monetary value by dividing the NPV over the factor for Present Worth of Annuity factor (PWA) (Khisk et al., 2003). The benefit of using EAC in addition to NPV is the comparability of EAC when investments have different life spans. It is an indicative value and thus not shows the real annual costs of owning and operating a building. The EAC is calculated using equations 5 and 6 (derived from (Kenton, 2020; Khisk et al., 2003)).

$$EAC = \frac{NPV}{PWA} \quad (5)$$

In equation 5, *NPV* is the Net Present Value calculated with equation 1, *PWA* is Present Worth of Annuity factor calculated with equation 6.

$$PWA = \frac{(1+d)^n - 1}{d(1+d)^n} \quad (6)$$

In equation 6, *d* is the expected real discount rate per annum, *n* is the number of years between the base data and the occurrence of the cost.

2.4.2. Sensitivity analysis

Cost assessment using LCC or WLC is always associated with a certain unreliability due to estimations. As was just mentioned, the discount rate is approximated and therefore introduces an uncertainty (Koninklijk Nederlands Normalisatie-instituut, 2017). Furthermore, the expected future transactions can differ from reality as for example maintenance is required more often than expected . Another factor is the life span of the building (Koninklijk Nederlands Normalisatie-instituut, 2017), since 50 years is an approximation and it is hard to predict what circumstances occur along the life cycle of the building. The state of the building might allow to extend the life span to 60 years, which has an impact on the NPV and EAC. These factors are considered to have the greatest impact on the results according to the NEN – ISO 15686-5:2017 (Koninklijk Nederlands Normalisatie-instituut, 2017). To account for this uncertainty and thus unreliability of the LCC/WLC analysis, a sensitivity analysis is performed. A sensitivity analysis establishes the effect of different parameters on the analysis results.

2.4.3. Sub conclusion

Concluding, several methods to appraise the investment of a building exist that vary in scope (see Figure 10). Life Cycle Costing (LCC) considers only the construction costs and operational costs and contains the smallest scope of the investment appraisal methods. On the other hand, Whole Life Costing (WLC) considers the largest scope and additionally includes additional direct- and indirect costs as well as externalities. For the assessment of different design alternatives the LCC is deemed most useful. An overview of the various investment appraisal methods can be found in Table 8.

Regardless of the choice for LCC, TCA or WLC, it is important to note that future costs or revenue should be discounted to calculate the present value of these transactions using equations 1 to 4. Furthermore, it is necessary to perform a sensitivity analysis to cope with the underlying uncertainty of calculation factors in the investment appraisal method. Also, it is useful to include the EAC within the sensitivity analysis to better assess the impact of a differing discount rate, life span or other uncertain factor.

Table 8: Overview of investment appraisal methods

	LCC	TCA	WLC
Direct costs	Included	Included	Included
Indirect costs	Included	Included	Included
Broader range of indirect costs	Excluded	Included	Included
Externalities	Excluded	Excluded	Included
Applicability in research	LCC only considers the direct and indirect costs of a building and therefore is the most suited for this research.	TCA considers a broader range of indirect costs, which are harder to come by and therefore make this method less suited.	WLC provides a holistic view of the costs of a building, but the externalities are hard to quantify, which

2.5. Biobased construction materials

This section aims to explain what biobased construction materials are, which examples currently exist and what the pros and cons are of these materials. As was already mentioned in the Introduction, biobased materials are materials that are made of renewable resources and (partly) consist of biological fibres (Quist, 2021b). More specifically, biobased materials contain the following properties according to the Council of Government Advisors (n.d.-b), which is also in line with the City Deal Circular and Conceptual construction:

a) From regenerative growth under ecological responsible conditions that preserve the harvest location;
b) Made from materials that grow back in nature within 100 years of harvesting;
c) No abiotic raw materials from geological formations, such as sand or clay;
d) Reusable as raw material in new construction material or nature after life cycle.

The use of biobased materials is regarded as a way to develop a circular economy (RIVM, n.d.) and has some distinct benefits. First of all, the use of biobased materials results in a lower climate impact (Dutch Green Building Council, 2020b; NIBE, 2019; Peñaloza, 2017; Van Dam & Van den Oever, 2019; Van Sante, 2022), due to a reduction in energy consumption during production (Yadav & Agarwal, 2021), the storage of CO_2 in biobased materials (Dutch Green Building Council, 2020b; Quist, 2021b; Van der Hoeven, 2022b), which results in a reduction of CO_2 emissions (NIBE, 2019). Furthermore, biobased materials have moisture regulating properties, which results in a better indoor living climate (Latif et al., 2015; NIBE, 2019; Van Dam & Van den Oever, 2019; Yadav & Agarwal, 2021). Additionally, biobased materials are lighter and therefore result in a lower CO_2 emissions for transport (Quist, 2021b; Van Sante, 2022), but also allow for quicker assembly without heavy equipment (Quist, 2021b; Van Sante, 2022).

On the other hand, the introduction of biobased materials currently also has its drawbacks. First, constructing with biobased materials is more expensive in comparison to traditional construction (CE Delft, 2021; Van der Hoeven, 2022b). In addition, certification of biobased construction materials proves to be difficult and therefore use is hampered by legislation (CE Delft, 2021). This is partially caused by the lack of industrialisation and upscaling of the biobased industry (CE Delft, 2021), although the upscaling of the biobased industry can result in other problems such as land-use. A scale-up of the biobased industry requires more soil cultivation and can result in the use of more pesticides and CO_2

emissions (Quist, 2021b). Also, biobased materials are ignitable, which creates the perception of being unsafe (Sandak et al., 2019).

Even though the amount of biobased construction materials is rather scarce and certification proofs to be hard, several biobased materials are becoming more common within the construction industry. The following paragraphs elaborate on the various biobased alternatives that exist and where these can be applied within the building.

It is important to note that not every building element has a biobased alternative. For example glass, sand or plaster currently do not have a biobased alternative. Also, bituminous roofing material does not have biobased alternative (WUR, 2022). Moreover, for some building elements biobased materials are less suited, such as the foundation or ground floor of a building. Were these to be constructed from wood, they are prone to rotting when the ground water level fluctuates and oxygen can access the wood (KCAF, 2022). However, this does not mean it is not possible to construct with wooden foundation piles, as can be seen in the city of Amsterdam (Gemeente Amsterdam, 2021).

2.5.1. Wood

Wood is currently the most commonly used biobased material in the construction industry and is used in the Structure, Skin and Space Plan of the apartment, but it only accounts for 2% of all building materials used in the Netherlands based on weight (NIBE, 2019). Within the structure Cross Laminated Timber (CLT), Laminate Veneer Lumber (LVL) or Glued Laminated Timber (GLULAM) is used. Figure 11 shows the build-up of these elements. Depending on how a tree log is cut one can create beams or veneer, which is a very thin sheet material. LVL is made from veneer that is stacked and glued together, whilst CLT and GLULAM are made from beams (Voos, n.d.). Depending on the way the beams are glued together, CLT or GLULAM is created. Usually these elements are made from pine wood, such as spruce or larch wood (Joost de Vree, n.d.-b; Van Dam & Van den Oever, 2019; Verdouw, n.d.).

Figure 11: Overview of build-up LVL, CLT, and GLULAM (Architectus, n.d.)

Within the skin of the apartment wood can be used in the façade elements, or as façade cladding, and to construct window frames. The façade can be constructed from timber frame elements filled with biobased insulation materials and finished with plasterboards on the inside and with brickwork on the outside. The traditional brickwork façade cladding can be replaced by wood as well, such as wooden panelling or Platowood as is shown in Figure 12.

Figure 12: Platowood wooden façade cladding (Architectenweb, n.d.)

Additionally, wood is used in the Space Plan in the form of doors and door sills. Also it is used to construct timber frame walls, which are then filled with insulation and finished with plasterboards.

Building philosophies using wood

The use of wood in the structure entails one of two building philosophies, namely elements or modules. The wooden elements philosophy entails a structure that contains floors, walls, columns and beams separately. While the modular construction philosophy uses modules to construct a building, similar to LEGO blocks. Figure 13 shows an overview of both construction philosophies. The benefit of using modules is the reduction in building time, since the modules can be constructed quickly at the construction site. However, it increases the material usage, since it has double walls and ceilings (Castelein, 2022b; Selek, 2022).

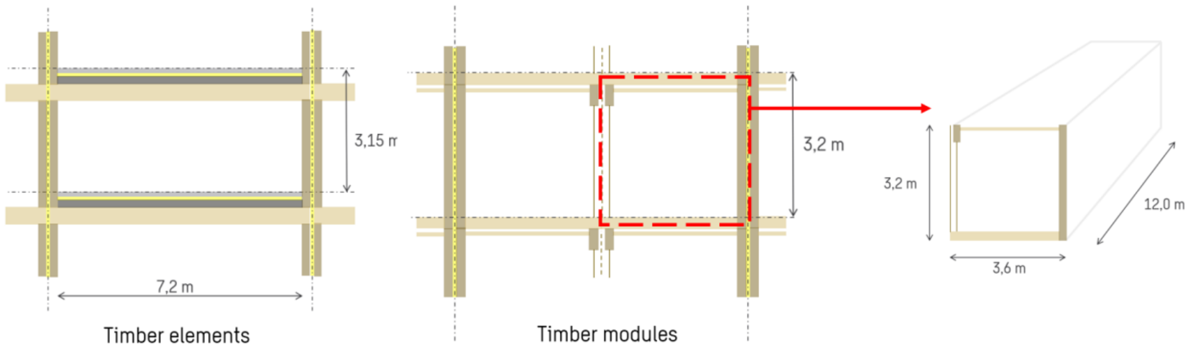


Figure 13: Overview of different construction philosophies (Castelein, 2022a, pp. 15–16)

As was already addressed, biobased materials are combustible and therefore require different treatment than concrete or steel to comply with the Dutch Building Decree. The Building Decree focuses amongst others on 1) structural safety during fire and 2) fire penetration & spreading are defined in terms of time. Standards regarding the structural safety during fire depend on the height of the highest floor of the building and range from 60 to 120. Regarding the fire penetration and spreading, the Building Decree states that the adjacent areas should not catch fire due to heat radiation within 60 minutes.

Important to note is the strength profile during fire of wood and steel shown in Figure 14. The strength profile indicates that wood loses its strength less quickly after initial burns in comparison to steel. This is caused by a coal layer that is created when wood is burned, which functions as a natural fire resistant layer.

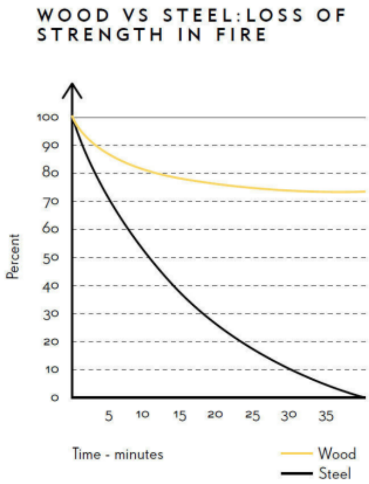


Figure 14: Strength profile Wood versus Steel (Vos et al., 2021, p. 44)

To ensure structural safety of a wooden structure during fire additional measures are required, such as 1) over-dimensioning or 2) fire-resistant covering, which can both be combined with a sprinkler. Over-dimensioning increases dimensions of the element to allow for inflammation of the surface without loss of the load-bearing ability and requires double walls or increase in material usage when strict standards apply. Therefore, fire-resistant covering is generally more affordable when designing higher buildings. The application of fire-resistant covering in the form of 2 plasterboards or special fire-resistant covering material creates a shell to prevent inflammation of the wood structure and thus loss of load-bearing capabilities. A schematic overview of what the available measures look like is shown in Figure 15.

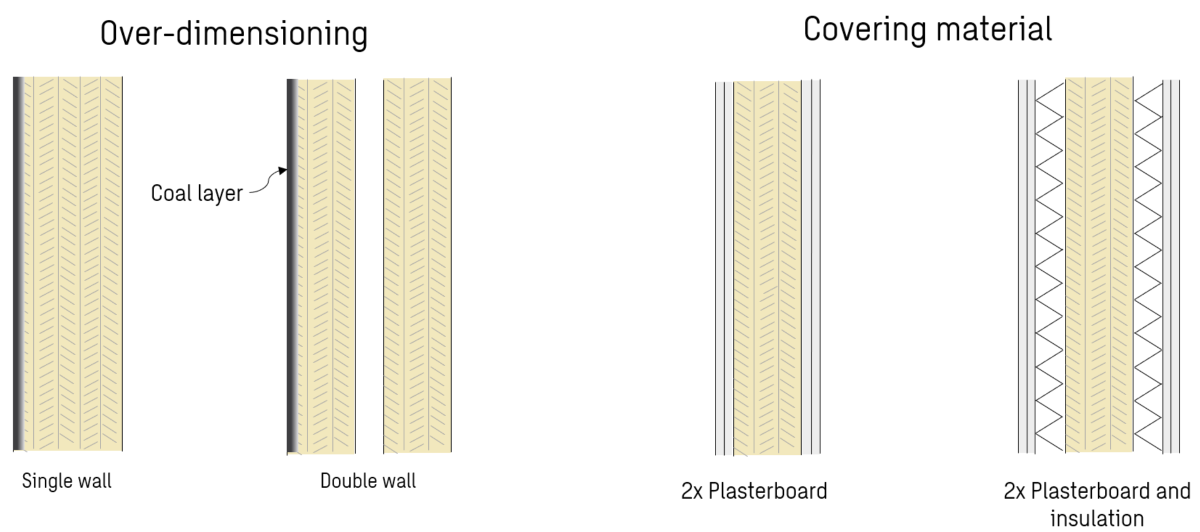


Figure 15: Overview of measures to comply with fire resistance requirements in the Building Decree

The Building Decree also lays down standards for air-noise and contact-noise levels travelling from one apartment to the adjacent apartment, which can be reduced with three design solutions, namely: 1) acoustic decoupling, 2) using a cavity, or 3) add mass. Figure 16 schematically shows the measures to comply with acoustic standards stated in the Building Decree.

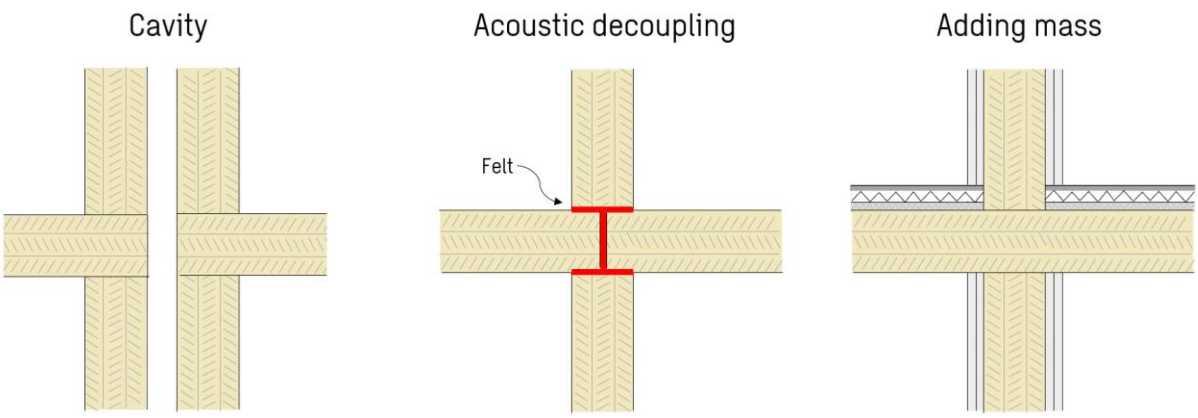


Figure 16: Overview of measures to comply with acoustic requirements in Building Decree

Acoustic decoupling means that noise cannot travel directly to the adjacent apartment, which can be applied in building with up to 6 layers, as this measure decreases the structural stability of the building (Vos et al., 2021). Second, a cavity (filled with insulation) reduces noise, but requires a double wall construction which increases material usage. The final measure is the addition of mass to the structure that functions as a vibration damper. In practice, 2 plasterboards are applied to the walls and an additional layer of sand, or gravel is used to add mass to the floor.

2.5.2. Flax

Flax is a biobased material that is regularly used as insulation material within the construction industry. Flax insulation is currently used as cavity, roof or floor insulation, and traditionally was used in combination with timber construction (Van Dam & Van den Oever, 2019). The harder pieces of the flax crop, called flax shives, are used to construct flax boards (EcoBouwAdvies, n.d.). These flax fibre boards are also used as insulation material within inner walls constructed by a company called Faay. Here the flax fibre boards are finished with plasterboards on both sides (Faay, n.d.). Both Faay and

Isovlas, one of the biggest suppliers of flax insulation, have certified (some of) their products to obtain a category 1 EPD in the NMD.

Flax is a crop that forms the basis for linen and linseed oil (EcoBouwAdvies, n.d.). After a growth period of 100 days (Wiersum Plantbreeding, n.d.), the linseeds are first removed from the crop before further processing to extract the flax fibres. Whereafter, the remaining flax fibres are used to construct flax insulation (see Figure 17).

Figure 17: Flax insulation (Van het Westeinde, 2021)

Flax insulation performs similar in comparison to stone wool in terms of insulation properties (UNFCCC, 2015). Furthermore, as of the 12th of July 2020, the EU taxonomy regulation came into force as well (European Commission, n.d.). The EU taxonomy is a classification system to guide the achievement of EU's sustai. Flax insulation obtains a better environment classification from NIBE and is considered to be the 'best' choice (class 1a), whereas stone wool is considered to be a 'bad' choice (class 6c) (NIBE, 2023a). Furthermore, the shadow costs in comparison of flax (€ 0,08) are lower in comparison to those of stone wool (€ 1,72) (NIBE, 2023b). Also, flax insulation can be fully recycled, whilst only 10 per cent of the stone wool can be recycled (NIBE, 2023b). However, the fire class rating for flax is C (flammable), while stone wool is inflammable and therefore scores a fire rating of A (Joost de Vree, n.d.-a; NIBE, 2023b) .

2.5.3. Hemp

Hemp is a biobased material that can be used to construct insulation material as well as hempcrete blocks used to build inner walls. It is a fast and easy to grow crop that produces several sub-products known in the construction industry for its insulation capacity, mechanical resistance of the fibres, and low density (HempFlax, n.d.; Sandak et al., 2019). Ultimately, the leaf and flower of the hemp plant are used to produce CBD oil, whereas the seeds and seed oil are used in nutrition (HempFlax, n.d.). For construction the husk of the hemp plant is the most useful. This is used to produce hemp concrete and flexible insulation material. To construct insulation materials, the harder wood core is used for insulation boards and the softer husk of the hemp plant is used to produce flexible insulation materials.

Hemp used as insulation material in the skin or space plan performs lower compared to flax or stone wool insulation in terms of thermal conductivity and fire rating. A hemp insulation mat has a thermal conductivity of 0.040 W/mK, whilst both flax and stone wool have a thermal conductivity of 0.035 W/mK (Groene Bouwmaterialen, n.d.; Kymäläinen & Sjöberg, 2008). This means hemp insulation allows more temperature to flow through the material compared to flax or stone wool. Furthermore, the fire rating of hemp insulation mats is E, indicating the insulation material is 'very flammable' (Joost de Vree, n.d.-a). Thermo-Hanf, IsoHemp, and HempFlax are suppliers of hemp insulation , but these have not certified their products to be part of the NMD.

Figure 18: Hempcrete blocks (Isohemp, n.d.-a)

In addition to insulation, hemp can also be used to construct hempcrete blocks for inner walls (see Figure 18) (IsoHemp, n.d.; Kennisbank Biobased Bouwen, n.d.). Hempcrete blocks are constructed from hemp, water and lime and have a lower density (340 kg/m^3) compared to sand-lime (1750 kg/m^3) or aerated concrete (575 kg/m^3) (IsoHemp, 2023; Kennisbank Biobased Bouwen, n.d.; Xella, n.d.; Yadav & Agarwal, 2021). However, the compressive strength of hempcrete also is lower (0,22 MPa) compared to sand-lime (12 MPa) and aerated concrete (3,6 MPa) (Calduran, n.d.; IsoHemp, 2023; Xella, n.d.). Also the fire class assigned to hempcrete is lower than sand-lime or aerated concrete, class B 'not easily inflammable' versus A1 'inflammable'. An advantage for using hempcrete for constructive elements in the building, is the fact that it also doubles as an insulation material with a thermal conductivity coefficient of 0.071 W/mk and therefore results in a better insulated building (Yadav & Agarwal, 2021). IsoHemp is a supplier of hempcrete blocks and has not certified its products to obtain an EPD in the NMD.

2.5.4. Straw

Straw is used as roofing material, but can also be used to construct façade elements that have high insulating capabilities. Straw is a residual product from the agriculture arising from cereals. Originally, straw was used as roof covering and has in addition to good insulating also proper moisturizing properties (Sandak et al., 2019; Strotec, n.d.; Yadav & Agarwal, 2021). For apartment buildings the use of straw for roofing material is unusual.

Currently, prefabricated straw façade elements can be used within the skin of a building as inner cavity leaf. These elements are constructed with a wooden structure, filled with straw and finished with natural gypsum and do not require additional insulation material since these elements deliver high insulating properties (Strotec, n.d.). However, to ensure this insulating performance more material is required, since the heat conductivity coefficient is higher for the straw elements (0.0645 W/mK) compared to flax or stone wool insulation discussed previously (Joost de Vree, n.d.-c). The fire class assigned to the straw façade elements is B 'not easily inflammable' (EcoCocon, n.d.-a). This is threefold, since densely packed straw (110 kg/m^3) within the element does not allow for any oxygen to keep a fire burning (EcoCocon, n.d.-b). Furthermore, during fire straw creates a natural coal layer that acts as a fire resistant layer similar to wood (EcoCocon, n.d.-b). Finally, the elements are finished with natural gypsum, which has high resistance for fire (EcoCocon, n.d.-b). EcoCocon is a big supplier of these façade elements and has certified its straw façade elements (see Figure 19) and therefore are implemented with category 1 data in the NMD.

Figure 19: Ecocon straw façade elements (Biobased Bouwen, n.d.)

2.5.5. Biobased materials in research

Table 9 provides an overview of commonly used biobased materials within scientific research. It can be seen that in every research timber is used as biobased alternative in the structure layer. With regards to the skin of the building, generally the insulation is replaced with a biobased variant, whereas the façade structure is not addressed. Lastly, the space plan of the building is commonly replaced with a wooden alternative. However, also straw or flax is considered as an alternative within scientific research.

Table 9: Overview of considered biobased alternatives in previous research

Source/Layer → ↓	Structure	Skin	Space Plan
(Braakman et al., 2021)	-Prefabricated wood structure -Wooden walls -Wooden roof	-Clay roof tiles -Flax insulation -Wood flooring	-Flax wall panels -Wood frame -Wood sills
(Rudraraju, 2020)	-Wooden roof structure -Timber floor slabs -Timber structure	-Biobased roof panel	-Wood elements (doors and window frames) -Recycled wooden internal and external ceilings
(Krasny et al., 2017)	-Wood structure	-Straw insulation -Biobased plaster	-Straw walls
(Di Biccari et al., 2019)		-Hemp insulation	-Wooden window frames
(Schulte et al., 2021)		-Wood fiber insulation -Hemp fiber insulation -Flax insulation -Miscanthus insulation	

2.5.6. Sub conclusion

All in all, this section elaborates on the various biobased construction materials available in the construction industry and used to conduct scientific research. First of all, several definitions of biobased are explored as well as the general pros and cons of biobased materials, such as moisturizing and insulation properties or certification problems. Furthermore, it was discovered that not for every building element a (fully) biobased alternative exists, such as glass or plasterboard. Besides a biobased alternative could not be or is less suitable, for example in case of a foundation or ground floor. Nonetheless, various biobased materials are used within the building layers Structure, Skin, and Space Plan.

To ensure a biobased structure, wood is most commonly used. It is applied in various forms, such as elements or modules. Within the skin of the building, wood is used to construct frames, which are then filled with a biobased insulation material, such as flax. Also, window frames and roof floors are constructed from wood. Wood is also applied in the Space Plan in the form of doors or door sills. Moreover, hempcrete is an biobased alternative for sand-lime stone bricks used to construct inner walls. Generally, the same trends can be seen within the considered biobased alternatives in scientific research.

Table 10: Overview of the original materials and the corresponding biobased alternatives considered in this research

Structure	**Original material**	**Biobased alternative**
Lead-bearing structure	In-Situ concrete	Wood (CLT and GLULAM)
Floors	Concrete slabs (Breedplaat)	Wood (CLT)
Skin		
Inner cavity leaf	HSB elements	HSB elements
Cavity insulation	Mineral insulation	Flax insulation
Outer cavity leaf	Brickwork	Wooden façade cladding
Window frames	PVC	Wood
Glazing	Glass	-
Space Plan		
Inner walls	Aerated concrete	Hempcrete blocks
Door sills	Steel	Wood
Doors	Wood	Wood
Floor finishing	Tiles	-
Wall finishing	Tiles or spray plaster	-
Ceiling finishing	Spray plaster	-

Consequently, this section provides input for the creation of design alternatives through listing the biobased alternatives for each building element considered in this research. This overview can also be seen in Table 10. Within this research, the structural elements in the alternatives are constructed from wood. The façade is constructed from a timber frame filled with flax insulation. The outer cavity leaf of the façade is constructed using wooden boards and filled with window frames made from wood. Moreover, the inner walls are constructed from hempcrete blocks, whereas the doors and door sills are made from wood. With regards to the building elements that do not have a (suitable) biobased alternative, the original material or an environmental friendly alternative is chosen. Due to the use of a wooden structure, additional fire and acoustic requirements apply, measures such as the use of plasterboards or cement screed are also taken into account.

3. Methodology

This chapter further elaborates on the methods used to execute the research. First, the data collection methods are addressed, followed by a description on the processing of the gathered data. At last, the analysis of the data is discussed including the intended results of the research.

3.1. Data collection

This section elaborates on the data collection executed in this research. To assess the level of circularity and life cycle costs of apartments the project's budget, data regarding the materialisation and corresponding quantities as well as technical drawings are required. Since the financial data is considered to be sensitive, projects linked to Sweco are sought, i.e. cases where construction calculations are performed by Sweco or a project manager from Sweco was involved, to stimulate data provision. However, the required data necessitates contact with external organisations as well, because not all data can be retrieved from within Sweco, due to their role in projects as an engineering and consultancy firm. In addition, external projects with no link to Sweco are sought to increase the chance on obtainment of project data.

The process starts with identifying the project's representatives, since they have authority to share the data. After identification of these representatives, their contact details are retrieved. In case the contact information of a project representative remains unknown, the organisation related to the project is contacted.

After retrieving the contact details, the representatives are approached via email. Follow-up calls are made to ensure continuation of the data collection process two days after the initial email. The function of the introductory email is twofold, it serves as a context setting measure, in which the context of the research is explained. Also, during the follow-up calls one can refer back to this email, which allows the representative more time to process the request. The email is send upfront to provide the representative a better understanding of the posed question and the context of the research. Consequently, project representatives related to 19 individual projects are contacted.

Ultimately, the data collection process resulted in retrieving workable project data from one project. This apartment building containing 107 apartments devoted to social- and medium rent housing is located in the city of Groningen. This project is called project X within this research. During execution of the research information or explanation was required. As such the corresponding project's representative was contacted and asked to provide this information or explanation.

3.2. Data analysis

After retrieving the required project data, it is used in the analysis phase. This phase entails the use of an assessment framework that assesses the level of circularity and life cycle costs for different design alternatives of apartments. This assessment framework is further discussed in section 3.2.2. The analysis of the results is built upon on different design alternatives, which are further discussed in section 3.2.1.

3.2.1. Design alternatives

Ultimately, this research focuses on the life cycle costs of apartments over an increasing level of circularity through the use of biobased materials. To guide this focus, various design alternatives are defined, which are expected to have a gradually increasing LoC. These design alternatives are developed based on the Shearing Layers model of Brand (1995, as cited in (Braakman et al., 2021). An overview of the layers considered is shown in Figure 20.

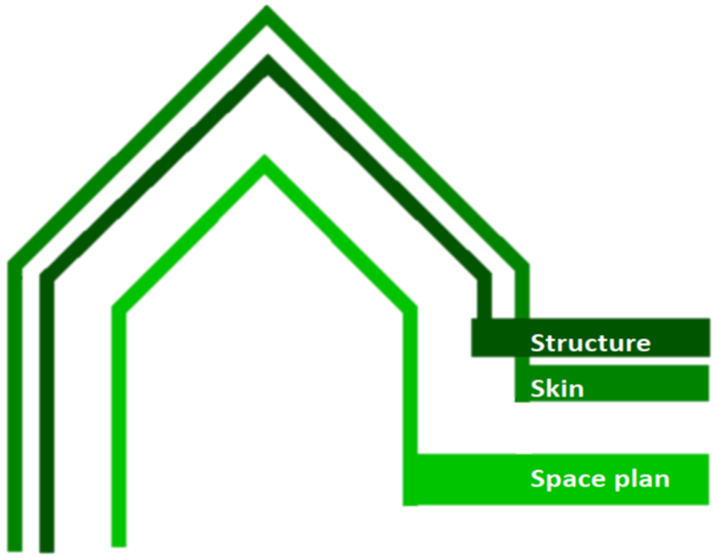
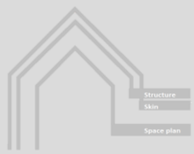
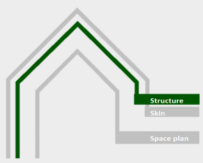
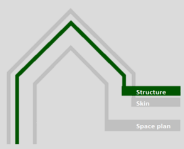
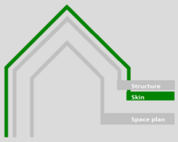
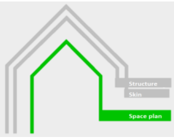
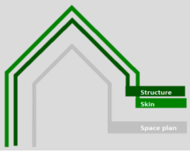
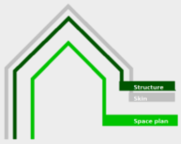
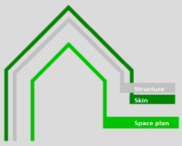
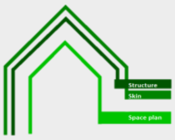


Figure 20: Overview of considered layers in research

The layers guide the generation of design alternatives by exchanging the original construction materials in a layer with biobased substitutes to increase the LoC. Table 11 provides an overview of the different design alternatives, where T represents the use of the original material in the specified layer. The letter B represents the use of biobased alternatives instead of the original materials. An example is the use of timber instead of concrete for the structure of buildings (alternative 1 in Table 11).

Table 11: Overview of design alternative methodology where B represents the use of an alternative biobased material and T the original material used in the project.

Alternative	Biobased layers	Structure	Skin	Space Plan
Base		T	T	T
1A		B	T	T
1B		B	T	T
2A		T	B	T

2B		T	B	T
3		T	T	B
4		B	B	T
5		B	T	B
6		T	B	B
7		B	B	B

The alternatives are constructed in such a way that a gradual increase in LoC is expected. Only alternative 1 and 2 have subvariants, since the literature review showed there are two choices available when considering a biobased structure, namely A) wood columns and beams or B) wood modules. For alternative 2, the subvariants are guided by the Municipal Architectural Guidelines. Subvariant A consists of a fully biobased materialisation. Although a façade with an outer cavity leaf made from bricks is not biobased, it might be required by the Municipal Architectural Guidelines and is therefore also considered as subvariant B of alternative 2.

Alternatives 4 to 7 are constructed by combining alternatives 1 to 3. Ultimately, one subvariant of both alternative 1 and 2 is chosen to develop the other alternatives. For alternative 1 an expert judgement is made by the wood constructor during the design session as to which subvariant is most suitable. In the case of alternative 2 it is opted to continue with subvariant A, since the scope of this research focuses on biobased materials.

Designing alternatives

During the execution of the research, the theoretical design alternatives defined in Table 11 are developed for project X. Within project X an average apartment is chosen as base alternative. The materialisation of this base alternative forms the foundation for the creation of the design alternatives. With the help of a structural engineer specialised in wood constructions, an architect, and a sustainability consultant these alternatives are elaborated for project X in a design session. The results of the design session are captured in materialisations for each design alternative of project X. These materialisations are derived from the project's budget and technical drawings and serves as input for the assessment framework to assess the level of circularity and the life cycle costs.

3.2.2. Assessment framework

To assess the LoC and LCC in this research an assessment framework is used. Based on the literature review it is decided to use a modified BCI calculation and a LCC assessment for the assessment framework, since the BCI score uses a single-point score and is less complex than the guideline from Platform CB'23. The LCC was picked due to the scope of this research. Important to note is that both assessment methods are validated by respectively a sustainability consultant specialized in measuring sustainability and construction cost expert. Moreover, the results are again validated with these experts to eliminate mistakes in the calculation and assessment. The following paragraphs elaborate further on the (considered) modifications made to the assessment framework as well as the assumptions with regards to the calculation of the LoC and LCC.

Level of Circularity

First, the inclusion of recycling process efficiency is considered, which was excluded by Verberne (2016b). A critical analysis of the BCI calculation resulted in the recommendation to use a standard value of 1 (Braakman et al., 2021). However, considering the scope and goal of this research it is opted to exclude the recycling process efficiency from the assessment framework in this research.

Second, modifications are considered to the Disassembly Index based on Van Vliet (2018) and Platform CB'23 (2022). The BCI calculation from Van Vliet et al. (2021) distinguishes the DI of the connection and the element with in total four indicators. However, Van Vliet (2018) identified the twelve most important technical, process and financial indicators for disassembly from the DDFs from Durmisevic (2006) and incorporated these in the original BCI calculation of Verberne (2016b). This assessment framework only includes the additional technical indicators, since the financial factors are incorporated in the LCC assessment and the process factors are seen as preconditions for disassembly and therefore do not influence the ability to disassemble directly (PIANOO, 2019). Ultimately, the DI uses seven indicators to assess the technical feasibility to disassemble. Table 12 shows an overview of the indicators used to assess the disassembly potential.

Table 12: Overview of indicators for DI

DI	Name	Abbreviation	Source
DI_c	Accessibility of Connection	AoC	(Van Vliet et al., 2021)
DI_c	Type of Connection	ToC	(Van Vliet et al., 2021)
DI_c	Assembly Sequence	Asq	(Van Vliet, 2018)
DI_e	Assembly Shape	Ash	(Van Vliet et al., 2021)
DI_e	Independency	Ind	(Van Vliet et al., 2021)
DI_e	Pattern of Relations	PoR	(Van Vliet, 2018)
DI_e	Method of Fabrication	MoF	(Van Vliet, 2018)

The equation to calculate the DI is shown in Figure 21. Van Vliet (M. Van Vliet, 2018) found that the indicators for DI_c en DI_e have an equal weight. Each indicator is scored based on the fuzzy variables shown in Appendix D, implemented from the sources listed in Table 12.

$$DI = \frac{DI_c + DI_e}{2} = \left(\overbrace{\frac{AoC + ToC + Asq}{6}}^{DI_c} + \overbrace{\frac{Ash + Ind + PoR + MoF}{8}}^{DI_e} \right)$$

Figure 21: Modified equation for calculating the Disassembly Index

Finally, a weight for each building layer to better represent the influence of the circularity of products with short life cycles compared to longer life cycles is considered (2016b). However, the BCI incorporates this phenomenon through the inclusion of the utility factor (BCI Gebouw, 2022b). In addition, it is argued that the ECI impedes the ability to assign products to a single building layer, which complicates the calculation (M. Van Vliet, 2018). Also, Verberne (2016b) mentioned that it is possible to exclude this aspect, since the assessment of this aspect is disputable.

Concluding, several modifications to the BCI calculation method are considered, but only one is modified, namely the inclusion additional DDFs. Additionally, assumptions are made to allow for the use of the assessment framework in this research. All assumptions are outlined in Appendix E. The following paragraph discusses the most important assumptions.

First, the elements listed in Table 1 are considered in this research, and thus incorporated in the assessment framework. Second, standard products are selected from the BCI database and this data is used within the assessment framework. The data specifies fractions for origin and end of life scenario, scores on disassembly factors, ECI, technical lifespan. Unless a specific end of life scenario is defined, the data within the database is used to determine this scenario. Third, the ECI values are derived from the BCI database and scaled towards the right dimensions. The ECI values within the database are based on the dimensions of the product and in case the actual dimensions differ from the database the ECI is scaled accordingly. Fourth, the assessment of the additional disassembly factors (Asq, PoR, and MoF) is performed according to the scoring tables from Van Vliet (2018) listed in Appendix D and is validated with an expert.

Life Cycle Costs

The LCC evaluated within this framework are divided over three phases, namely the (a) Construction phase, (b) Operation phase, and (c) End of Life phase. Figure 22 provides an overview of the costs considered in the assessment framework.

As can be seen in Figure 22, phase A considers the construction costs for the elements considered in the research. The general costs apart from the construction site costs are excluded from analysis. These costs include a margin for profit, risk and to cover general contractor costs. These costs are dependent on the contractor and can differ between projects (Vroege, 2022), which makes comparison difficult. A division is made between labour, material and subcontractor costs to gain better insights into the impact of biobased materials on the LCC.

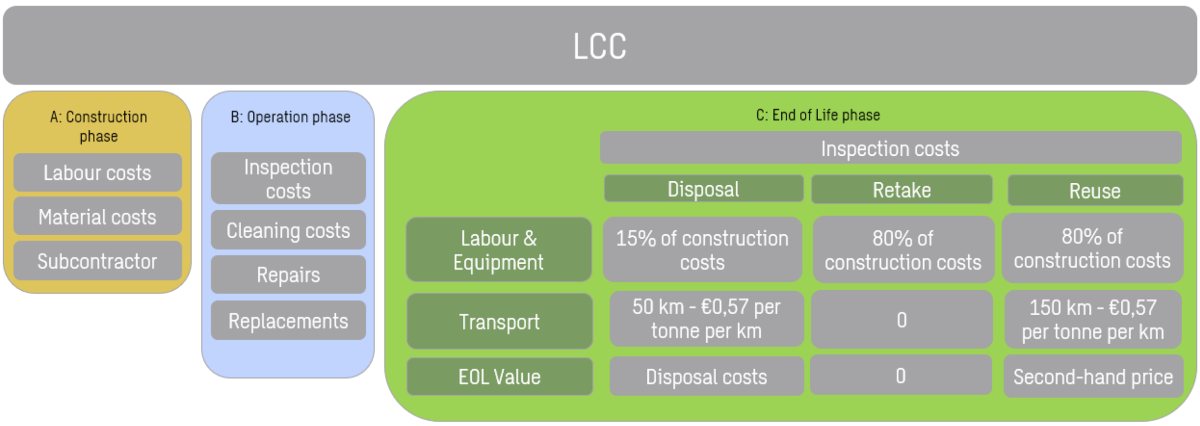


Figure 22: Overview of considered aspects in LCC

In phase B the operational expenditures are considered, which are mainly related to maintenance. The inspection costs relate to annual checks of building elements, while cleaning costs relate to periodical cleaning of elements. Replacements and repairs refer to respectively planned and unplanned maintenance. All costs apart from the repairs are discounted towards their present value to account for uncertainties using the equations described in section 2.4.1 or Appendix E. The repairs cannot be discounted, because the occurrence of these costs is uncertain and therefore cannot be linked to moment in time. Consequently, a time-cost pair cannot be determined and as such these costs cannot be discounted (Koninklijk Nederlands Normalisatie-instituut, 2017).

The last phase considers the costs to dismantle the building after its life span. Depending on the EOL scenario of a building element, the expenditures for labour & equipment and transport are considered and set off against the residual value of the building element. The building requires an inspection to determine the definitive EOL scenario, which is also included in the analysis. Similar to the operational costs, all costs are discounted to account for uncertainties in the future.

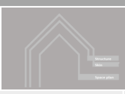
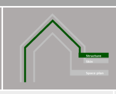
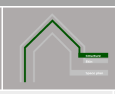
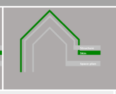
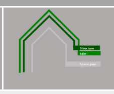
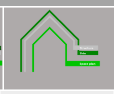
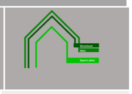
Ultimately, the LCC assessment considers three life cycle phases, each with their own cost aspects (see Figure 22). Additionally, assumptions are made with regards to the calculation of the LCC, which are shown in Appendix E as well. The most important assumptions are also discussed in the following paragraphs.

First, the costs are in principle derived from project budgets, otherwise price indications from a construction costing agency are used. The construction costs are indexed to the general new residential construction index from BDB (2023b) for the month January 2023 (index is 115,16), as the price indications are retrieved in January 2023 from the construction costing agency. Second, the cleaning and maintenance costs are retrieved from Ibis Main version 6.6 and indexed to the residential maintenance index from BDB (2023b) for the month January 2023 (index is 111,97). This software is used within Project X to determine the operational costs. Third, the end of life costs for each product are dependent on the waste scenario of that product. Each scenario entails different assumptions regarding the end of life costs based on expert knowledge and previous research which are underpinned more in detail in Appendix E. Fourth, future costs with the exception of repairs are discounted towards their present value with the equations 1, 2, and 3 as described in section 2.4.1. Since the costs considered in the LCCA are real costs, equation 4 is not used described in section 2.4.1 is not used. Repairs are not discounted since these are unplanned and do not have a specific occurrence year. The real discount rate is respectively assumed to be 2.25% (Werkgroep discontovoet 2020, 2020).

3.3. Analyze & Conclude

This subsection further elaborates on the data analysis after the results are generated. The results arising from the assessment framework contain a LoC and LCC for each alternative, similar to what is shown in Table 13.

Table 13: Expected results from assessment framework

	Base	1A	1B	2A	2B	3	4	5	6	7
										
LoC	0.36									
LCC(€)	49.006									

Consequently, a relationship between the building circularity and the life cycle costs of a building is endeavoured to retrieve for Project X. The analysis focuses on the NPV of each design alternative to capture the effect of a design choice. Furthermore, an analysis is performed to assess the impact of applying biobased materials within a single building layer. Through comparison of alternatives 1,2, and 3 with the base scenario, this impact can be assessed.

3.3.1. Sensitivity analysis

As is discussed in the literature review the life cycle costs assessment requires to perform a sensitivity analysis to manage the uncertainties during the life cycle of the building. Various factors are considered in this analysis, such as the life span, discount rate, and maintenance costs.

4. Results

The results of the research are discussed in this chapter. First, the design alternatives that were created are discussed. Subsequently, the results of the assessment framework are presented for each of these design alternatives, which are then further analysed with the sensitivity analysis.

4.1. Design alternatives

During the design session, the design alternatives for the apartment in project X are developed. This section further elaborates on the created design alternatives, starting off with the base scenario which resembles the original materialisation of project X. Figures 23 and 24 show the position of the apartment in the building.

Figure 23: Location outer façade apartment in project X

Figure 24: Location inner façade apartment in project X

Several key parameters of project X are shown in Table 14, such as the gross floor area of the building and the number of apartments. Also, shape factors are included in Table 14, which can characterise the building and help compare buildings with each other.

Table 14: Overview of key parameters Project X

Parameters Project X	Value
General	
Area (Gross floor area)	10.769 m^2

# of apartments	108
Average area per apartment	99.7 m^2
# of levels	3-6 layers
Shape factors	
Gross façade area/Gross floor area	0.63
Open façade/Gross façade area	0.37
Apartment	
Width	7200 mm
Depth	10000 mm
Gross height	3000 mm
Net height	2650 mm

During the development of the different design alternatives, the application of biobased materials in the structure layer also effects the skin and space plan of the apartment. The floor construction of alternative 1A and 1B is thicker than the base alternative, which impacts the gross height of the apartment. To maintain the characteristics of the apartment as much as possible, the required net height of the apartment is set at 2650 mm. To maintain the net height of 2650 mm, the gross height of the alternatives using a biobased structure is larger. The higher gross height also impacts the façade area. Consequently, the change in façade area is counted towards the façade elements and cladding, since the window frames and glazing are assumed to be constant.

The use of a biobased structure also influences the space plan of the apartment. Since the inner wall highlighted in red in Figure 25 is no longer constructed from aerated concrete. This function is taken over by the wood structure. The resulting materialisations for each design alternative are displayed in the following paragraphs.

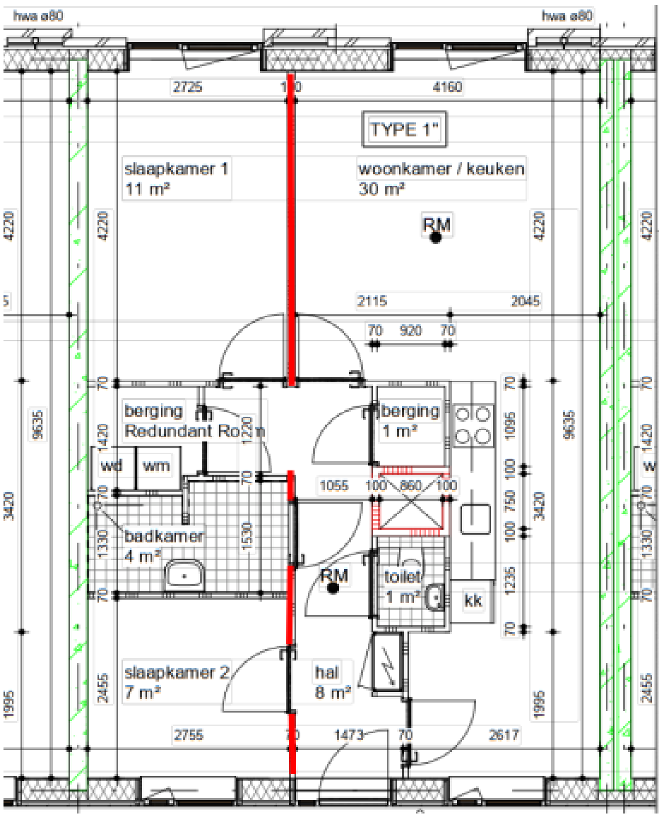


Figure 25: Overview floor plan apartment in project X

4.1.1. Base

The materialisation of the base alternative serves as a foundation for the creation of the other design alternatives and uses the original materials. Table 15 provides an overview of the materialisation of the base alternative. It can be seen that base alternative already contains several wood building elements, which are categorised as biobased, such as the façade cladding or the door sills.

Table 15: Materialisation of base alternative (Grey= original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	In-situ concrete wall	250 mm	30 m^2
Floors	Concrete slabs ("Breedplaat")	70 + 190 mm	71,4 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with mineral insulation	300 mm	25 m^2
Outer cavity leaf (inner façade)	Wooden Façade cladding	18 mm	13,3 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	11,7 m^2
Window frames	PVC window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	30,3 m^2
	Aerated concrete G4/600	100 mm	18,8 m^2
	Aerated concrete G5/800	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2
Ceiling finishing	Spray plaster	-	64 m^2

4.1.2. Alternative 1A

Alternative 1A is a subvariant that considers wooden columns and beams for the biobased structure. Table 16 provides an overview of the materialisation of alternative 1A. Since the floor construction is larger than the base alternative, the gross height of the apartment is increased to maintain the same net height within the apartment. Additionally, some inner walls are replaced by a timber frame wall with four structural columns to ensure structural strength, because of the changes in aerated concrete. Moreover, the CLT ceiling remains in sight, which means the ceilings are not finished with spray plaster and therefore not listed in Table 16.

Table 16: Materialisation of alternative 1A (Green= Biobased alternative, Blue= Indirect change, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	CLT wall	140 mm	28,7 m^2
	GL24H beam	120x300x10000 mm	2 pcs.

	GL24H column	200x400x2870 mm	4 pcs.
	Flax insulation timber frame wall	200 mm	13,3 m^2
	Plasterboards timber frame wall	2x12,5 mm	39,6 m^2
Floors	CLT floor	160 mm	71,4 m^2
	Gravel layer	100 mm	64 m^2
	Flax floor insulation	50 mm	64 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with mineral insulation	300 mm	25,4 m^2
Outer cavity leaf (inner façade)	Wooden Façade cladding	18 mm	13,5 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	11,9 m^2
Window frames	PVC window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	27,5 m^2
	Aerated concrete G4/600	100 mm	17,7 m^2
	Aerated concrete G5/800	100 mm	10,4 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2

4.1.3. Alternative 1B

Alternative 1B is a subvariant that considers wooden modules for the biobased structure. Table 17 provides an overview of the materialisation of alternative 1B. Similar to alternative 1A the gross height changes induce a modification to the façade area and aerated concrete inner walls. Moreover, the ceilings are not finished with spray plaster and therefore not listed in Table 17, this means the CLT remains in sight.

Table 17: Materialisation of alternative 1B (Green= Biobased alternative, Blue= Indirect change, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	CLT wall	100 mm	57,4m^2
	Flax insulation timber frame wall	35 mm	57,4 m^2
	Plasterboards timber frame wall	2x12,5 mm	57,4 m^2
	CLT wall	100 mm	36,7 m^2
	Flax insulation timber frame wall	200 mm	36,7 m^2
	Plasterboards timber frame wall	2x12,5 mm	36,7 m^2
	Flax cavity insulation	40 mm	18,5 m^2
Floors	CLT floor	120 mm	71,4 m^2
	Gravel layer	100 mm	64 m^2

	Flax floor insulation	50 mm	64 m^2
	Cement screed	70 mm	64 m^2
	CLT floor	60 mm	71,4 m^2
	Flax cavity insulation	100 mm	71,4 m^2
Skin			
Inner cavity leaf	HSB Façade element with mineral insulation	300 mm	27,2 m^2
Outer cavity leaf (inner façade)	Wooden Façade cladding	18 mm	14,4 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	12,8 m^2
Window frames	PVC window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	27,5 m^2
	Aerated concrete G4/600	100 mm	17,7 m^2
	Aerated concrete G5/800	100 mm	10,4 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2

4.1.4. Alternative 2A

Alternative 2A is a subvariant that considers a fully biobased skin. Table 18 provides an overview of the materialisation of alternative 2A. Also, the wooden façade cladding at the inner façade was already part of the base alternative, but is considered a biobased material and therefore highlighted in green.

Table 18: Materialisation of alternative 2A (Green= Biobased alternative, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	In-situ concrete wall	250 mm	30 m^2
Floors	Concrete slabs ("Breedplaat")	70 + 190 mm	71,4 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with flax insulation	320 mm	25 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,3 m^2
Outer cavity leaf (outer façade)	Wooden façade cladding	18 mm	11,7 m^2
Window frames	Wooden window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.

	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	30,3 m^2
	Aerated concrete G4/600	100 mm	18,8 m^2
	Aerated concrete G5/800	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2
Ceiling finishing	Spray plaster	-	64 m^2

4.1.5. Alternative 2B

Alternative 2B is a subvariant that considers biobased HSB façade elements with a brickwork finishing. Table 19 provides an overview of the materialisation of alternative 2B. Alternative 2A considers the brickwork façade cladding similar to the base alternative, which are therefore displayed in grey. There are no further indirect changes when biobased materials are applied within the Skin of the apartment.

Table 19: Materialisation of alternative 2B (Green= Biobased alternative, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	In-situ concrete wall	250 mm	30 m^2
Floors	Concrete slabs ("Breedplaat")	70 + 190 mm	71,4 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with flax insulation	320 mm	25 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,3 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	11,7 m^2
Window frames	Wooden window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	30,3 m^2
	Aerated concrete G4/600	100 mm	18,8 m^2
	Aerated concrete G5/800	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2
Ceiling finishing	Spray plaster	-	64 m^2

4.1.6. Alternative 3

Alternative 3 considers a biobased space plan for the apartment in project X. Table 20 provides an overview of the materialisation of alternative 3. As can be seen at the bottom of Table 20, there are no biobased alternatives for spray plaster or tiles.

Table 20: Materialisation of alternative 3 (Green= Biobased alternative, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	In-situ concrete wall	250 mm	30 m^2
Floors	Concrete slabs (“Breedplaat”)	70 + 190 mm	71,4 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with mineral insulation	300 mm	25 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,3 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	11,7 m^2
Window frames	PVC window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	Hardboard with tubular filling	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Wooden door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Hempcrete	70 mm	30,3 m^2
	Hempcrete	100 mm	18,8 m^2
	Hempcrete	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2
Ceiling finishing	Spray plaster	-	64 m^2

4.1.7. Alternative 4

Alternative 4 considers a biobased structure and skin for the apartment in project X. Table 21 provides an overview of the materialisation of alternative 4.

Table 21: Materialisation of alternative 4 (Green= Biobased alternative, Blue= Indirect change, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	CLT wall	140 mm	28,7 m^2
	GL24H beam	120x300x10000 mm	2 pcs.
	GL24H column	200x400x2870 mm	4 pcs.
	Flax insulation timber frame wall	200 mm	13,3 m^2
	Plasterboards timber frame wall	2x12,5 mm	39,6 m^2
Floors	CLT floor	160 mm	71,4 m^2
	Gravel layer	100 mm	64 m^2
	Flax floor insulation	50 mm	64 m^2

	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with flax insulation	320 mm	25,4 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,5 m^2
Outer cavity leaf (outer façade)	Wooden façade cladding	18 mm	11,9 m^2
Window frames	Wooden window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	HDF-Alu-HDF front door	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Steel door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Aerated concrete G4/600	70 mm	27,5 m^2
	Aerated concrete G4/600	100 mm	17,7 m^2
	Aerated concrete G5/800	100 mm	10,4 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2

4.1.8. Alternative 5

Alternative 5 considers a biobased structure and space plan for the apartment in project X. Table 22 provides an overview of the materialisation of alternative 5.

Table 22: Materialisation of alternative 5 (Green= Biobased alternative, Blue= Indirect change, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	CLT wall	140 mm	28,7 m^2
	GL24H beam	120x300x10000 mm	2 pcs.
	GL24H column	200x400x2870 mm	4 pcs.
	Flax insulation timber frame wall	200 mm	13,3 m^2
	Plasterboards timber frame wall	2x12,5 mm	39,6 m^2
Floors	CLT floor	160 mm	71,4 m^2
	Gravel layer	100 mm	64 m^2
	Flax floor insulation	50 mm	64 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with mineral insulation	300 mm	25,4 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,5 m^2
Outer cavity leaf (outer façade)	Brickwork + PIR Insulation and steel frame	-	11,9 m^2
Window frames	PVC window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			

Doors	Hardboard with tubular filling	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Wooden door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Hempcrete	70 mm	30,3 m^2
	Hempcrete	100 mm	18,8 m^2
	Hempcrete	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2

4.1.9. Alternative 6

Alternative 6 considers a biobased skin and space plan for the apartment in project X. Table 23 provides an overview of the materialisation of alternative 6. The green rows in Table 23 represent biobased materials. There are no biobased alternative for glass, spray plaster or tiles.

Table 23: Materialisation of alternative 6 (Green= Biobased alternative, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	In-situ concrete wall	250 mm	30 m^2
Floors	Concrete slabs ("Breedplaat")	70 + 190 mm	71,4 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with flax insulation	320 mm	25 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,3 m^2
Outer cavity leaf (outer façade)	Wooden façade cladding	18 mm	11,7 m^2
Window frames	Wooden window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	Hardboard with tubular filling	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Wooden door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Hempcrete	70 mm	30,3 m^2
	Hempcrete	100 mm	18,8 m^2
	Hempcrete	100 mm	21,5 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2
Ceiling finishing	Spray plaster	-	64 m^2

4.1.10. Alternative 7

Alternative 7 considers a fully biobased materialisation for the apartment in project X. Table 24 provides an overview of the materialisation of alternative 7. Within Table 24, the green rows represent biobased materials, whilst the blue cells consider indirect changes due to the use of biobased materials in other building elements. Similar to alternative 1A, 1B, 4, and 5, the gross height of the apartment is changed and an inner wall is replaced, which are highlighted blue.

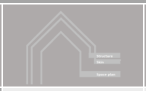
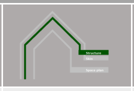
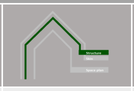
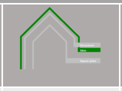
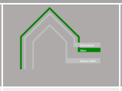
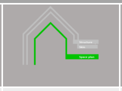
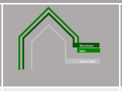
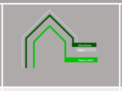
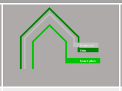
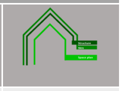
Table 24: Materialisation of alternative 7 (Green= Biobased alternative, Blue= Indirect change, Grey= Original material)

Structure	Product	Dimension	Quantity
Lead-bearing structure	CLT wall	140 mm	28,7 m^2
	GL24H beam	120x300x10000 mm	2 pcs.
	GL24H column	200x400x2870 mm	4 pcs.
	Flax insulation timber frame wall	200 mm	13,3 m^2
	Plasterboards timber frame wall	2x12,5 mm	39,6 m^2
Floors	CLT floor	160 mm	71,4 m^2
	Gravel layer	100 mm	64 m^2
	Flax floor insulation	50 mm	64 m^2
	Cement screed	70 mm	64 m^2
Skin			
Inner cavity leaf	HSB Façade element with flax insulation	320 mm	25,4 m^2
Outer cavity leaf (inner façade)	Wooden façade cladding	18 mm	13,5 m^2
Outer cavity leaf (outer façade)	Wooden façade cladding	18 mm	11,9 m^2
Window frames	Wooden window frames	-	15,1 m^2
Glazing	HR +++	-	10,5 m^2
Space Plan			
Doors	Hardboard with tubular filling	56 mm	1 pcs.
	Hardboard with honeycomb filling	2315x930x40 mm	8 pcs.
Inner sills	Wooden door sills	-	8 pcs.
	Wood front door sill	-	1 pcs.
Inner walls	Hempcrete	70 mm	27,5 m^2
	Hempcrete	100 mm	17,7 m^2
	Hempcrete	100 mm	10,4 m^2
Wall finishing	Spray plaster	-	8,8 m^2
	Tiles	-	31,3 m^2
Floor finishing	Bathroom tiles	-	3,8 m^2

4.2. Level of Circularity

This section elaborates on the level of circularity of each alternative. An overview of the LoC scores for each alternative can be found in Table 25. The illustration indicating the biobased layer for each alternative is shown in Figure 20 in Section 3.2.1.

Table 25: Results LoC analysis

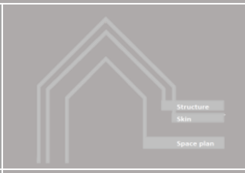
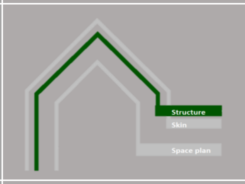
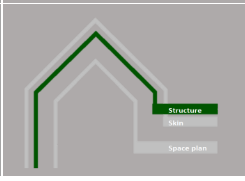
	Base	1A	1B	2A	2B	3	4	5	6	7
										
LoC	0.36	0.48	0.51	0.36	0.37	0.30	0.49	0.44	0.29	0.45

The following subsections elaborate further on the differences in LoC between the alternatives. First, the influence of each building layer is analysed separately. Subsequently, the alternatives that combine the different layers are discussed. Finally, some general remarks with regards to the results are made.

4.2.1. Structure

The results show that both wooden elements and modules (alternatives 1A & 1B) used as structure of the apartment allow the LoC to increase from 0.36 to respectively 0.48 and 0.51 (Table 25). Table 26 provides an overview of the average MCI (Material Circularity Indicator) and DI (Disassembly Index) for both the load-bearing structure and the flooring of the apartment. The table shows that the difference in DI between the traditional and biobased alternatives is larger for the load-bearing structure than the floor of the apartment (0.53 and 0.52 versus 0.27 and 0.32).

Table 26: Overview of MCI and DI for alternatives base, 1A, and 1B (Green= improvement, Red= reduction)

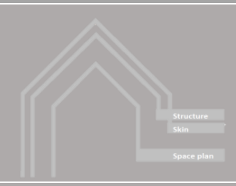
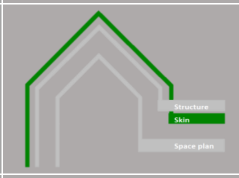
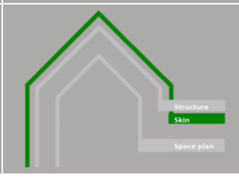
Alternative		Load-bearing structure		Floor	
		MCI	DI	MCI	DI
Base		0.56	0.10	0.67	0.19
1A		0.60 ↑	0.63 ↑	0.59 ↓	0.46 ↑
1B		0.56 –	0.62 ↑	0.68 ↑	0.51 ↑

Further analysis shows that the difference in MCI for alternatives Base, 1A and 1B is small in comparison to the difference in DI, meaning the DI mainly causes the difference in LoC. The spread of the MCI between the alternatives is 0.04 for the load-bearing structure, whereas the spread for the MCI of the floor is 0.08. The DI on the other side has a spread of consequently 0.53 for the load-bearing structure and 0.32 for the floor, which explains the difference in LoC between the base alternative and alternatives 1A and 1B.

4.2.2. Skin

Table 27 shows the MCI and DI of the Skin for alternatives 2A and 2B (biobased Skin). It can be seen that the effect of a biobased skin on the LoC is limited. A closer look at the MCI and DI of these alternatives displays small differences in both the MCI and DI of the skin in different alternatives (see Table 27).

Table 27: Overview of MCI and DI for alternatives Base, 2A, and 2B (Green = improvement, Red= reduction)

		MCI skin	DI skin
Base		0.43	0.62
2A (fully biobased façade)		0.41 ↓	0.60 ↓
2B (façade with brickwork finishing)		0.46 ↑	0.62 -

An interesting note is the fact that alternative 2B (0.46) obtains a higher MCI than alternative 2A (0.41). This is caused by a shorter technical lifespan and incineration waste scenario in case a wooden façade cladding is used, which results in a higher LFI and thus lower MCI.

Another note is that even though the façade elements are filled with flax insulation in alternative 2A and 2B, they obtain an MCI of 0 in all alternatives. Due to a short technical lifespan and high LFI of plasterboards, the impact of the biobased insulation material is insignificant. Table 28 shows a detailed overview of the relevant characteristics for products part of the façade elements.

Table 28: Overview of determining characteristics MCi for façade element filled with either mineral or flax insulation

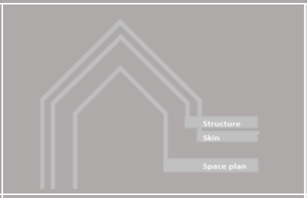
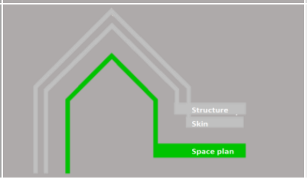
Product	L_t (years)	L_w (years)	$F(X_p)$	ECI	LFI
Mineral insulation	75	50	0.6	€35,07	66,64
Flax insulation	75	50	0.6	€8,46	0,51
Plasterboards	25	50	1.8	€21,48	41,89

It is shown that the utility factor (F(Xp)) of the plasterboards is 1.8, in comparison to the 0.6 of the insulation material. These utility factors are caused by the technical life span of the material. Since the façade consists of elements, the lowest technical lifespan is taken into account when calculating the utility factor, which is 25 years. Furthermore, the LFI takes the ECI of the products into account, which is high for both mineral insulation and plasterboards. Ultimately, the ECI results in such a high LFI that the impact of the insulation material on the MCI is insignificant.

4.2.3. Space Plan

Finally, the impact of the Space Plan is assessed. As can be seen in Table 25, the LoC of the apartment decreases from 0.34 to 0.27 when biobased materials are applied in the Space Plan. Table 29 shows the average MCI and DI of the Space Plan in the base alternative (0.47 and 0.53) and alternative 3 (0.33 and 0.49). The lower value for alternative 3 can be traced back to three reasons.

Table 29: Overview of MCI and DI of the Space Plan for alternatives Base and 3 (Green= improvement, Red= reduction)

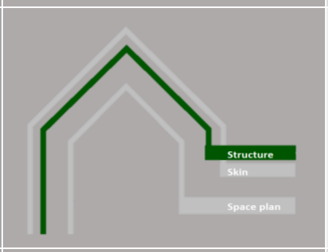
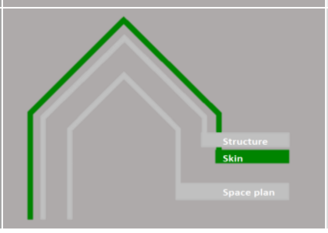
		MCI Space Plan	DI Space Plan
Base		0.47	0.53
3		0.33 ↓	0.49 ↓

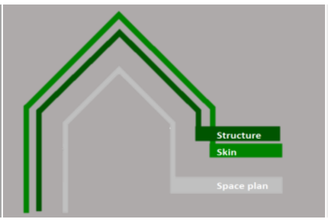
First of all, the inner walls are constructed from hempcrete instead of aerated concrete. Due to the lower technical lifespan and high LFI of hempcrete, the resulting MCI is higher for the base alternative. Additionally, the DI of hempcrete is lower, which is caused by the values for the disassembly factors derived from the BCI database. Third of all, the steel inner sills within the apartment have a lower LFI and ECI, which result in a higher MCI (0.82 versus 0.71) in comparison to the wooden inner sills of alternative 3. Finally, the front door has a higher LFI despite the lower ECI, which is caused by incineration waste scenario of wood.

4.2.4. Combination of building layers

As was just mentioned, the Structure has a significant impact on the circular performance, whereas the impact of the Skin is limited and that of the Space Plan is negative. Alternative 4 combines a biobased Structure with a biobased Skin, which results in an LoC of 0.44. An overview of the MCI and DI per layer and alternative is displayed in Table 30. It can be seen that there only is a difference of MCI and DI in the Space Plan. The MCI remains 0.50, while the DI decreases to 0.54. This can be traced back to the absence of spray plaster on the ceiling.

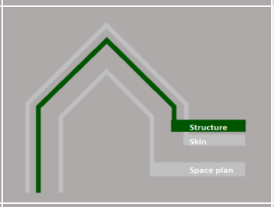
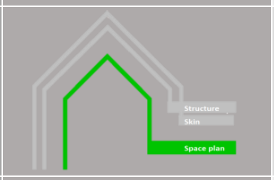
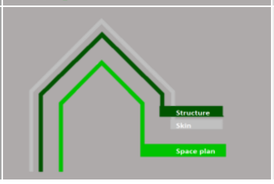
Table 30: Overview of MCI and DI for alternatives 1A, 2A, and 4 (Bold=dominant alternative)

		Structure		Skin		Space Plan	
		MCI	DI	MCI	DI	MCI	DI
1A		**0.60**	**0.56**	0.43	0.62	**0.50**	**0.56**
2A		0.63	0.15	**0.41**	**0.60**	0.47	0.53

4		**0.60**	**0.56**	**0.41**	**0.60**	**0.50**	**0.54**

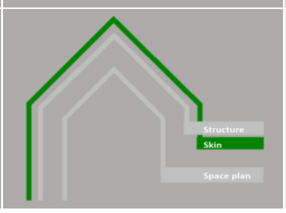
Alternative 5 achieves a LoC of 0.39 through combining a biobased Structure and Space Plan. Table 31 provides an overview of the MCI and DI for each building layer in alternatives 1A, 3, and 5. It is shown that the values are very similar to corresponding layer. However, there is a small difference in the MCI and DI of the Space Plan and the corresponding dominant layer (in alternative 3). This is caused by the absence of spray plaster on the ceilings in alternative 5.

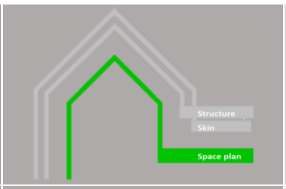
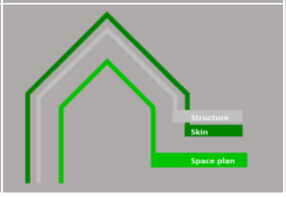
Table 31: Overview of MCI and DI for alternatives 1A, 3, and 5 (Bold=dominant alternative)

		Structure		Skin		Space Plan	
		MCI	DI	MCI	DI	MCI	DI
1A		**0.60**	**0.56**	0.43	0.62	0.50	0.56
3		0.63	0.15	0.43	0.62	**0.33**	**0.49**
5		**0.60**	**0.56**	0.43	0.62	**0.35**	**0.50**

A combination of a biobased Skin and Space Plan is made in alternative 6, which results in a LoC of 0.24. As can be seen in Table 32, the MCI and DI for the building layers follow from alternative 2A and 3.

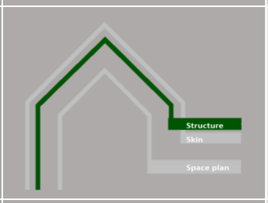
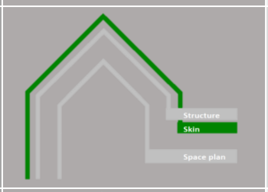
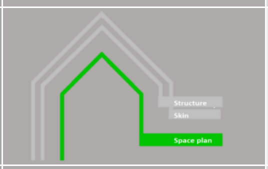
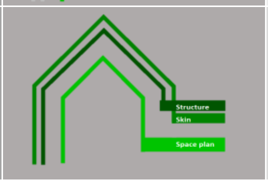
Table 32: Overview of MCI and DI for alternatives 2A, 3, and 6 (Bold=dominant alternative)

		Structure		Skin		Space Plan	
		MCI	DI	MCI	DI	MCI	DI
2A		0.63	0.15	**0.41**	**0.60**	0.47	0.53

3		0.63	0.15	0.43	0.62	**0.33**	**0.49**
6		0.63	0.15	**0.41**	**0.60**	**0.33**	**0.49**

Combining all biobased building layers in alternative 7 entails a 15 per cent increase in LoC (+0.05). Table 33 shows the MCI and DI values for alternatives 1A, 2A, 3, and 7. Further analysis shows the Structure of the apartment displays the biggest increase in LoC when applying biobased materials in a single building layer.

Table 33: Overview of MCI and DI for alternatives 1A, 2A, 3, and 7 (Bold=dominant alternative)

		Structure		Skin		Space Plan	
		MCI	DI	MCI	DI	MCI	DI
1A		**0.60**	**0.56**	0.43	0.62	0.50	0.56
2A		0.63	0.15	**0.41**	**0.60**	0.47	0.53
3		0.63	0.15	0.43	0.62	**0.33**	**0.49**
7		**0.60**	**0.56**	**0.41**	**0.56**	**0.35**	**0.50**

4.2.5. Points of attention LoC assessment

During analysis several points of attention arose, such as the technical life span of some of the building materials, the End of Life scenario of wood, and the difference in disassembly scores. The following paragraphs further elaborate on these discussion points.

Additional Disassembly factors

The first point of analysis is the inclusion of the additional disassembly factors. As was discussed in Section 3.2.2, three additional disassembly factors were included in the disassembly index. Although Van Vliet (2018) adjusted the Disassembly Determining Factors (DDFs) to be used in the BCI, the added factors are not part of the BCI method from BCI Gebouw (2022b). Therefore, part of the sensitivity analysis is to assess the influence of the added factors, such that it can be determined what the sensitivity of the LoC to these additional factors is. Figure 26 provides an overview of the results of this analysis and displays the results without the additional DDFs in dark green. The columns shown in light green are the LoC values based on the assessment framework described in Section 3.2.2.

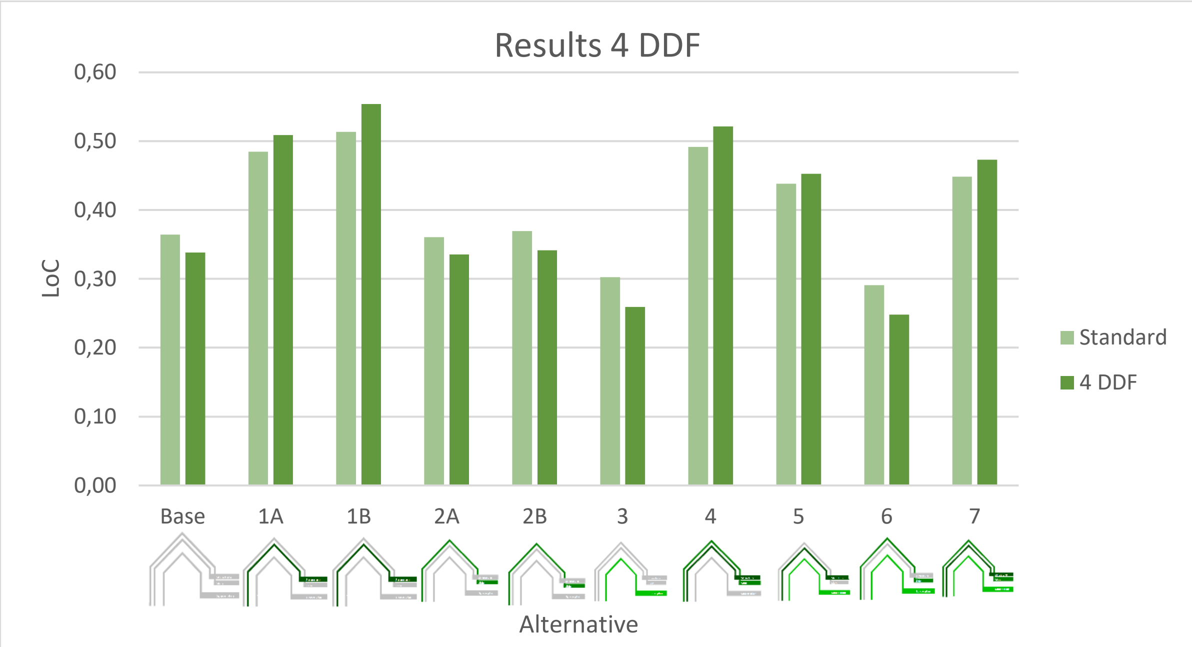


Figure 26: Results sensitivity analysis disassembly factors

The results above show there is not much difference in the resulting LoC when the three additional disassembly factors are included. A positive influence is noted in alternatives that use a biobased structure, hence alternative 1A, 1B, 4, 5, and 7. This is explained through the fact that wooden structural elements are often prefabricated, which scores higher on the third added disassembly factor Method of Fabrication (MoF). The score on the other added DDFs, Assembly sequence (Asq) and Pattern of Relations (PoR), is very similar with a small advantage for wood.

Furthermore, it is noted that the LoC of the alternatives that only include a biobased Skin, biobased Space Plan or a combination (alternatives 2A, 2B, 3, 6) show a negative effect when the additional DDFs are removed. This is caused by the fact that the building elements in these layers score better on these DDFs.

Concluding, the analysis shows that the influence of additional disassembly factors in the assessment framework is not exceptionally large and is can be explained. Therefore, it is concluded that the added disassembly factors provide a deeper assessment of the disassembly potential of building elements.

Technical life span

The short technical life spans of plasterboards and hempcrete (i.e. both 25 years) result in lower MCI values than expected, due to the higher utility factor, which accounts for replacement materials. A side-effect of this phenomenon is that discrepancies arise between the maintenance planning and the calculation of the LoC. Applying a more realistic life span provides a MCI that better represents the reality. According to NIBE (2023b), the life span of similar façade elements is 75 years, whilst all inner wall constructions in the NIBE database have a life span of 60 years (NIBE, 2023b). Isohemp (n.d.-b) states that their blocks maintain their strength as long as a proper finishing is used. Therefore, an additional analysis is performed considering modified technical lifespans for both the plasterboards in the façade elements and the hempcrete blocks. Ultimately, a technical life span of 50 years is chosen to maintain a realistic scenario considering both the original data and the data from NIBE. The results are shown in Figure 27, in which the adjusted life span are shown in dark green.

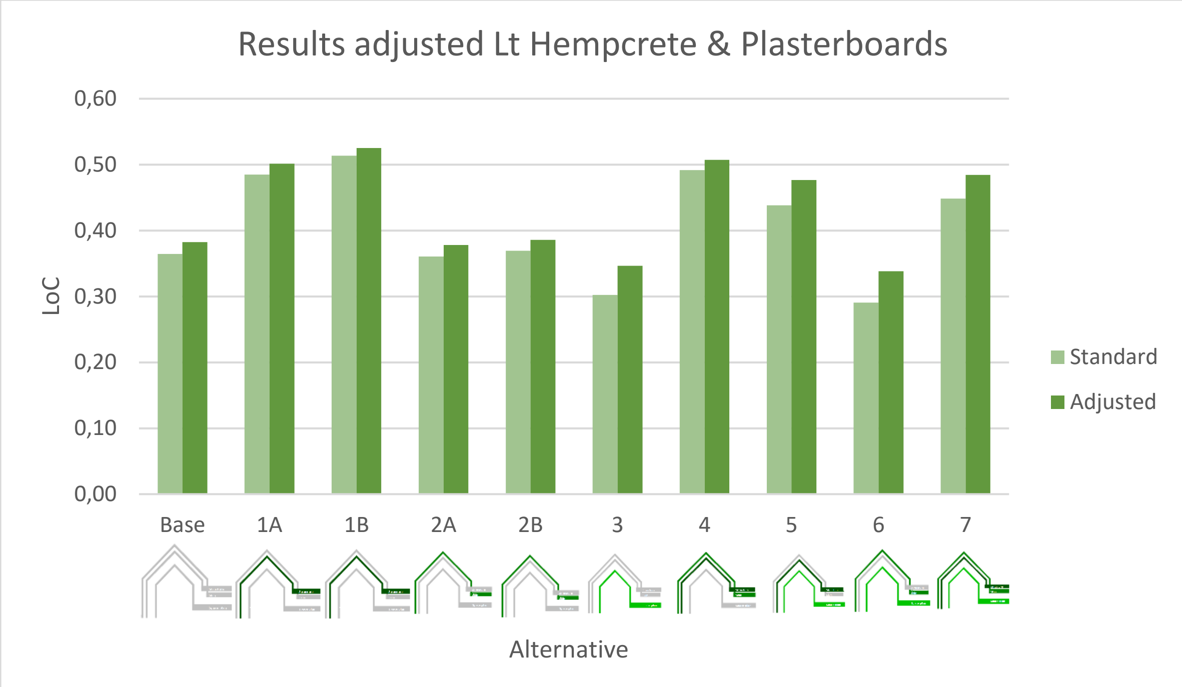


Figure 27: Results LoC with adjusted technical lifespan for plasterboards and hempcrete blocks

Figure 27 shows the LoC increases slightly when the technical life span of plasterboards and hempcrete blocks is increased due to the difference in utility factor. The MCI for the façade elements increases with 0,14 (+14%) when a longer technical life span is considered for the plasterboards. Whereas the MCI for hempcrete blocks show an increase of 0.46 (+511%) with a longer technical life span.

It is concluded that the adjusted technical life span for plasterboards and hempcrete blocks are more appropriate, since the LoC assessment displays a more realistic behaviour.

End of Life scenario wood

Additionally, the incineration scenario of biobased products is questionable. Since the incineration scenario is used to calculate the LFI, the MCI is impacted negatively. As was mentioned in Appendix E, the standard products from the BCI database are used to retrieve the product data. The underlying LCA considers an incineration scenario for these products, while recycling might be more appropriate (Alba Concepts, 2021; Centrum Hout, 2021). Research shows that recycling of demolition wood is also technically feasible (Azambuja et al., 2018; Ormondroyd et al., 2016). Therefore, recycling is considered as EOL scenario for wood in another analysis to assess the impact of the incineration EOL scenario on the LoC.

The results are shown in Figure 28 and display an overall increase of the LoC (dark versus light green), likely caused by the fact that the base alternative already contains a significant amount of wooden materials in each building layer. The difference between the standard and adjusted LoC increases with the amount of biobased materials applied. Ultimately, it is concluded that an adjusted EOL scenario for wood has a positive influence on the LoC.

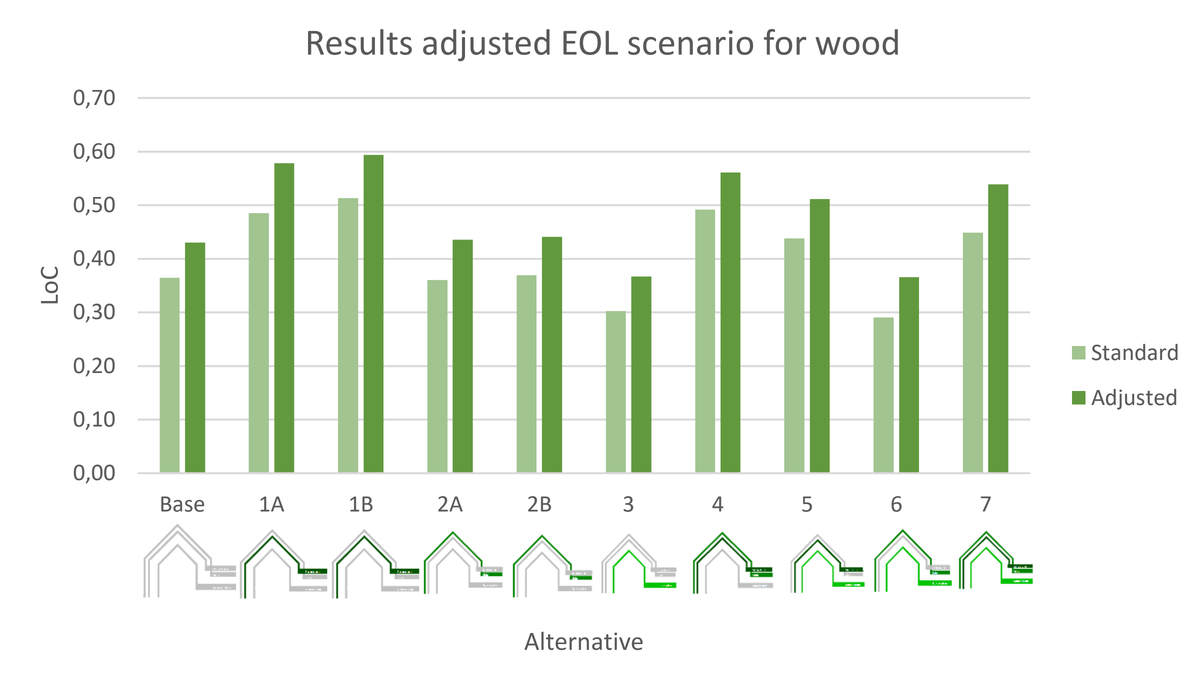


Figure 28: Results adjusted End of Life scenario for wood

Revised base design

Next, the current base alternative already contains various biobased materials, which clouds the improvement in LoC when biobased materials are used as the LoC is higher compared to a base alternative that does not contain any biobased materials. Therefore, an additional analysis is performed to assess the influence in case the base alternative contains less biobased materials. The results are shown in Table 35. The changes made to the base alternative to develop the revised base alternative are displayed in Table 34.

Table 34: Changes made to original base alternative to create revised base alternative

Building element	Original Base alternative	Revised base alternative
Façade cladding	Bricks (outer façade) & wood (inner façade)	Bricks (outer & inner façade)
Front door	HSB inner construction filled with PUR insulation and finished with HDF-Alu-HDF	Steel door filled with PUR insulation
Inner doors	Hardboard with honeycomb filling	Steel filled with steel structure and honeycomb filling

Table 35: Results on MCI, DI, and BCI for the original and revised base alternative

	Structure		Skin		Space Plan		Total
	MCI	DI	MCI	DI	MCI	DI	LoC
Base	0.63	0.15	0.43	0.62	0.47	0.53	0.36
Revised Base	0.63 -	0.15 -	0.39 ↓	0.62 -	0.56 ↑	0.53 -	0.40 ↑

Table 35 shows unexpected results, since the LoC for the revised base alternative obtains a higher LoC. Further analysis shows that the MCI for the Space Plan is higher than the original base alternative, caused by the use of steel products, which have a lower LFI. The MCI for the Skin is lower, because the wooden façade cladding is replaced by brickwork, which has a lower MCI.

As was just discussed, the EOL scenario of wood is questionable, therefore the revised base alternative is also compared to the base alternative with an adjusted EOL scenario for wood. Table 36 displays the results of this analysis.

Table 36: Results on MCI, DI, and BCI for the adjusted and revised base alternative

	Structure		Skin		Space Plan		Total
	MCI	**DI**	**MCI**	**DI**	**MCI**	**DI**	**LoC**
Base (Adjusted EOL scenario Wood)	0.63	0.15	0.50	0.62	0.61	0.53	0.43
Revised Base	0.63 -	0.15 -	0.39 ↓	0.62 -	0.56 ↓	0.53 -	0.40 ↓

It is observed that this comparison results in a lower LoC for the revised base alternative when compared to the base alternative with adjusted EOL scenario for wood. Moreover, it can be seen that the MCI for base with adjusted EOL scenario is higher for both the Skin and the Space Plan. This is caused by the relatively high amount of wooden materials in the original base scenario.

Ultimately, it is concluded that the difference between the base scenario with an adjusted EOL scenario for wood and the revised base design is small (-0,03 or -7%).

Reuse future scenario

Additionally, an analysis is performed on the circular strategy 'Designing with reused objects' (Platform CB'23, 2021a), since Reuse was not considered in this research. Project X did not include any products or elements that are intended to be reused after the buildings life span. However, Market and governmental developments show that reuse of materials should become more common (Landman, 2022).

Therefore, an additional analysis is performed to gain insights into the potential result in LoC, when products are reused after its life span. Within the BCI database the standard products are replaced with products that consider a Reuse EOL scenario. The results of this analysis are shown in Figure 29, where light green represents the standard EOL scenario and dark green a Reuse EOL scenario.

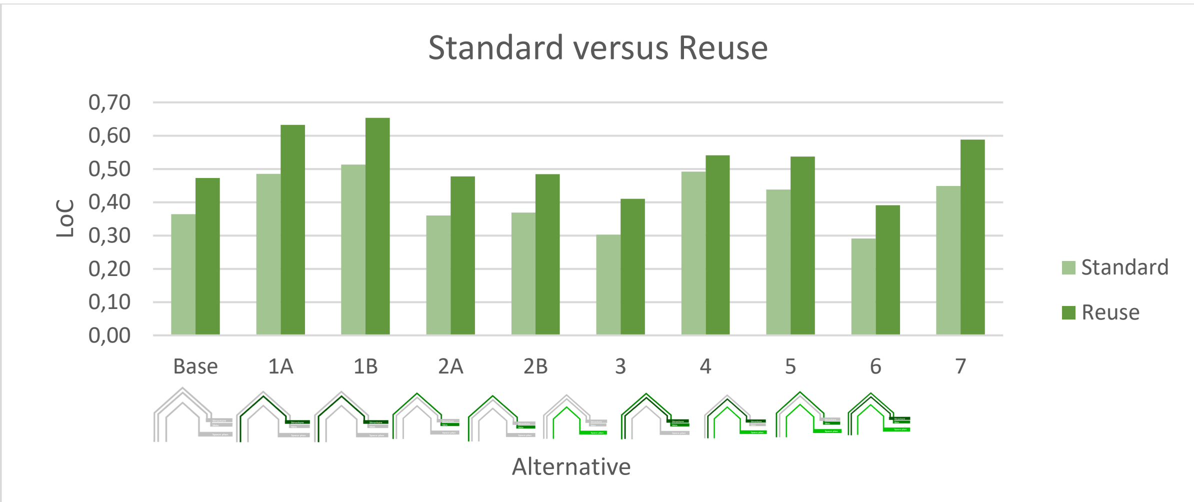


Figure 29: Results sensitivity analysis reuse as end of life scenario

As can be seen in Figure 29, the consideration of a Reuse EOL scenario results in higher levels of circularity for all alternatives. The largest difference (+36%) can be seen for alternative 3, which is caused by an increase in the LFI. Since the waste fraction considers 100% reuse, the influence of the waste fraction on the LFI is none and the LFI is only dependent on the origin fractions. The smallest difference (+10%) noted from Figure 29 is for alternative 4. Similar behaviour can be seen when considering a recycle EOL scenario for wood, which was discussed in section 4.3.5. However, the difference is smaller (+0,10)because only the waste fractions of wooden products are adjusted in that analysis.

Ultimately, it can be concluded that considering a Reuse EOL scenario for alternatives results on average in an increase of 29% in LoC.

Disassembly index

Another point of attention is the fact that the disassembly factors considered in the BCI database show irregularities. As was just mentioned the DI of hempcrete is lower compared to similar inner wall constructions. It became apparent that three disassembly factors are scored differently.

First of all, the Accessibility of Connection for hempcrete blocks (0,1) differs from the aerated concrete blocks (0,4). Second, the Assembly Shape of hempcrete is 0.1 compared to 1.0 for aerated concrete. Finally, the factor Independency is scored 0.1 for hempcrete instead of 0.4 for aerated concrete. However, both materials are used for inner walls and finished with spray plaster. Furthermore, the way in which these products are constructed is similar. To maintain unity in the scoring of the DI and ensure a fair comparison the score for hempcrete blocks should be adjusted to 0,4.

4.2.6. Sub conclusion LoC

The results show that the impact of the structure has the biggest influence on the LoC of the apartment. Solely a biobased structure entails an increase of 0.12-0.15 in LoC, caused by an increase in DI. The MCI remains similar or is lower when using wooden elements, due to a high LFI caused by the considered waste scenario of wood. Furthermore, applying biobased materials in the Skin has a limited impact on the LoC, due to the fact that wood has a high LFI and the adverse calculation of the ECI. In addition, not every building element in the Skin has a biobased alternative, such as glass or plasterboards. Finally, a biobased Space Plan has a negative impact on the LoC. Similar to Skin, the Space Plan contains building elements for which a comparable biobased alternative does not exist. Also, a high LFI for wood further increases the negative impact of a biobased Space Plan.

In addition, this section assesses the LoC of the alternatives combining different biobased building layers as well. In principle it can be seen that the LoC for alternatives 4 to 7 logically follows the combination of building layers. However, differences can be seen when a combination is made with a biobased structure, due to the absence of spray plaster ceilings. This entails a higher MCI for the Space Plan.

All in all it is concluded that a biobased structure has the biggest influence on the LoC, as the LoC increases with 33 to 42 per cent (+0.12 to +0.15). The biobased skin has a negligible impact on the LoC, whilst the use of biobased materials in the space plan entails a negative impact on the LoC of about 17 per cent (-0,06). Combining building layers shows in general an accumulation effect on the LoC, which means that for instance combining a biobased skin and space plan results in an LoC that is 0.07 lower. When a biobased structure is applied, the spray plaster finishing on the ceiling is removed, which therefore positively impacts the LoC. This means combining a biobased structure with another building layer results in a higher effect than the expected accumulated effect. Hence, it is expected that combining a biobased structure and space plan results in an LoC that is 0.06 higher. However, the LoC of alternative 5 is 0.08 higher than the base alternative, which shows an strengthening effect when a biobased structure is used.

4.3. LCC

An overview of the results of the LCCA can be found in Figure 30. The exact results of the LCCA are listed in Table 40 of Appendix F. It is shown that alternative 1B entails the highest LCC of all alternatives followed by alternative 7. Compared to the base alternative these values are roughly 22 per cent higher, mainly dictated by the increase in construction costs. Furthermore, it can be seen that alternative 2A and 2B cause the lowest rise in LCC with 2-3%. Alternatives 3 to 6 have a 6 to 17 per cent increase in LCC. The following subsections further elaborate on the specific life cycle phases. To ensure visibility and interpretation of the data, the axis from Figures 31 to 33 differ from Figure 30.

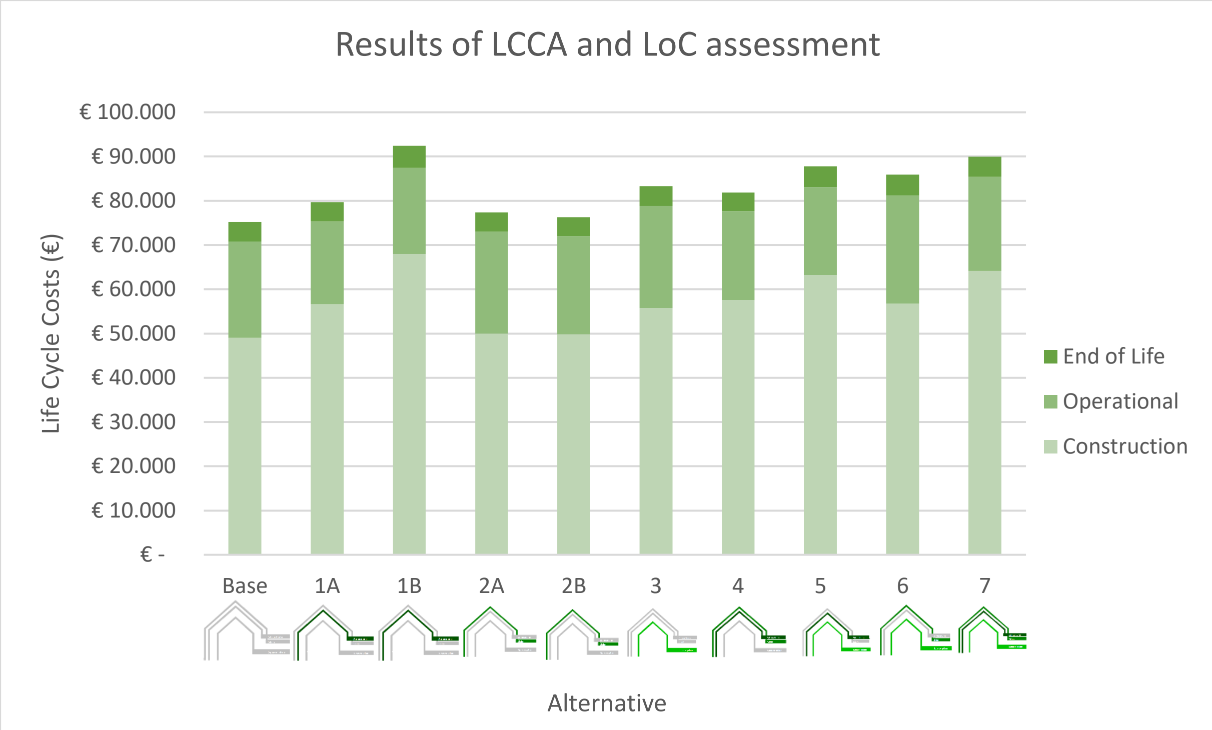


Figure 30: Overview of results LCCA

4.3.1. Construction costs

Table 41 of Appendix F displays an overview of the exact construction costs split into costs for material, labour, and subcontractor, which are also displayed graphically in Figure 31.

The impact on construction costs when using biobased materials in the skin (alternatives 2A and 2B) is significantly less and results in an increase in construction costs of 2 per cent compared to the base alternative. This price difference is caused by the wooden window frames instead of PVC window frames, which are more expensive. On the other hand, the façade elements are slightly cheaper in comparison to the base alternative. Furthermore, it can be seen that the difference between wooden and brickwork façade cladding is very small.

Using biobased materials in the space plan results in an increase of 14 per cent in construction costs. This increase is linked to the hempcrete blocks and inner door sills, which are significantly more expensive than the base alternative. The inner front door however is less expensive, but it does not compensate for the more expensive inner walls and door sills.

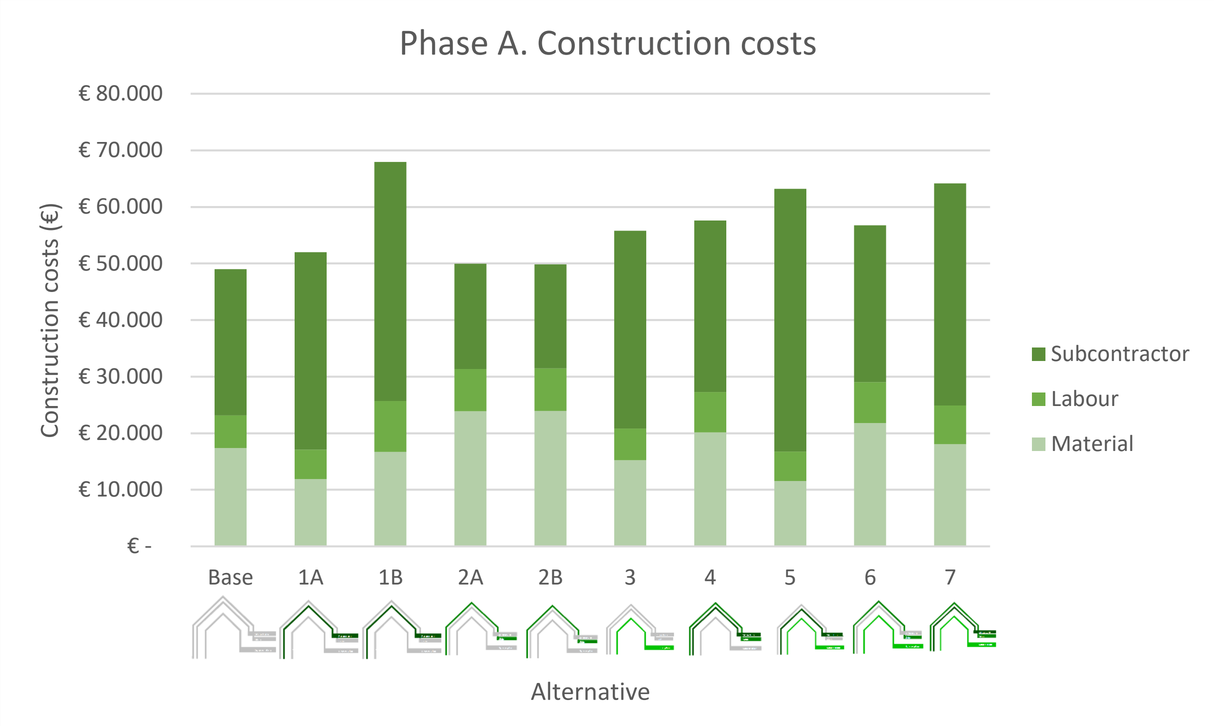


Figure 31: Overview of results LCCA phase A. Construction costs

Alternatives 4 to 7 display similar increases in construction costs as described above. For example alternative 4, which combines alternatives 1A and 2A shows that the increase in construction costs is 18 per cent. Whereas, alternatives 1A and 2A separately cause an increase of respectively 16 and 2 per cent in construction costs. This relation is true for alternatives 4 and 6. The difference between the summed increase of the separate alternatives and alternatives 5 and 7 differ with 1 per cent. This difference is explained by the absence of spray plaster on the ceilings and a reduction in the amount of aerated concrete for the inner walls.

4.3.2. Operational costs

This subsection focuses on the operational costs. Table 42 of Appendix F displays an overview of the exact operational costs split into costs for inspections, maintenance, repairs, and cleaning, which are also displayed graphically in Figure 30. Be aware that the scale of Figure 32 is different from Figure 30. Important to note is the absence of inspection costs, which are not found within the operational budgets for project X.

As can be seen in Figure 32, alternative 6 displays the largest operational costs (+12%) whilst alternative 1A entails the lowest operational expenditures (-14%). Even though the costs for repairs are higher due to higher construction costs and the larger façade causes higher cleaning costs. The operational costs for alternative 1A are lower compared to the base alternative, which is caused by the maintenance costs, since due to the absence of spray plaster on the ceilings no replacements are necessary. Since no other changes are made and the structure does not require any maintenance or cleaning the resulting maintenance costs of alternative 1A and 1B are lower (-14% and -11%).

Alternatives 2A, 4, 6, and 7 contain a fully biobased façade, which impacts the operational costs negatively (resulting in operating costs of respectively 6%, -8%, 12%, and -2%). The maintenance costs related to the biobased façade are higher in comparison to other alternatives, which is caused by the replacement costs of the wooden window frames as well as the required painting cycles that are associated with wooden window frames. Although cleaning costs are not considered for wooden window frames (but are considered for PVC window frames), the paint cycle of wood requires a higher investment in operational expenditures. Additionally, the use of wood façade cladding creates higher maintenance and cleaning costs in comparison to a brickwork façade cladding. This is reflected in the 4% difference between alternative 2A and 2B. The positive impact of using a biobased structure (alternative 4 and 7) results in the lower operational costs, whilst also considering the negative impact of the biobased façade.

Figure 32: Overview of results LCCA phase B. Operational costs

The additional operational expenditures of a biobased space plan are limited to a 6 per cent increase caused by the higher maintenance costs for the wooden door sills, as well as the higher repair costs. The cleaning costs are only marginally larger for alternative 3.

Alternative 4 combines alternative 1A (biobased Structure) and 2A (biobased Skin), and results is a decrease of 8 per cent in operational costs. Compared to the base alternative the maintenance costs are lower due to the inclusion of a biobased structure, which eliminates the spray plaster ceilings. Although the biobased Skin has a negative impact, the resulting operational costs turn out lower. Alternative 5 (biobased Structure and Space Plan) displays lower maintenance costs, but higher repair and cleaning costs, ultimately resulting in a decrease of 8 per cent in operational expenditures. The alternative with the highest operational costs is alternative 6 (biobased Skin and Space Plan), due to higher maintenance and repair costs for wood building elements.

4.3.3. End of life costs

This subsection focuses on the end of life costs. Table 43 in Appendix F displays an overview of the exact operational costs split into costs for labour & equipment, transport, and value, which are also displayed graphically in Figure 33, note that the scale is different from Figure 30. Important to note is that it became apparent that the client of project X does not work with retake guarantees from producers. Moreover, reuse of products is not considered for Project X.

As can be seen in Figure 33, alternative 1B entails the highest end of life costs which are 13 per cent higher in comparison to the base alternative. The transport costs of alternative 1B are lower due to the lower weight of the building materials. However, the costs for labour & equipment nullifies these benefits. A similar principle holds for alternative 1A, but ultimately results in lower EOL costs due to lower labour & equipment costs.

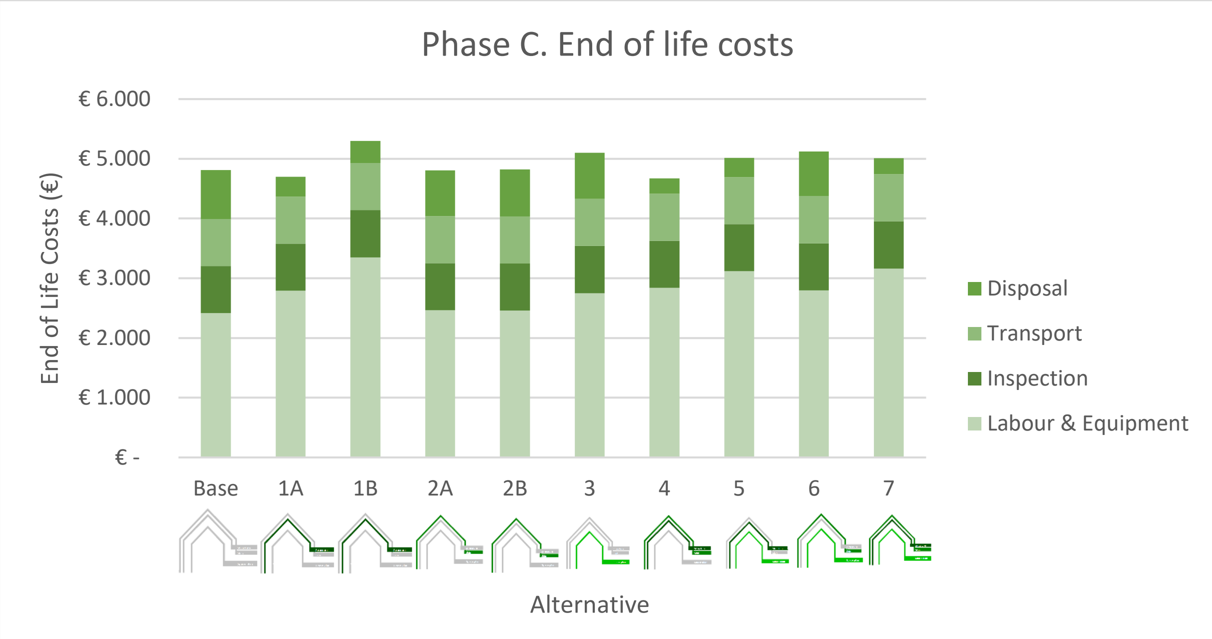


Figure 33: Overview of results LCCA phase C. End of life costs

The end of life costs for alternatives 2A and 2B show a small decrease (-1% and -2%) from the base alternative. The division of costs shifts more towards labour & equipment and entails slightly lower transport and disposal costs, which is caused by higher construction costs and lower weight of the materials. Alternative 3 displays the same phenomenon, but has higher labour & equipment costs and therefore shows a 3% increase compared to the base alternative.

While looking at alternatives 4 to 7 it can be seen that the transport costs are lower. Also alternative 6 without a biobased structure entails lower transport costs, but the higher weight of the traditional structure reduces the difference to ultimately an increase of 6 per cent in LCC. Furthermore, these alternatives all have significantly higher labour & equipment costs.

4.3.4. Points of attention LCCA

To interpret the results of the LCCA properly, some discussion on the analysis is required. This subsection elaborates on several points of discussion regarding the LCCA.

Weight of construction costs

The first discussion points relates to the assumptions made in the assessment framework based on the construction costs. For example the disassembly cost of building elements are calculated as a percentage of the initial construction costs for that element, as is also the case for repairs. Consequently, the construction costs not only influence the results of phase A, but also phase B and C. Although these assumptions are necessary to construct a LCCA it has a big impact on the end result of the LCCA, which is linked to the second point of discussion.

Distribution of life cycle costs

Second, the proportions of the costs for phase A, B and C are unevenly distributed. Taking a closer look at the distribution of costs over the life span of the apartment shows that on average 69% of the LCC is assigned to construction costs, whereas 26% and 5% respectively are assigned to the operational and End of Life costs. Therefore, the impact of the end of life costs is low, which is caused by that the fact that future costs are discounted. As was already explained in section 3.3.1. this is common practice to account for uncertainty. In practice however, this means that with a life span of 50 years, only 9 per cent of the total end of life costs are taken into account within the LCC, and thus also 9 per cent of the potential benefits are taken into account. Together with the first discussion point results in the conclusion that the influence of the construction costs is large. Consequently, the exact influence of the construction costs is further analysed in section 5.3.

Maintenance & Cleaning costs

Third, the costs for maintenance and cleaning is derived from the software Ibis Main 6.6. After consulting the maintenance manager of project X it became clear that these costs do not represent the direct costs for performing the maintenance activity. Instead these costs are used to reserve money for maintenance, consequently a price offer is retrieved from a contractor depending on the activity. However, the maintenance manager indicated that these prices do provide a proper basis to approximate what the costs for maintenance and cleaning will be. Nonetheless it was expressed that a fluctuation of roughly 20 per cent can occur. The effect of this uncertainty is further analysed in section 5.4.

Wooden façade cladding

The fourth point of discussion is related to the maintenance activities listed in the maintenance planning. Within the design alternatives, Platowood Fraké is used as wooden façade cladding. According to the maintenance planning, the cladding material is requires new paint every 7 years even though Platowood does not prescribe any maintenance activity apart from cleaning. The LCCA included the maintenance prescriptions of the manufacturer, since further analysis revealed that the wood is "platonised" and therefore differs from traditional wooden cladding material. As such, the impact of wooden façade cladding might not be reflected in case traditional wooden façade cladding is used. Figure 34 shows the results of this analysis.

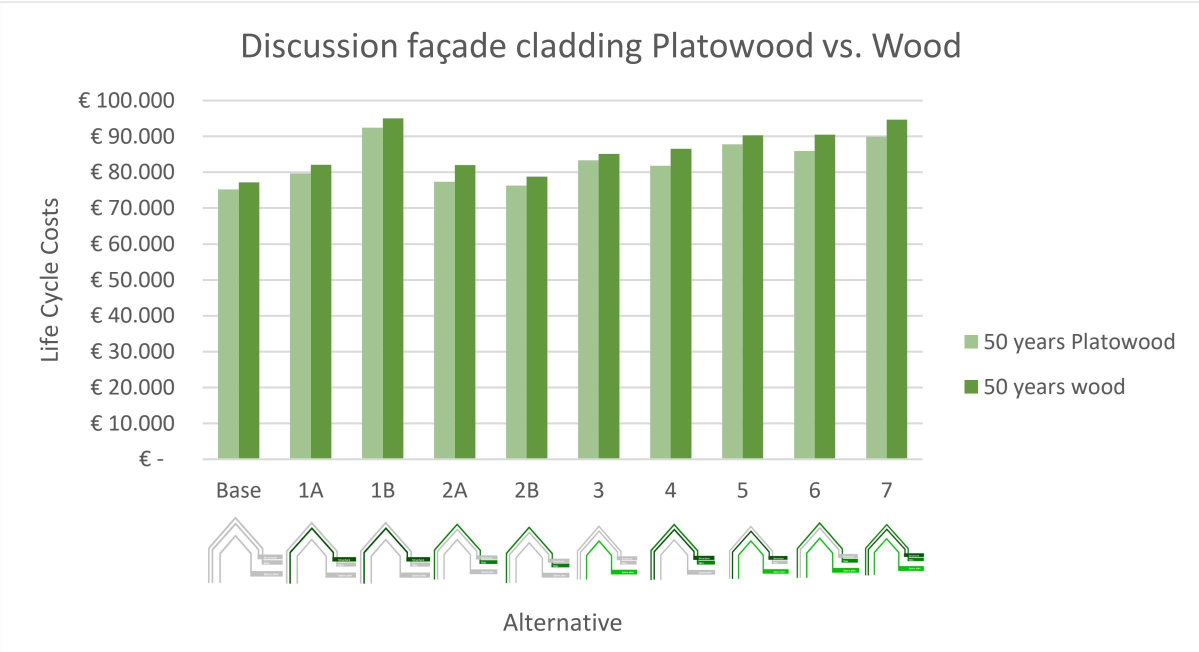


Figure 34: Results discussion façade cladding Platowood versus Wood

It is found that the life cycle costs of normal wooden façade cladding (dark green column) are higher in comparison to Platowood (light green column), due to the required maintenance activities. The traditional wooden façade cladding requires a new paint layer every 7 years, and a new paint system every 28 years, which negatively impacts the operational costs.

Life span
Another point of discussion is the considered life span of materials. In case of window frames this is 49 years, whilst the life span of the building is considered to be 50 years. This implies that the window frames are replaced in the last year before disassembly of the building, which seems unrealistic. Logically, one would not replace the window frames in the last year before disassembly.

4.3.5. Sub conclusion LCCA

All in all, it is concluded that biobased materials cause an increase in life cycle costs of up to 23 per cent. The biggest influential factor in the determination of the LCC are the construction costs, (69%) followed by respectively the operational expenditures (26%) and the end of life costs (5%).

Further analysis showed that a biobased structure using the module philosophy (alternative 1B) is the most costly in terms of life cycle costs, since it requires more material to ensure structural stability, maintain net apartment height and comply with the Building Decree. A biobased structure entails higher repair costs but does not require additional investments in maintenance, cleaning or inspections. Indirectly it causes lower maintenance costs, because the CLT ceiling remains in sight and therefore does not require spray plaster finishing. Within the end of life costs, the lower weight of a biobased structure causes lower transport costs. However, the high construction costs result in high disassembly costs, which nullifies the benefit of lower transport costs.

With regards to a biobased skin, it can be seen that the overall LCC rises with 2 to 3%, mainly caused by an increase in operational expenditures. The use of wooden instead of PVC window frames increases the construction costs slightly, whereas the construction costs for wooden façade cladding is similar to that of brickwork. However, the operational expenditures increase due to cleaning and replacement of the wooden façade cladding. Moreover, the wooden window frames require new paint layers every 7 years, which is translated into higher operational costs. The difference in end of life costs is small to none, as the transport and disposal costs are slightly lower but the labour & equipment costs are higher.

The overall LCC increase with approximately 11% when a biobased space plan is introduced in the apartment. This increase is mainly caused by higher construction and operational costs. It is found that the hempcrete blocks and wooden inner door sills require additional investments to construct and to maintain, but also to disassemble. Ultimately, this results in 3 per cent higher end of life costs.

In general, the effects on the LCC occurring in individual layers accumulate in the alternatives in which building layers combined. Apart from exceptions such as not finishing the ceiling with spray plaster and larger façade area when a biobased structure is applied.

It is concluded that a biobased structure has the biggest influence on the LCC with an increase of 6 to 23 per cent depending on the building philosophy, whilst a biobased skin and space plan respectively increase the LCC with 3 and 11 per cent. Combining these layers will result in accumulated differences, so combining a biobased structure (+6%) and skin (+3%) will cause a 9 per cent increase in LCC.

4.4. Relationship LoC and LCC

The previous subsections described the LoC and LCC of each alternative. This subsection further elaborates on the relationships between these results. A combined overview of the results can be found in Figure 35. It can be seen there is a large difference between the magnitude of the construction, operational and end of life costs. This is partly caused by the fact future costs are discounted, but also partly because these costs are lower.

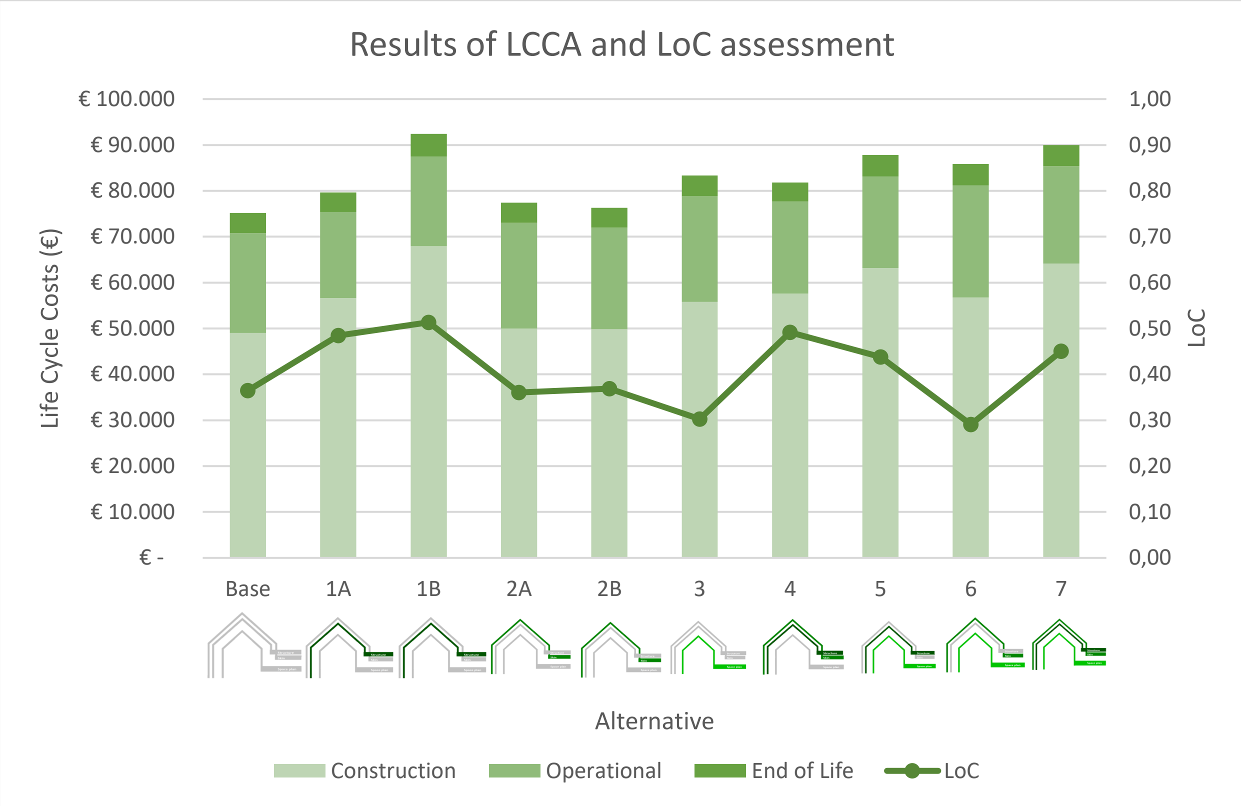


Figure 35: Overview of results LoC and LCCA per alternative

To properly assess the relationship between the LoC and LCC, the alternatives are ranked in terms of LoC. Figure 36 provides an overview of the ranked alternatives including the corresponding LoC and LCC, where from left (highest LoC) to right (lowest LoC) the LoC decreases.

In Figure 36 it can be seen that alternative 1B has the highest LoC (0.51) and LCC, whilst alternative 4 and 1A have a LoC and LCC that is lower, which is caused by the additional materials used in alternative 1B. Relatively, the biobased structure of alternative 1B contains more wood in comparison to the biobased structure of alternative 1A, since the modules of alternative 1B result in double walls and ceilings. However, the additional materials also entail higher LCC (+17%).

Alternative 4 combines a biobased structure with a biobased skin and results in both a higher LoC (+0,01) and LCC (+3%) compared to alternative 1A. Since alternative 4 includes the circular benefits of a biobased skin, as well as the increase in LCC. Whilst, this is not the case for alternative 1A.

Alternative 1B, 4, and 1A score better in terms of circularity compared to alternative 7 (respectively +0.06, +0.04, and +0.03), since these scores are not reduced by the influence of the space plan. Interesting to see are the lower increase in LCC of both alternatives 4 and 1A (respectively +9% and +6%), primarily caused by lower construction costs. The higher construction costs of alternative 1B predominantly lead to the highest LCC (+23%) of all alternatives.

Alternative 5 (biobased Structure and Space Plan) and 7 (fully biobased) display a higher LoC (respectively +0.08 and +0.09) than the base alternative, but are accompanied by a rise in LCC as well (respectively +17% and +20%). The increase in LoC is caused by the inclusion of a biobased structure, but as was already mentioned in section 4.2.4 is reduced by the inclusion of a biobased Space Plan.

Alternative 7 has a slightly higher LoC due to the inclusion of a biobased skin, but the influence on LoC is minimal as are the additional LCC.

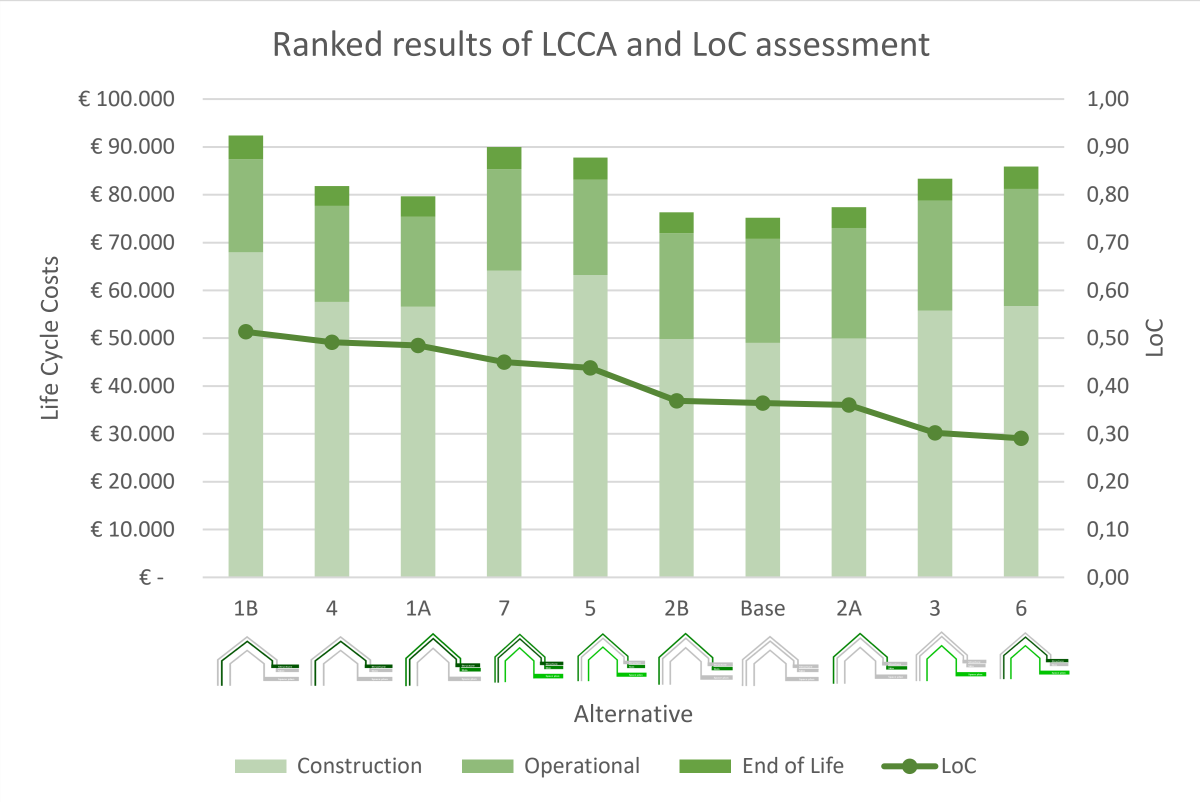


Figure 36: Overview of results LoC and LCCA ranked on LoC per alternative

Looking further at Figure 36 shows that alternative 2A has an LoC equal to the base alternative, but involves higher LCC (+3%). Alternative 2B (biobased Skin) entails a higher LoC (+0.01) than the base alternative and alternative 2A, despite the fact that a brickwork façade cladding is used, but also entails higher LCC (+2%).

Ultimately, it can be seen that the base alternative has a higher LoC (+0.06 and +0.07) but lower LCC (-11% and -14%) in comparison to alternative 3 (biobased Space Plan) and 6 (biobased Skin and Space Plan). It can be concluded that introducing a biobased space plan is a more costly and ineffective measure to increase the LoC of an apartment, despite the fact of also introducing a biobased skin.

5. Sensitivity analysis

As was mentioned in section 3.2.2, the performed analysis is prone to mistakes due to various uncertainties. A sensitivity analysis is performed to better understand the results and what the influence is of these uncertainties. The following subsection elaborate on the various points of analysis.

5.1. Life span

Another uncertainty that influences the results is the life span of the building. This has effect on the NPV and LoC of the building. These values are affected by the life span, since additional maintenance activities and thus new materials have to be used result in differences in costs and circular performance. It was assumed that a building has a life span of 50 years, but due to unforeseen circumstances this life span can be decreased or extended. Therefore, the sensitivity analysis assesses the relationship of LCC and LoC over life spans of 40, 60, 70, and 80 years as well. Because the life span of buildings is increasing (Vlaanderen Circulair, 2023), the sensitivity analysis focuses more on longer rather than shorter life spans.

5.1.1. LoC

First, the effect on the LoC of the apartment is discussed. Figure 37 shows the LoC for each alternative over various life spans. Important to note is that the scale is adjusted to better display the differences between alternatives better. It can be seen that the LoC for all alternatives reduces when the life span increases.

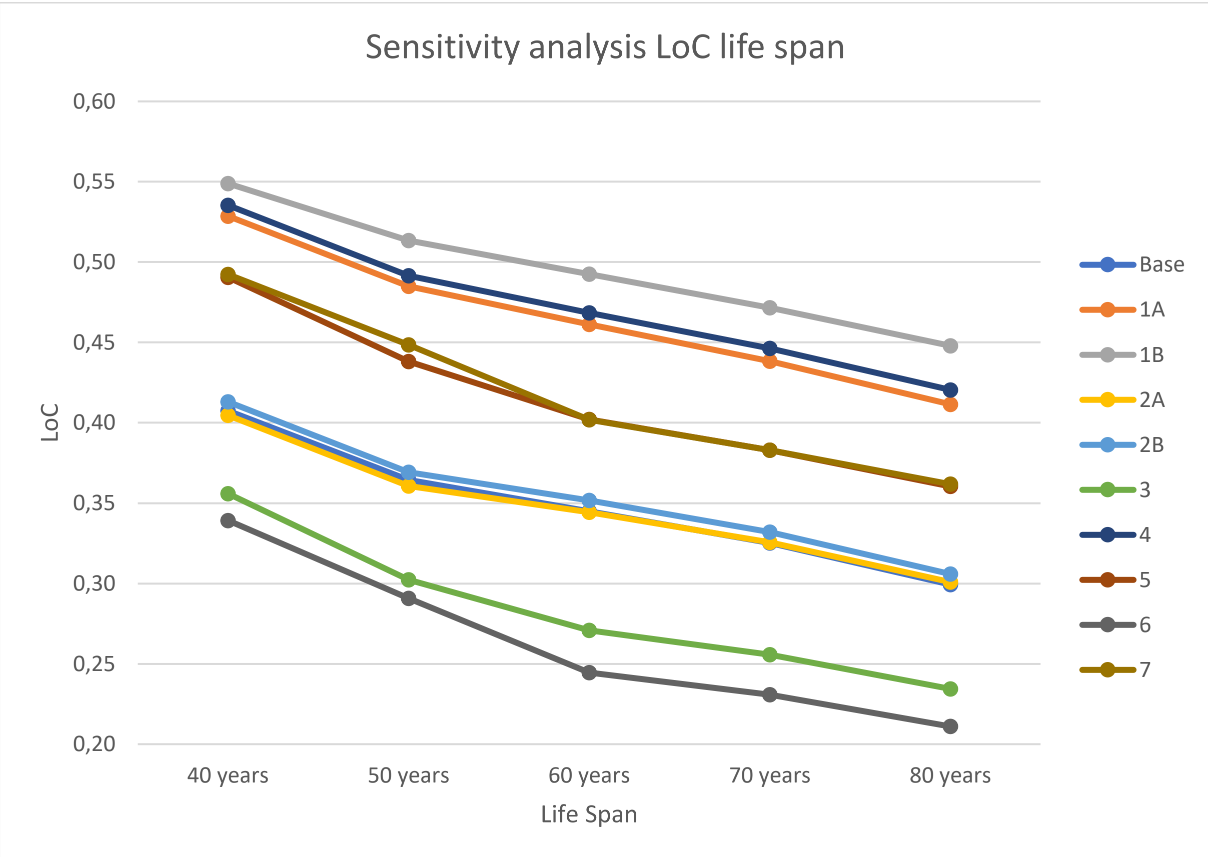


Figure 37: Results sensitivity analysis life span

Important to note is the fact that the results of the LoC lie very closely together with differences of 0.1 in LoC occurring very regularly. Since there is no other clear relationship to be distinguished between alternatives, it is concluded that in general the LoC of buildings lowers over longer life spans due to the additional use of materials incorporated in the calculation of the utility factor. The differences in ranking between the alternatives are likely due to rounding of the scores, which coming to the surface when longer life spans are applied as the effect of these rounding errors is strengthened.

5.1.2. LCC

Figure 38 displays the results of different life spans on the LCC for all alternatives. The Figure shows that a longer life span entails a larger LCC for each alternative. The lowest LCC (on average -6% compared to 50 years) is regarded at a life span of 40 years, which is caused by the lower maintenance costs. A large fraction of building elements that require maintenance have a replacement cycle of 49 years, which means these replacement costs are not included when a life span of 40 years is considered. Additionally, this also means that the difference between the LCC when longer life spans are considered, is only induced by the cleaning costs, as the next replacement cycle ends in year 98. Important to note is the fact that costs are discounted to their present value, the influence of future replacement and cleaning cost is lower. Consequently, the LCC for longer life spans differs on average with 0.2%.

Ultimately, it is concluded that a different life span has limited influence on the LCC, especially when longer life replacement cycles are present.

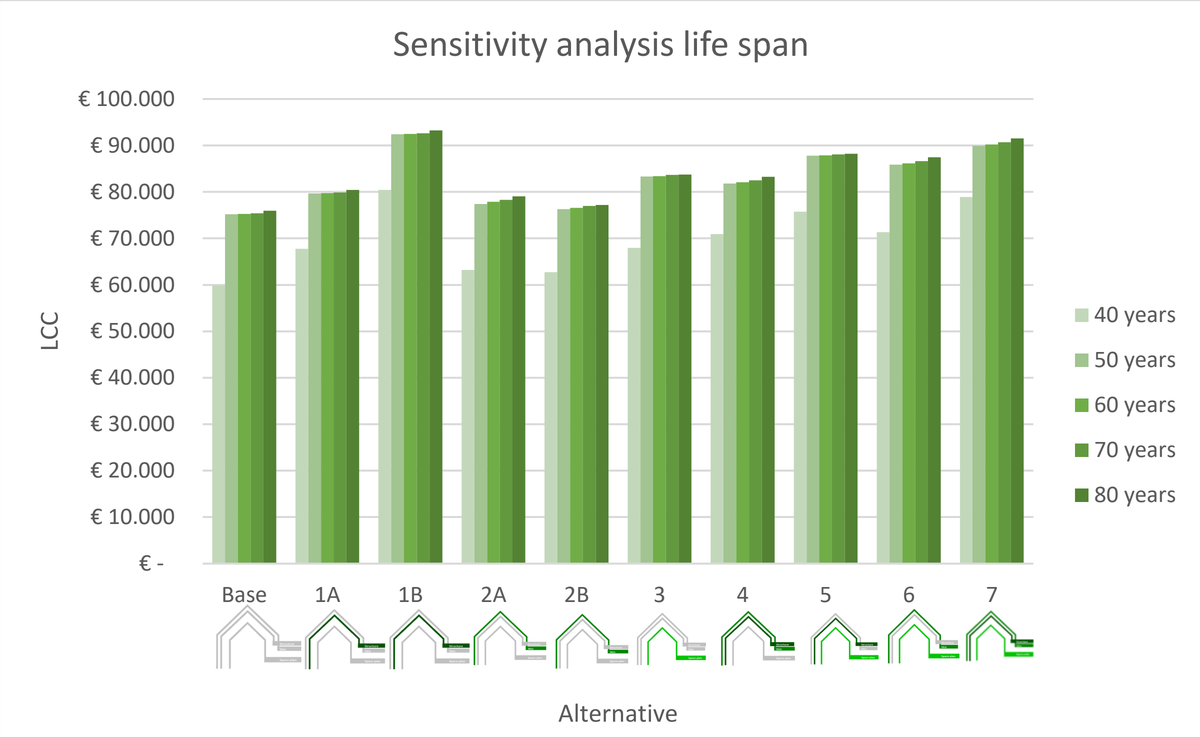


Figure 38: Results sensitivity analysis life span LCC

5.2. Discount rate

The discount rate is one of the uncertainties when costs are discounted. Therefore, the sensitivity of the discount rate is also assessed in this analysis. The government set the real discount rate at 2,25 per cent, but also indicated a lower and upper bound. These bounds will be used to conduct the sensitivity analysis. It was determined that the lower bound of the discount rate is 1,85% and the upper bound is set at 2,65% (Werkgroep discontovoet 2020, 2020). Figure 39 displays the results of this analysis.

Figure 39 shows that the sensitivity of the LCC to a varying discount rate is 2%. As is expected a higher discount rate entails lower LCC and vice versa, which is also displayed in Figure 39. It is concluded that the sensitivity of the results caused by a varying discount rate is non-existent.

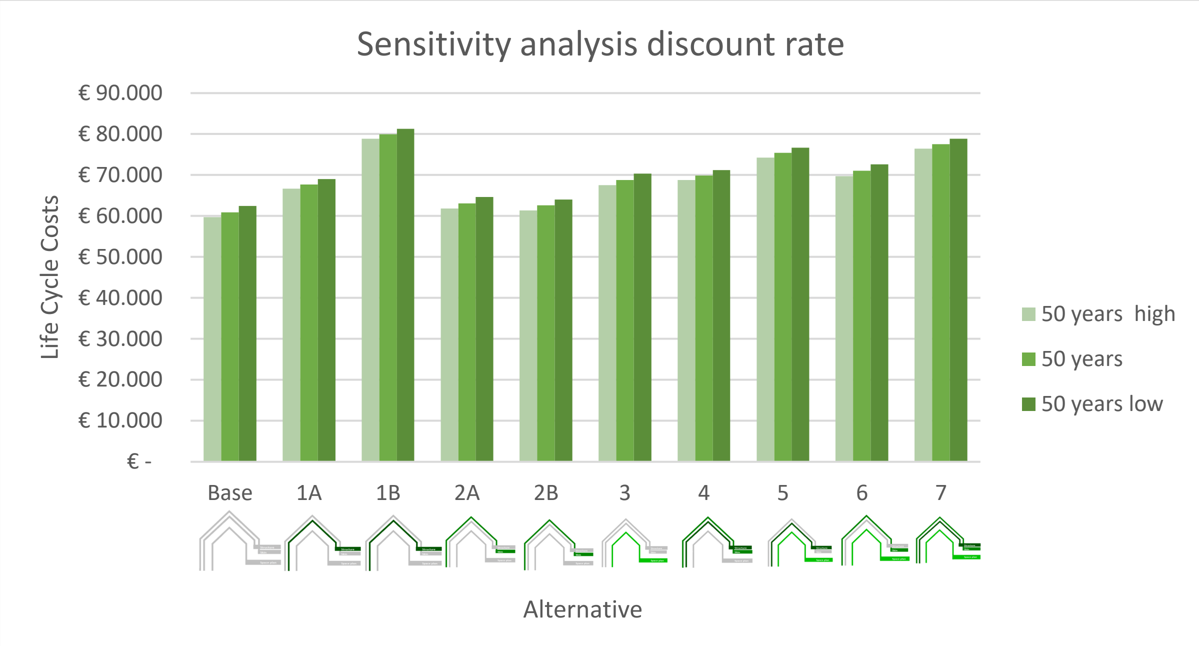


Figure 39: Results sensitivity analysis discount rate

5.3. Construction costs

As was discussed in section 4.3.4 the weight of the construction costs in the LCCA is high. Therefore, it is opted to execute an additional sensitivity analysis to assess the sensitivity of the results to 10% differences in construction costs (-10% and +10%). The results are shown in Figure 40, it can be seen that the overall behaviour of the LCC is in line with expectations, i.e. the LCC in- or decreases with the construction costs.

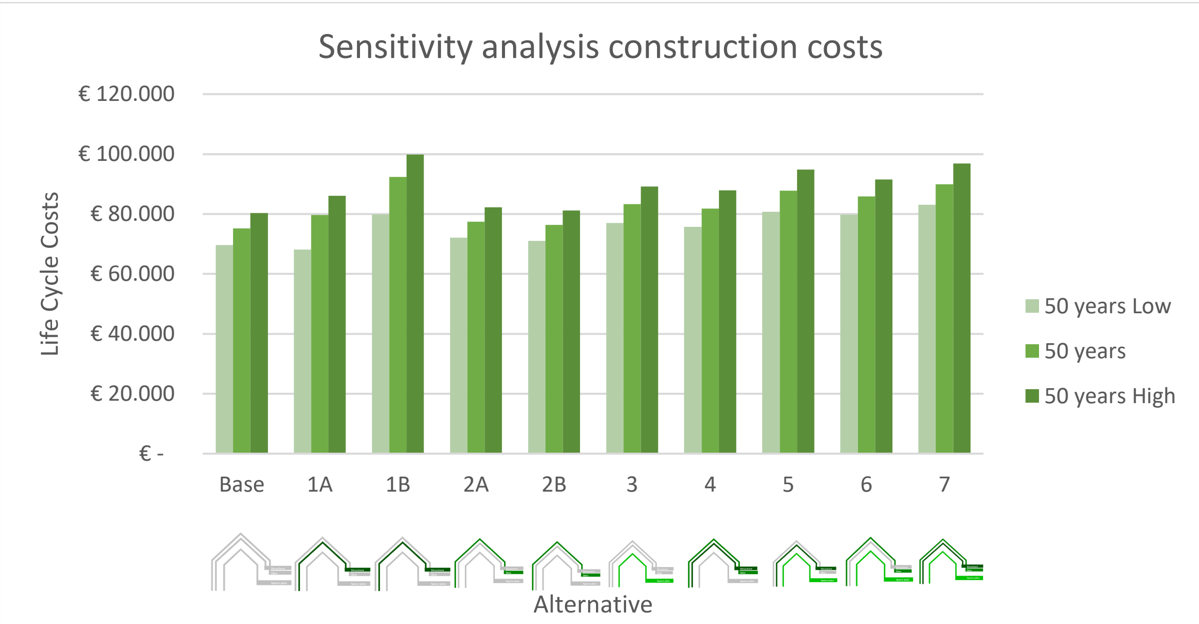


Figure 40: Results sensitivity analysis construction costs

On average the LCC differs between -9% and +7% when the construction costs differ with -10% and +10%. As expected, the construction costs are most influenced by the construction costs with on average -11% and +9%. However, the operational costs and End of Life costs also differ with -3% to +2% and -7% to +6% respectively. Also bearing in mind that part of the End of Life costs based on the construction costs are discounted, this analysis shows that these costs are highly dependent on the construction costs.

Further analysis showed that for alternatives 1A and 1B (biobased Structure) display LCC alterations of -14% to +8%. The relatively high decrease for these alternatives is also traced back to the high influence of the construction costs on the operational and End of Life costs.

Ultimately, it is concluded that the results of this research do not alter if construction costs de- or increase, but it is important to note the high influence of the construction costs on the LCC when conducting further research. Consequently, assumptions not only based on the construction costs would results in a smaller correlation between the operational and End of Life costs with the construction costs.

5.4. Maintenance & Cleaning costs

One of the discussion points of the LCCA considers the uncertainty of the maintenance & cleaning costs. These costs can fluctuate approximately up to 20 per cent according to the maintenance department that maintains project X. Therefore the fluctuation of maintenance costs is included in the sensitivity analysis, of which the results are shown in Figure 41.

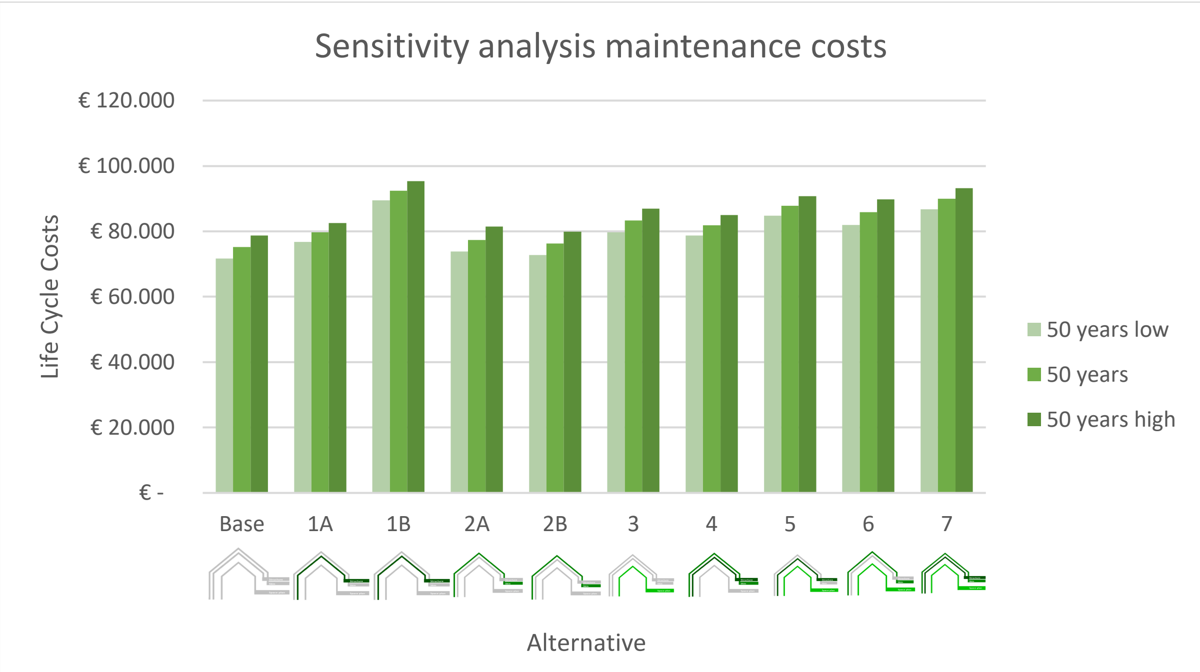


Figure 41: Results sensitivity analysis maintenance costs

Figure 41 displays the LCC fluctuates up to 4% if the maintenance costs fluctuate change 20%. The relative low influence of maintenance costs is explained through the composition of operational costs, the present value of future costs, and the costs of a biobased structure. First, the operational costs are not solely defined by the maintenance & cleaning costs, since repairs are also taken into account. Second, the operational costs are discounted, which reduces the monetary value considered in the LCC and thus the effect. Finally, similar behaviour to the effect of the inflation rate is noted, hence the higher construction costs of a biobased structure reduces the influence of the maintenance costs on the LCC.

5.5. End of Life costs

In addition to the construction and operating costs, it is important to conduct a sensitivity analysis for the EOL costs, as this provides insight into the effects of price differences over 50 years. Therefore, a sensitivity analysis is performed for -10% and +10% in EOL costs. Figure 42 provides the results of this analysis.

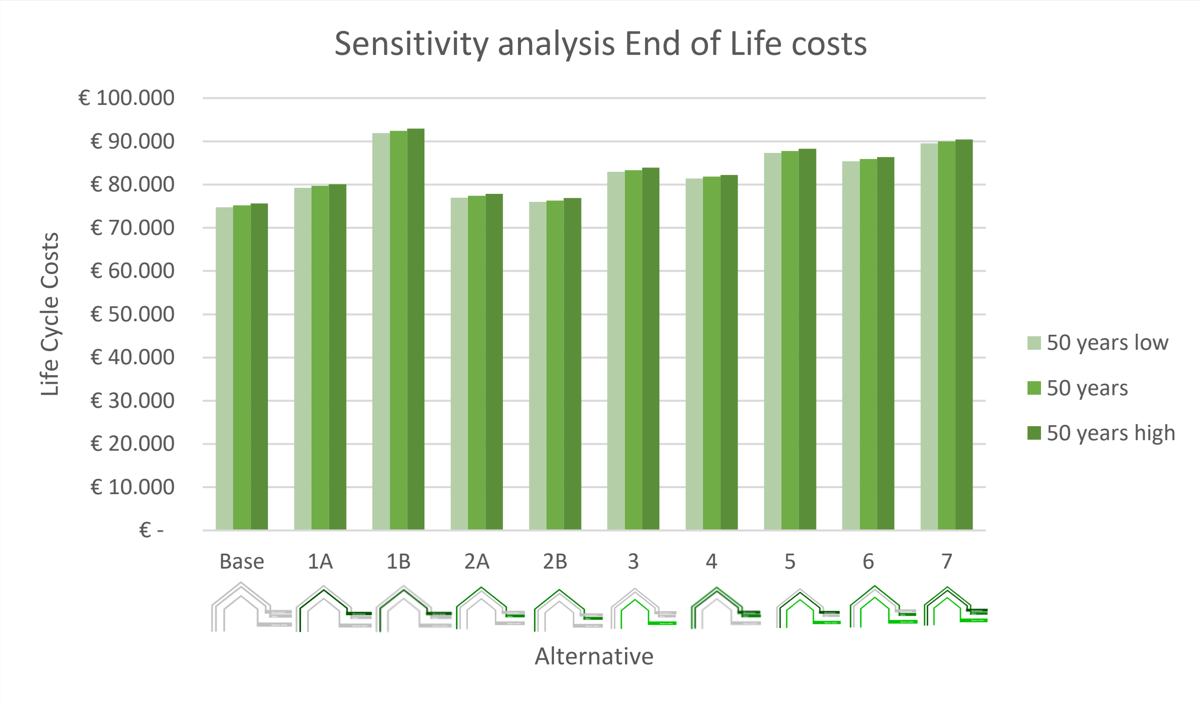


Figure 42: Results sensitivity analysis End of Life costs

On average the LCC fluctuates with 1% when the EOL costs fluctuate with 10%. Since these costs are numerically lower in comparison to the costs in for construction and operation, and these costs are discounted results in the limited influence of the EOL fluctuations. Consequently, it can be concluded that the sensitivity of the results to fluctuations in the EOL costs are negligible.

6. Discussion

Ultimately, this research analysed how the relationship between the Life Cycle Costs and Level of Circularity of newly constructed apartments is affected by the use of only biobased construction materials.

This research demonstrates that the use of biobased materials entails both an increase in LoC and LCC based on the different design alternatives constructed with biobased materials for a single apartment in the case study project (project X). It is shown that the application of biobased materials in the Structure building layer has the most effect on the LoC. As the amount of biobased material used in the Structure is relatively high in comparison to other building layers, this causes a large increase in LoC between +33% and +41% depending on the building philosophy.

Furthermore, it became evident that the application of a biobased structure is the most cost-effective measure to increase the level of circularity of apartments, as the LoC increases with 33% and the LCC increase with 6%. Consequently, this means that an 1% increase in costs returns a 5,5% increase in LoC. Constructing both the Structure and Skin of the apartment from biobased construction materials results in a higher LoC (+35%), but in a lower ratio between LCC and LoC, namely a 4% increase in LoC per 1% increase in LCC. This difference is mainly caused by the additional operational costs for maintenance of wooden window frames and façade cladding of a biobased Skin.

Additionally, this research showed that a biobased Space Plan has a negative effect on both the LCC (+11%) and LoC (-17%) resulting in a ratio of -1,6% in LoC per every 1% increase in LCC. This is caused by the lower technical life span of the hempcrete inner walls, combined with the LFI of the wooden inner sills and front door as these result in a lower MCI.

Generally, this research has shown that the use of biobased materials increases the costs of apartment during its life cycle and returns a higher level of circularity. Depending on the location of the biobased materials in the building, the ratio between the increase in LCC and increase in LoC differs. These findings suggest that it is unprofitable to use biobased materials solely focusing on the monetary aspects. However, the externalities of a higher LoC score are not monetized. Furthermore, the current price levels are expected to drop when further developments are made in the territory of biobased materials.

Additionally, this research identified additional developments are required in terms of measuring circularity in general. The scarce amount of data currently implemented in the databases proves to be unrealistic in some instances, which clouds the assessment of circularity. An example is the contradictory result that the application of biobased materials within the Space Plan shows a negative effect. Further analysis showed that unrealistic values for the technical lifespan or waste fractions were considered.

6.1. Contributions

This research contributes to literature by addressing the economic dimension of circular construction, which was defined as a research gap in Section 1.1.1. More specifically, this research investigates the circular business models by assessing the costs over the life cycle of an apartment including the long-term benefits that occur at the end of the life cycle. Assessing the LCC is the first step into Whole Life Costing, where externalities are also quantified and taken into account. In addition, the scientific contribution is displayed by recommendations for further research from other research. Firstly, Braakman et al. (2021) researched the relationship between the level of circularity and the life cycle costs of a one-family house. Ultimately, one of their limitations and thus recommendations for future research was the single case used as validation. Therefore, Braakman et al. (2021) recommend to research the relationship further by means of assessing other comparable cases. Furthermore, Already, research is executed into the differences in LCC between traditional and circular buildings by Draaijer (2020). However, it was recommended to assess circularity in a quantified way, which is in line with the quantitative approach of this research.

Although there is a scarce amount of literature that focuses on the economic dimension of circular construction. The research's findings contradict with the literature that currently exists, since the LCC increases when more biobased materials are used. According to Rudraraju (2020), the use of biobased materials results in lower LCC due to lower operational and EOL costs combined with comparable construction costs. However, this research showed that there is an increase in LCC when biobased materials used, since a significant increase of construction costs can be seen when using biobased materials. Furthermore, the maintenance costs for an apartment that contains more biobased materials in the Skin are higher due to the additional painting cycles from wood.

In addition to the economic dimension, this research explored the use of biobased construction materials. Previous research from Többen & Opdenakker (2022) mention that additional research is required into the investment related to the application of a circular strategy in construction projects, in this case 'design with renewable materials'. Previous research has assessed the LCC of various biobased components, such as biobased multilayer panels and insulation materials. Also, the relation between the MCI and LCC of an office building is assessed when biobased materials are used by Rudraraju (2020). Moreover, a comparison has been made between a biobased house and a concrete house in terms of LCC and LoC by Krasny et al. (2017). This research on the other hand addressed the LoC and LCC of an apartment made from biobased materials, which is an object that was not yet investigated.

Additionally, this research focused on the assessment of circularity and gained insights that are important for further development of these assessment methods. It became apparent that the underlying data used to assess circularity in project is very important for the reliability of the results. Currently, unrealistic values are assigned for the scarce amount of biobased materials present in the NMD or BCI database. Pinpointing these discrepancies aids further development of these methods, and also provides other assessors with points to be aware of when using these assessment methods.

Also, biobased materials are relatively new to the construction industry and therefore lots of uncertainties regarding the use of biobased construction materials exist. This research has identified the most commonly used biobased materials within the industry and created various design alternatives with these materials. The effects of specifically biobased materials on the relation between LCC and LoC was unexplored as well.

In addition, to the above-mentioned scientific contributions, this research also has practical contributions. First of all, the gained insights into the effects of biobased materials on both the LoC and LCC help project managers at Sweco better advise clients. When project managers are able to advise clients on the most cost-efficient measures to increase the LoC of their apartment buildings, this creates an advantage over other engineering and consultancy firms. Also, the information regarding biobased materials in this research creates a wider awareness amongst the project managers, which can help to use more biobased materials in the construction industry.

The latter contribution is also focused on the societal contributions of this research. As the goal is to have a fully circular economy in 2050. This research shows the circular potential when using biobased materials. Consequently, this research can stimulate the construction industry to utilise biobased materials by showing their potential in terms of LCC and LoC. Ultimately, an uptake in the use of biobased construction can aid the transition to a circular construction industry.

6.2. Research limitations

The above-mentioned differences can potentially be explained by some limitations of this research. These limitations are discussed in the following paragraphs.

6.2.1. Assumptions

One of the assumptions in this research is to exclude the Services from the scope of this research, since these do not have a biobased alternative and costs are dependent on the end-user. This exclusion has a significant impact on the operational costs and thus the LCC. It is important to note that the operational costs related to the Services can account for 52% of the total operational costs (Kaming, 2017). Also, the impact on construction costs is significant (Centrum Hout, 2021). However, little is known about the impact on the required installations related to biobased construction. All in all, it is important to note that the Services costs are not included within this research.

Additionally, this research uses data for standard products from the BCI Gebouw database, which does not specifically take reuse or recycle into account. The data for the end of life or waste scenario is based on LCA data. However, these standard products usually contain a linear end of life scenario, which negatively impacts the LoC of the apartment. The BCI database contains products that specifically focus on reuse or recycling of that product in the future, but due to the assumption to use standard products in this research unless the project data indicated otherwise. These products are neglected, since the project data did not specifically indicated reuse or recycle waste scenario in the future. Although, the effects on the LoC were assessed in the sensitivity analysis, this analysis was limited to the LoC and rather simplistic.

6.2.2. Data collection & use

The data collection for this research proved to be very hard and ultimately resulted in a single case study. Especially the gathering of appropriate financial data for this research was hard, because of a reluctance to share this information in 'public'. To illustrate 19 project representatives were contacted for this research, which resulted in ultimately 1 usable case, which lead to a single-case study research.

The fact this research deals with a rather new concept in the industry makes it even harder to retrieve usable financial data, since contractors want to keep their cards close to their chest. Several times it was reasoned that competitors could also review the financial data despite the fact the data handled confidentially and not be published. Furthermore, the price-competitiveness within the industry combined with the fact that every contractor is experimenting with timber construction results in a reluctance to share financial data, since no contractor happily hands over their trump card.

Ultimately, this research turned into a single-case study rather than a multiple-case study research, which allows for a deeper analysis of the single case, but reduces the wider scientific view that might be desired. Even though Flyvbjerg (2006) discussed that a single-case study is scientifically relevant, additional cases allowed to generate a wider perspective, which further increased the scientific value of the results.

In addition, it became apparent during execution of this research that the circularity assessments of buildings requires further development, especially with regards to the EPDs in the underlying database used in these assessments. The introduction of the new EN15804+A2 that entails the execution of new LCA's for all products, combined with the innovativeness of biobased materials means there is a scarce amount of high-quality and certified data of biobased products present in databases. Ultimately, the circularity assessments of buildings that contain these type of materials is hampered and requires a further development of the underlying database.

6.2.3. Externalities

This research solely focuses on the direct (construction and end of life) and indirect (operational) costs of the building elements in the scope. Consequently, the added benefits of using biobased materials, such as faster construction, lighter equipment, fewer workers and the inclusion of lighter foundation due to the lower weight are not considered in this research (Centrum Hout, 2021; Smith et al., 2018; Thomas & Ding, 2018). For example the reduction in construction time is roughly 20 per cent compared to a traditional construction (Centrum Hout, 2021; Forestry Innovation Investment & Binational Softwood Lumber Council, 2014; Thomas & Ding, 2018).

The exclusion of these factors is caused by the scope that only focuses on a single apartment, because it was impossible to develop the design alternatives within the set time frame of this research. Also, the lack of data played a role, since the transition from a concrete to a wood structure is not feasible for every apartment building. Therefore, it was attempted to gather different projects that could be regarded as design alternative on itself. However, as was just discussed, only 1 usable project could be included within this research, despite the fact that data from 5 projects was retrieved. The four other projects are excluded from the scope, because these building were designed in such a way that transitioning to a wood structure was infeasible.

Concluding, it is important to note these benefits are excluded from this research and might reduce the additional costs of using a wood structure. It is hard to determine the exact reduction that is possible, since this is dependent on the size of the building, the contractor, and the way in which the building is designed.

Also, the externalities arising from the use of biobased materials are not considered within this research, such as in improved indoor climate, the carbon sequestration of biobased materials or local production of biobased materials (Arcadis, 2022; Karjalainen & Ilgın, 2022; Quist, 2021b). The quantification of these externalities requires a separate research, which means it is impossible to properly assess and include the effects of these externalities within this research.

Lastly, the externalities around a (domestic) biobased industry are not considered as well. Although biobased materials can have an important role within the construction industry in the future, there are still doubts regarding the feasibility and effects of a large (domestic) biobased industry. To properly implement biobased construction, the availability of biobased materials is of the essence (TNO, n.d.-c). Due to the increased demand and interest of various types of biobased materials, the allocation of local production might prove to be difficult (Göswein et al., 2021; Quist, 2021b; Studio Marco Vermeulen, 2020b). Furthermore, the environmental impact of increased cultivation within the Netherlands might result in negative externalities (Quist, 2021b).

7. Conclusion

This chapter answers the research questions stated within section 1.7 and concludes on the main research question. Additionally, this chapter elaborates on the recommendations for further research in section 7.3.

7.1. Research questions

"What is the theoretical relationship between the LCC and LoC of apartments using biobased construction materials?"

According to the literature review the LCC can be lowered when constructing with biobased materials, due to lower maintenance costs and similar construction prices. In addition, the construction prices could decrease due to industrialisation and optimalisation of the biobased industry, resulting in lower production prices. Furthermore, research showed that the use of biobased materials entails an increase of LoC. However, quantifying the impact of biobased materials is difficult due to the scarce amount of literature and the differences in assumptions and methods used within these research.

All in all, the relationship between LCC and LoC based on literature shows that an increasing LoC also entails a lower LCC when using biobased construction materials.

"Which biobased construction materials are currently used within the construction industry in the Netherlands?"

Wood is the most commonly used biobased product in the construction industry. This material can be used within the Structure, Skin, and Space Plan, but requires special attention when applied in the structure of a building in terms of fire resistance and sound insulation. Furthermore, flax is commonly used as biobased insulation material within buildings and has similar insulating properties as traditional insulation materials such as glass or stone wool, but lower environmental costs. Hemp can also be used as insulation material, but can also be used to construct hempcrete blocks which are used for inner walls or cavity leafs.

Important to note is that not all materials have a biobased alternative, such as glass or plasterboard. Moreover, it is not desirable for every building element to be replaced by a biobased alternative, such as the ground floor or foundation of a building due to the potential to rot when ground water levels fluctuate.

"What is the impact of applying biobased materials in one layer of the building based on the layers of Brand in terms of life cycle costs and level of circularity?"

The Structure layer of an apartment has the most influence on both the LoC and LCC. The LoC increases with 33% to 47% depending on the EOL scenario considered for wood, whilst the LCC increases with 11% for a building that implements a biobased structure. The DI for a biobased structure is much higher compared to a traditional structure. Furthermore, the wooden elements are more expensive compared to the traditional materials used. Also, additional material is required to comply with the Building Decree regarding fire resistance and acoustic performance, which further increases the construction costs.

The Skin building layer shows limited to no influence on the LoC (0% to +3% when recycle scenario for wood is considered) and LCC (+4%) of the apartment. Depending on the EOL scenario of wood the LoC displays an increase from 0% to 3%. It became apparent that the use of façade elements limits the influence of biobased insulation material, due to the inclusion of plasterboards. These plasterboards have a low utility factor and high LFI. Also, not every element has a biobased alternative to replace it with. Finally, the use of wooden façade cladding entails a lower MCI, due to a lower technical life span and the large fraction of the wooden façade cladding that has an incineration waste scenario. The LCC increases with 4% when biobased materials are used. This difference is caused by the increased maintenance costs for the wooden window frames and façade cladding, which requires a new paint layer every 7 years.

Finally, the Space Plan of the apartment shows a negative influence on both the LoC (-17%) and LCC (+13%). The negative influence on the LoC is caused by a short technical life span and incineration waste scenario for hempcrete blocks. Additionally, the wooden door sills and doors have a lower MCI due to their LFI and ECI values, as well as the wood incineration waste scenario. The increase in LCC is caused by the higher construction price of hempcrete blocks and the wooden door sills.

"How do the life cycle costs of apartments (partly) constructed of biobased materials vary with the level of circularity?"

The combination of a biobased structure and skin (alternative 4) displays an increase in LoC of 36% and an increase in LCC of 9%. The absence of spray plaster on the ceilings when a biobased structure is applied results in a strengthening effect on the LoC and LCC. The same phenomenon occurs when combining a biobased structure and space plan (alternative 5), which displays an increase of 22% in LoC and 17% in LCC. However, the combination of a biobased skin and space plan (alternative 6) does not benefit from this effect and displays a decrease of 19% in LoC and 14% increase in LCC. Ultimately, the fully biobased design (alternative 7) shows an increase of 25% in LoC with a 20% increase in LCC.

Generally, the LCC increases when the LoC increases for apartments constructed with biobased materials. Except when the Space Plan is constructed from biobased materials, since there is a negative effect on both the LoC (-19%) and LCC (+14%).

7.2. Main research question

"How does the use of biobased construction materials within newly constructed apartments affect the relationship between the life cycle costs and level of circularity?"

In general both the LoC and LCC increase when more biobased materials are used. Biobased materials entail higher costs in all life cycle stages. This is caused by a combination of a higher price of biobased materials, the additional maintenance that is required and the higher labour & equipment costs when disassembling the biobased building elements. Additional benefits such as faster construction time and lighter equipment are currently not taken into account and will likely reduce the construction costs. Moreover, the exclusion of Services in this research results in lower operational costs. Biobased materials also increase the LoC, since a higher biobased fraction results in a higher MCI. Furthermore, the structural elements constructed from biobased materials are easier to disassemble and therefore score higher on the DI. The effects in LoC could become larger when a more realistic waste scenario is considered for biobased materials, i.e. wood.

Ultimately, it can be seen that a biobased structure has the biggest influence on both the LCC and LoC. The design constructed with a biobased structure from wooden modules results in the largest increase of both LCC (+23%) and LoC (+0.15 or 42%). Alternatives that contain a biobased structure from wooden elements display increases in LCC between 6 and 20% and increase in LoC between 22 and 36%. The most cost-effective alternatives are 1A (biobased Structure) and 4 (biobased Structure and

Skin), as these entail respectively an increase in LCC of 6% and 9%, while the LoC increases with respectively 33% and 36%.

All in all, it is concluded that the relation between Life Cycle Costs and Level of Circularity is influenced positively as well as negatively by the use of biobased materials. The most cost-efficient use of biobased materials entails an increase of 6% in Life Cycle Costs, but also displays a significant increase in Level of Circularity of 33%. It is expected the increase in LCC will become lower as time passes. As developments within the construction and biobased industry will likely result in lower prices. Moreover, the additional benefits of constructing with timber are not assessed within this research, which also increases the positive influence of the use of biobased materials. Furthermore, the LCC is constructed partly based on assumptions, which means the results can differ from reality. From the conducted sensitivity analysis it was concluded that these effects are limited.

7.3. Recommendations for further research

Some recommendations for further research have emerged during the execution and discussion of this research, which are discussed in the following paragraphs.

First, it was established that some important aspects such as the effects of installations, the additional benefits of constructing with timber and potentially the externalities of constructing with biobased materials are excluded. Whereas, these aspects have an influence on both the LCC and LoC of the apartment. Enlarging the scope of future research to include these aspects results in a better representation of the true value of the use of biobased materials. Therefore, it is important to broaden the scope to includes these aspects in further research.

Second, the reuse of (biobased) construction materials was discussed. A small analysis showed that a significant improvement can be regarded when building elements are to be reused in the future. However, problems arise regarding quality, guarantees, compliance with the Building Decree, which shows the urgency for further research. Moreover, appraisal of reused construction materials are highly dependent on the quality, deterioration of the product, as well as the development within the construction industry as big innovations might result in products becoming obsolete.

Third, it was discussed this research is based on a single-case. Although, all assumptions made in the assessment framework are underpinned, there are still uncertainties regarding the price of (biobased) construction materials. The current market prices retrieved from a construction costing agency are based on references, which are likely to also contain certain risk reservations. In addition, the design alternatives change when another case is considered, which influences the materialisation and quantities used for the design. The inclusion of different situations and design alternatives allows for better generalization of the results and conclusions. Therefore, it is important to include multiple cases in future research.

Fourth, the performance of the currently available circularity assessment methods was discussed. Especially, the LCA data that is underlying to the data gathered in the database is important for a further development of circularity assessment methods. The waste scenario for wood for example is considered to be incineration, while recycling is also technically feasible and is already done in the United Kingdom. Also, the technical life span for several products has proved to be unrealistic. The same holds for the DI scores for some products in the BCI database. Also, the transition to the new legislation (EN15804+A2) regarding the execution of LCAs is still in progress. This new way of conducting LCAs also incorporates carbon sequestration of biobased products, which is currently not taken into account. These are all examples progress is still to be made with regards to circularity assessment methods. Therefore, it is recommended to perform future research into these methods.

Lastly, the feasibility of a (domestic) biobased industry was discussed. It became apparent that biobased materials are relatively expensive, due to the lack of industrialisation and novelty of the biobased industry. The upscale of the biobased industry can help to reduce the barriers of using biobased materials. Also, there are concerns regarding the feasibility of a biobased industry, especially taking additional supply chains and land use into consideration. Assessment of the feasibility of a (domestic) biobased industry can help to answer these questions and provide a boost to a material transition to more biobased materials. Therefore, further research should be focussed on the feasibility of a (domestic) biobased industry).

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Appendices

Appendix A – Barriers for implementing CE in construction industry

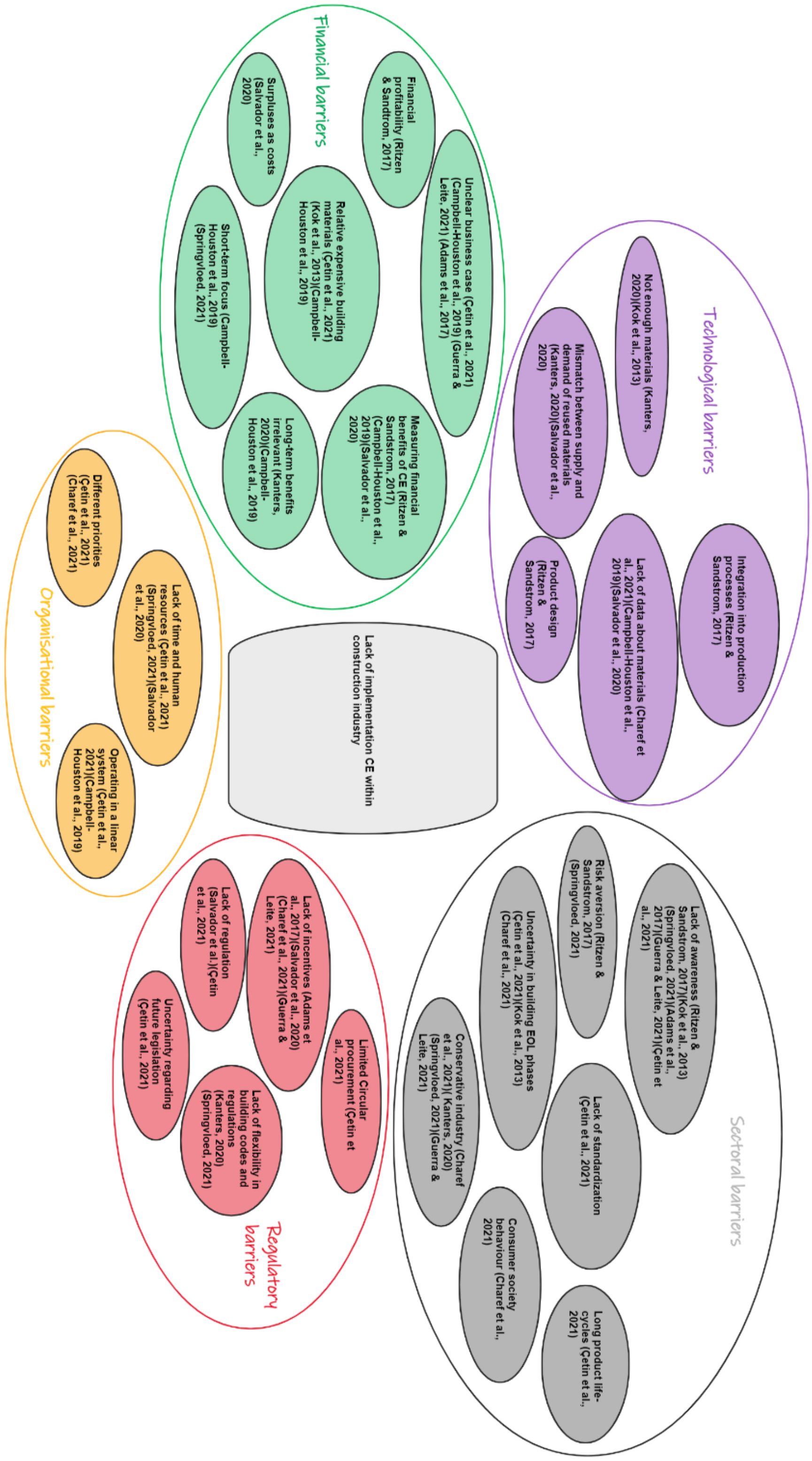

Figure 43: Enlarged overview of barriers to implementing CE in construction industry

Appendix B – Formulas BCI calculation

04 REKENREGELS BCI MEETMETHODE

04.01 Material Circularity Index (MCI)

De MCI van een product wordt berekend volgens de onderstaande formule:

$$MCI = max\left(0,\ \left(1 - LFI_p * F(X_p)\right)\right)$$

Waarbij:

$$LFI = \frac{n_p + s_p + v_p}{2}$$

$$F(X_p) = \frac{0{,}9}{\frac{l_t}{l_w}}$$

MCI	Material Circularity Index
n_p	Herkomst van materialen, nieuw (%)
s_p	Toekomstscenario van materialen, storten (%)
v_p	Toekomstscenario van materialen, verbranden (%)
LFI_p	Linear Flow Index, het gedeelte materiaal met een lineair herkomstscenario of een lineair toekomstscenario
$F(X_p)$	Utiliteitsfactor over de technische en werkelijke levensduur van product (p)
l_t	Technische levensduur
l_w	Werkelijke levensduur

Figure 44: Formulas MCI for BCI calculation (BCI Gebouw, 2022a, p. 19)

04.02 Losmaakbaarheidsindex (LI)

De LI van een product wordt berekend volgens de onderstaande formule:

$$LI_p = \frac{2}{\frac{1}{LIc} + \frac{1}{LIs}}$$

Waarbij:

$$LIc = \frac{2}{\frac{1}{DK_p} + \frac{1}{RO_p}}$$

$$LIs = \frac{2}{\frac{1}{TV_p} + \frac{1}{ToV_p}}$$

LI	Losmaakbaarheidsindex
LIc	Losmaakbaarheidsindex van de connectie
LIs	Losmaakbaarheidsindex van de samenstelling
TV_p	Type verbinding van product p
ToV_p	Toegankelijkheid verbinding van product p
DK_p	Doorkruisingen van product p
RO_p	Randopsluiting van product p

04.03 Product Circularity Index (PCI)

De PCI van een product wordt berekend volgens de onderstaande formule:

$$PCI = \sqrt{MCI * LI}$$

Figure 45: Formulas DI and PCI for BCI calculation (BCI Gebouw, 2022a, p. 20)

Table 37: Assessment table for DI (BCI Gebouw, 2022a, p. 9)

Type verbinding (TV)	Toegankelijkheid van de verbinding (ToV)	Randopsluiting (RO)	Doorkruisingen (DK)
Droge verbinding (1,0).	Vrij toegankelijk zonder extra handelingen (1,0).	Open – geen belemmering voor het (tussentijds) uitnemen van producten of elementen (1,0).	Geen doorkruisingen – modulaire zonering van producten of elementen uit verschillende lagen (1,0).
Verbinding met toegevoegde elementen (0,8).	Toegankelijk met extra handelingen die geen schade veroorzaken (0,8).	Overlapping – gedeeltelijke belemmering voor het (tussentijds) uitnemen van producten of elementen (0,4).	Incidentele doorkruisingen van producten of elementen uit verschillende lagen (0,4).
Directe integrale verbinding (0,6).	Toegankelijk met extra handelingen met volledig herstelbare schade (0,6).	Gesloten – volledige belemmering voor het (tussentijds) uitnemen van producten of elementen (0,1).	Volledige integratie van producten of elementen uit verschillende lagen (0,1).
Zachte chemische verbinding (0,2).	Toegankelijk met extra handelingen met gedeeltelijk herstelbare schade (méér dan 20% van de waarde) (0,4).		
Harde chemische verbinding (0,1).	Niet toegankelijk – onherstelbare schade aan het product of omliggende producten (0,1).		

04.04 Element Circularity Index (ECI)

De ECI van een samengesteld element wordt berekend volgens de onderstaande formule:

$$ECI = \sqrt{MCI_e * LI_e}$$

Waarbij:

$$MCI_e = max\left(0,\ \left(1 - LFI_e * F(X_e)\right)\right)$$

$$LFI_e = \frac{1}{\sum_{i=1}^{p} MKI_p} * \frac{\left((\sum_{i=1}^{p} MKI_p * n_p) + (\sum_{i=1}^{p} MKI_p * s_p) + (\sum_{i=1}^{p} MKI_p * v_p)\right)}{2}$$

$$F(X_e) = \frac{0{,}9}{\frac{\min(l_t)}{\min(l_w)}}$$

$$LI_e = \frac{2}{\frac{1}{LIc} + \frac{1}{LIs}}$$

ECI	Element Circularity Index
$i = 1 \rightarrow p$	Alle deelproducten 1 tot en met p die onderdeel zijn van element e
LFI_e	Linear Flow Index, het gedeelte materiaal met een lineair herkomstscenario of een lineair toekomstscenario van element p
MKI_p	MKI van deelproduct p die onderdeel uitmaken van element e
$\min(l_t)$	De minimale technische levensduur van deelproducten 1 tot en met p die onderdeel zijn van element e
$\min(l_w)$	De minimale werkelijke levensduur van deelproducten 1 tot en met n die onderdeel zijn van element e
LI_e	Losmaakbaarheidsindex van element e

Figure 46: Formulas ECI for BCI calculation (BCI Gebouw, 2022a, p. 21)

04.05 Building Circularity Index (BCI)

De BCI van een gebouw wordt berekend volgens de onderstaande formule:

$$BCI = \frac{1}{\sum_{i=1}^{n} MKI_n} \cdot \sum_{i=1}^{n}\left((MKI_p * PCI_p) + \sum_{i=1}^{p} MKI_p * ECI_e\right)$$

Waarbij:

BCI	Building Circularity Index
$i = 1 \rightarrow n$	Alle producten en elementen die deel uitmaken van het gebouw
MKI_n	Milieukosten Indicator (MKI) van producten en elementen n
MKI_p	Milieukosten Indicator (MKI) van producten p
$\sum_{i=1}^{p} MKI_p$	Som van de Milieukosten Indicator van de deelproducten p die onderdeel uitmaken van element e

Figure 47: Formulas for calculation of BCI (BCI Gebouw, 2022a, p. 22)

Appendix C – Considered elements within LCC/WLC

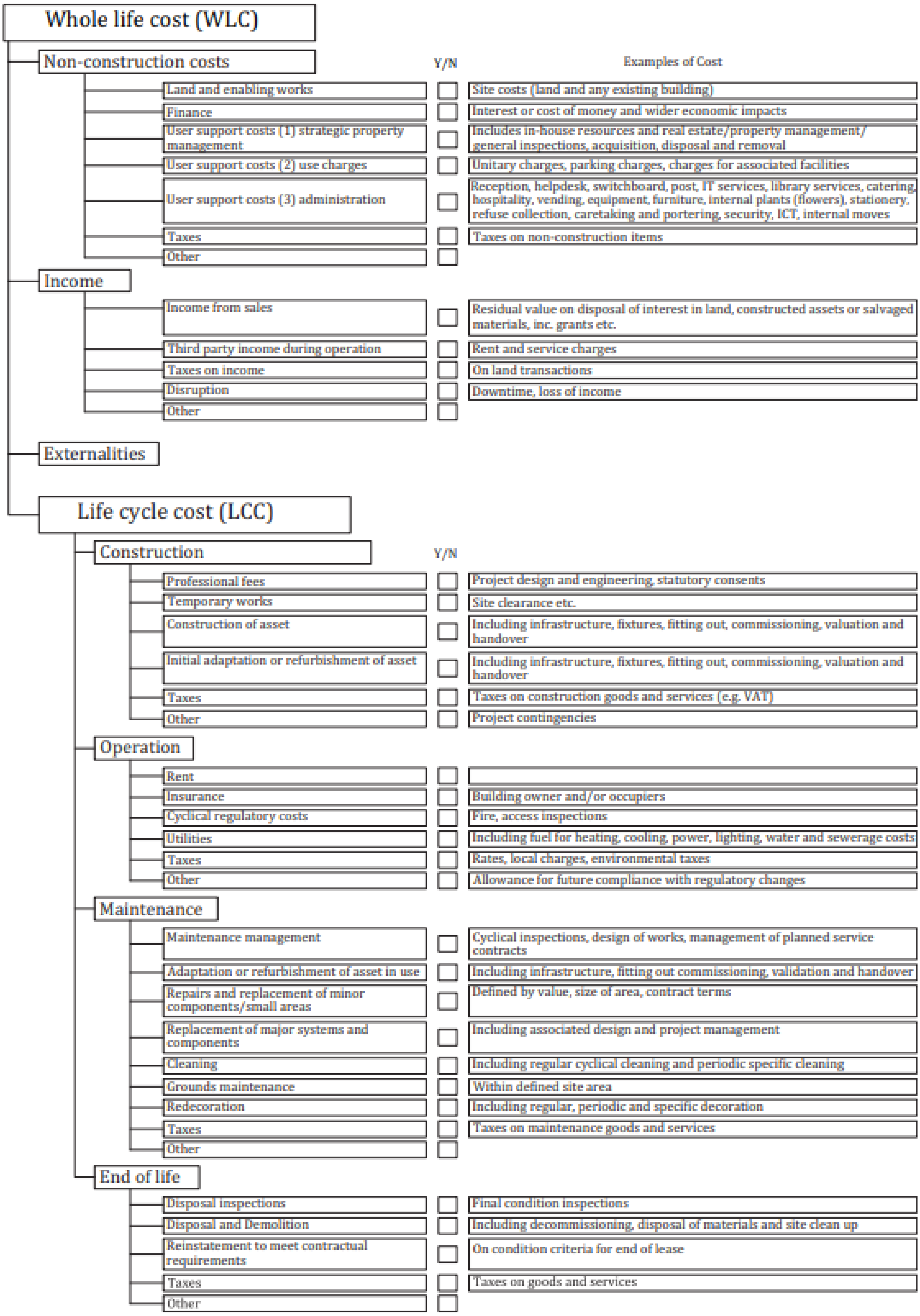

Figure 48: Overview of considered elements LCC/WLC within NEN-ISO 15686-5:2017 (Koninklijk Nederlands Normalisatie-instituut, 2017)

Appendix D – Modified LoC calculation

MCI

04 REKENREGELS BCI MEETMETHODE

04.01 Material Circularity Index (MCI)

De MCI van een product wordt berekend volgens de onderstaande formule:

$$MCI = max\left(0,\ \left(1 - LFI_p * F(X_p)\right)\right)$$

Waarbij:

$$LFI = \frac{n_p + s_p + v_p}{2}$$

$$F(X_p) = \frac{0{,}9}{\frac{l_t}{l_w}}$$

MCI	Material Circularity Index
n_p	Herkomst van materialen, nieuw (%)
s_p	Toekomstscenario van materialen, storten (%)
v_p	Toekomstscenario van materialen, verbranden (%)
LFI_p	Linear Flow Index, het gedeelte materiaal met een lineair herkomstscenario of een lineair toekomstscenario
$F(X_p)$	Utiliteitsfactor over de technische en werkelijke levensduur van product (p)
l_t	Technische levensduur
l_w	Werkelijke levensduur

Figure 49: Formulas MCI for BCI calculation (BCI Gebouw, 2022a, p. 19)

DI

$$DI = \frac{DI_c + DI_e}{2} = \left(\overbrace{\frac{AoC + ToC + Asq}{6}}^{DI_c} + \overbrace{\frac{Ash + Ind + PoR + MoF}{8}}^{DI_e}\right)$$

Where:

DI_c	Disassembly Index of connection
DI_e	Disassembly Index of composition
AoC	Accessibilty of Connection
ToC	Type of connection

Asq Assembly sequence

Ash Assembly Shape

Ind Independency

PoR Pattern of Relations

MoF Method of Fabrication

PCI

$$PCI = \sqrt{MCI \times DI}$$

Where:

PCI Product Circularity Indicator or product p

ECI

$$ECI = \sqrt{MCI_e \times DI_i}$$

$$MCI_e = \max\left(0, \left(\frac{(R_{i,e} + B_{i,e} + H_{i,e} + R_{o,e} \times \mu_r + H_{o,e})}{2} - LFI_e \times F(X_e)\right)\right)$$

$$LFI_e = \frac{1}{\sum_{i=1}^{p} MKI_p} \times \frac{((\sum_{i=1}^{p} MKI_p \times n_p) + (\sum_{i=1}^{p} MKI_p \times s_p) + (\sum_{i=1}^{p} MKI_p \times v_p))}{2}$$

$$F(X_e) = \frac{0{,}9}{\frac{\min(l_t)}{\min(l_w)}}$$

$$DI = \frac{DI_c + DI_e}{2} = \left(\overbrace{\frac{AoC + ToC + Asq}{6}}^{DI_c} + \overbrace{\frac{Ash + Ind + PoR + MoF}{8}}^{DI_e}\right)$$

Where:

ECI Element Circularity Indicator of element e

MCI_e Material Circularity Indicator of element e

DI_i Disassembly Index of element e

BCI

04.05 Building Circularity Index (BCI)

De BCI van een gebouw wordt berekend volgens de onderstaande formule:

$$BCI = \frac{1}{\sum_{i=1}^{n} MKI_n} \cdot \sum_{i=1}^{n}\left((MKI_p * PCI_p) + \sum_{i=1}^{p} MKI_p * ECI_e \right)$$

Waarbij:

BCI	Building Circularity Index
$i = 1 \rightarrow n$	Alle producten en elementen die deel uitmaken van het gebouw
MKI_n	Milieukosten Indicator (MKI) van producten en elementen n
MKI_p	Milieukosten Indicator (MKI) van producten p
$\sum_{i=1}^{p} MKI_p$	Som van de Milieukosten Indicator van de deelproducten p die onderdeel uitmaken van element e

Figure 50: Formulas for calculation of BCI (BCI Gebouw, 2022a, p. 22)

Appendix D – Fuzzy variables scoring tables indicators DI

Accessiblity of Connection (AoC)	Fuzzy variable/Score
Freely accessible without additional operations	1,0
Accessible with additional operations that cause no damage	0,8
Accessible with additional operations causing completely repairable damage	0,6
Accessible with additional operations causing partial repairable damage (more than 20% of the worth)	0,4
Inaccessible causing damage beyond repair	0,1

Type of Connection	Fuzzy variable/Score
Dry connection	1,0
Connection with added elements	0,8
Direct integral connection	0,6
Soft chemical connection	0,4
Hard chemical connection	0,1

Assembly sequence	Fuzzy variable/Score
Same level / Same level	1,0
High level / Low level	0,5
Low Level / High Level	0,1

Assembly shape	Fuzzy variable/Score
Open- No obstruction for disassembly	1,0
Overlapping- Partial obstruction for disassembly	0,6
Closed – Complete obstruction for disassembly	0,1

Independency	Fuzzy variable/Score
Modular zoning – No interferences	1,0
Incidental interference with products or elements	0,4
Complete integration of products and elements	0,1

Pattern of relationship	Fuzzy variable/Score
One or two connections	1,0
Three connection	0,6
Four connections	0,4
Five or more connections	0,1

Method of fabrication	Fuzzy variable/Score
Pre-made geometry	1,0
Half-standardised geometry	0,5
Geometry made on the construction side	0,1

Appendix E – Assumptions assessment framework

Assumptions Level of Circularity assessment

- The building elements as listed in table 1 are considered in the analysis.
- In principle, the standard products from the BCI database are considered, unless the EOL scenario indicates reuse as origin or waste scenario. The data regarding the technical lifespan, origin and waste scenario fractions, ECI and disassembly factors is retrieved from the corresponding product in the database.
- Multiple products are considered to be an element when they arrive as one element on the construction site (M. Van Vliet et al., 2021) and the AoC indicator is >0,6 (M. Van Vliet, 2018). In case an element is considered, the calculation rules described by BCI gebouw (2022b) apply.
- The EOL scenario considered in the assessment is in principle based on the project data. Otherwise, the EOL scenario described in the BCI Gebouw database is considered. In case both sources do not specify an EOL scenario, an educated guess is made based on research of Iacovidou & Purnell (2016).
- In case the life span cannot be retrieved from the project data, the life span for the apartment buildings considered in this research is 50 years based on the Building Decree.
- The ECI values are scaled to display the correct value per unit. The ECI values in the BCI database are specific for the dimensions of that product. When the actual dimensions differ from that in the database, the ECI should be scaled accordingly.
- The assessment of the disassembly indicators Assembly Sequence, Pattern of Relations, and Method of Fabrication are assessed using the scoring tables from Van Vliet (2018) and then validated with an expert.

Assumptions Life Cycle Costs Analysis

- The LCC analysis is conducted from the perspective of the client, where the client is responsible for the construction and after construction becomes the owner of the apartment building.
- The following costs (as described in NEN15686) are excluded from the analysis:
  - Site costs
  - Design/Engineering costs
  - Regulatory/Planning costs
  - Commissioning costs/fees
  - Business use of in-house resources and administration
  - Indirect costs
  - Energy and Water usage
  - Residual site value
- In case the life span cannot be retrieved from the project data, the life span for the apartment buildings considered in this research is 50 years based on the Building Decree.
- The construction costs are in principle derived from the project budget and indexed for month January 2023 using the BDB (2023b) index for new residential construction (index = 115,16). In case the construction costs cannot be derived from the projects budget, a price indication from IGG (construction costing agency) is used. These prices are not indexed, since they are retrieved in January 2023.
- The cleaning and maintenance costs are retrieved from the software Ibis Main version 6.6, which is also used in project X to construct the operational costs budget. The reference date of these prices is November 2022 and therefore requires indexing to January 2023 using the BDB index for residential maintenance (index = 111,97).
- The costs for unplanned maintenance (repairs) is assumed to be 5% of the construction costs for products in the structure and 10% of the construction costs for products in the Skin and Space Plan. This difference is related to the higher unlikeliness that the structure requires repairs.

- The end of life costs are determined for each product separately and dependent on the waste scenario of that product. Consequently, each scenario entails different assumptions regarding the end of life costs, which are further discussed below:
  - Disposal: The labour & equipment are assumed to be 15% of the construction costs of that product/element based on expert knowledge (IGG, 2023). Regarding the transport costs it is assumed a disposal site is located within 50 km and the costs are €0,57/tonne/km. The EOL value are assumed to be similar to the disposal costs of the product/element (Platform CB'23, 2022, p. 48). The disposal costs are calculated using contractor prices for disposing construction- and demolition waste .
  - Retake: The labour & equipment costs are assumed to be 80% of the construction costs of the product/element based on expert knowledge (IGG, 2023). The transport costs are 0, since it is assumed that the supplier is responsible for the transport. The EOL value is assumed to be 0, since the supplier gains ownership of the product/element and therefore the financial benefits or expenses.
  - Reuse: Similar to the Retake scenario the labour & equipment costs are assumed to be 80% based on expert knowledge (IGG, 2023). The transport costs are assumed to be 0, since the buyer of the reused part is responsible for the transport to either a storage facility or a construction site. Regarding the EOL value the second-hand price for the same product in similar condition is assumed. Due to the high variability and uncertainty of this second-hand price it is assumed the second-hand price 25% of the construction costs.
- All future costs are discounted to their present value using the formulas stated in the NEN-ISO 15686-5:2017. Since the costs included in the analysis consist of the current monetary values excluding inflation adjustment, the discount factor is calculated using formula 3 of the NEN-ISO 15686-5:2017, also shown below (Koninklijk Nederlands Normalisatie-instituut, 2017, p. 27).

$$q_{d,nc} = \frac{1}{(1+d)^n + (1+a)^n} \tag{7}$$

- The discount rate applied used to calculate the present value of future costs is assumed to be 2.25% (Werkgroep discontovoet 2020, 2020).
- The escalation (or inflation) rate is assumed to be 2.3% (BDB, 2023a; Peppelman, 2023).
- The inspection costs are calculated with the assumption that a person requires 2 days of inspection and 1 day of report writing with an hourly wage of €100,- which results in €2400,- of inspection costs.

Appendix F – Results

LoC

Table 38: Overview of results LoC calculation - standard

	Structure		Skin		Space Plan		Total
	MCI	DI	MCI	DI	MCI	DI	BCI
Base	0.63	0.15	0.43	0.62	0.47	0.53	0.36
1A	0.60 ↓	0.56 ↑	0.43 -	0.62 -	0.50 ↑	0.56 ↑	0.48 ↑
1B	0.62 ↓	0.57 ↑	0.43 -	0.62 -	0.50 ↑	0.53 -	0.51 ↑
2A	0.63 -	0.15 -	0.41 ↓	0.60 ↓	0.47 -	0.53 -	0.36 -
2B	0.63 -	0.15 -	0.46 ↑	0.62 -	0.47 -	0.53 -	0.37 ↑
3	0.63 -	0.15 -	0.43 -	0.62 -	0.33 ↓	0.49 ↓	0.30 ↓
4	0.60 ↓	0.56 ↑	0.41 ↓	0.60 ↓	0.50 ↑	0.54 ↑	0.49 ↑
5	0.60 ↓	0.56 ↑	0.43 -	0.62 -	0.35 ↓	0.50 ↓	0.44 ↑
6	0.63 -	0.15 -	0.41 ↓	0.60 ↓	0.33 ↓	0.49 ↓	0.29 ↓
7	0.60 ↓	0.56↑	0.41 ↓	0.60 -	0.35 ↓	0.50 ↓	0.45 ↑

Table 39: Overview of results LoC calculation - adjusted EOL scenario wood

	Structure		Skin		Space Plan		Total
	MCI	DI	MCI	DI	MCI	DI	BCI
Base	0.63	0.15	0.50	0.62	0.61	0.53	0.43
1A	0.69 ↑	0.56 ↑	0.50 -	0.62 -	0.64 ↑	0.56 ↑	0.58 ↑
1B	0.69 ↑	0.57 ↑	0.50 -	0.62 -	0.64 ↑	0.53 -	0.59 ↑
2A	0.66 ↑	0.15 -	0.65 ↑	0.60 ↓	0.61 -	0.53 -	0.44 ↑
2B	0.66 ↑	0.15 -	0.61 ↑	0.62 -	0.61 -	0.53 -	0.44 ↑
3	0.62 ↓	0.15 -	0.50 -	0.62 -	0.49 ↓	0.49 ↓	0.37 ↓
4	0.69 ↑	0.56 ↑	0.65 ↑	0.60 ↓	0.64 ↑	0.54 ↑	0.56 ↑
5	0.69 ↑	0.56 ↑	0.50 -	0.62 -	0.52 ↓	0.50 ↓	0.51 ↑
6	0.66 ↑	0.15 -	0.65 ↑	0.60 ↓	0.49 ↓	0.49 ↓	0.37 ↓
7	0.69 ↑	0.56↑	0.65 ↑	0.60 -	0.52 ↓	0.50 ↓	0.54 ↑

LCC

Table 40: Overview of results LCCA

Alternative	Phase A.	Phase B.	Phase C.	Total
Base	€ 49.006	€ 21.773	€ 4.406	€ 75.186
1A	€ 56.610 ↑	€ 18.773 ↓	€ 4.291 ↓	€ 79.675 ↑
1B	€ 67.963 ↑	€ 19.468 ↓	€ 4.992 ↑	€ 92.422 ↑
2A	€ 49.974 ↑	€ 23.045 ↑	€ 4.384 ↓	€ 77.403 ↑
2B	€ 49.841 ↑	€ 22.161 ↑	€ 4.327 ↓	€ 76.329 ↑
3	€ 55.783 ↑	€ 23.007 ↑	€ 4.537 ↑	€ 83.327 ↑
4	€ 57.579 ↑	€ 20.091 ↓	€ 4.158 ↓	€ 81.828 ↑
5	€ 63.198 ↑	€ 19.931 ↓	€ 4.672 ↑	€ 87.800 ↑
6	€ 56.750 ↑	€ 24.462 ↑	€ 4.672 ↑	€ 85.884 ↑
7	€ 64.149 ↑	€ 21.247 ↓	€ 4.570 ↑	€ 89.966 ↑

Table 41: Results LCCA phase A. Construction costs

	Material	Labour	Subcontractor	Total
Base	€ 17.356	€ 5.815	€ 25.835	€ 49.006
1A	€ 11.905 ↓	€ 5.171 ↓	€ 34.894 ↑	€ 51.970 ↑
1B	€ 16.714 ↓	€ 8.975 ↑	€ 42.273 ↑	€ 67.963 ↑
2A	€ 23.896 ↑	€ 7.477 ↑	€ 18.601 ↓	€ 49.974 ↑
2B	€ 23.911 ↑	€ 7.544 ↑	€ 18.386 ↓	€ 49.841 ↑
3	€ 15.248 ↓	€ 5.559 ↓	€ 34.975 ↑	€ 55.783 ↑
4	€ 20.142 ↑	€ 7.125 ↑	€ 30.312 ↑	€ 57.579 ↑
5	€ 11.520 ↓	€ 5.211 ↓	€ 46.467 ↑	€ 63.198 ↑
6	€ 21.789 ↑	€ 7.221 ↑	€ 27.740 ↑	€ 56.750 ↑
7	€ 18.051 ↑	€ 6.869 ↑	€ 39.229 ↑	€ 64.149 ↑

Table 42: Results LCCA phase B. Operational costs

	Inspections	Maintenance	Repairs	Cleaning	Total
Base	€ -	€ 16.670	€ 4.084	€ 1.020	€ 21.773
1A	€ -	€ 13.309 ↓	€ 4.376 ↑	€ 1.088 ↑	€ 18.773 ↓
1B	€ -	€ 13.368 ↓	€ 4.987 ↑	€ 1.112 ↑	€ 19.468 ↓
2A	€ -	€ 18.459 ↑	€ 4.181 ↑	€ 646 ↓	€ 23.045 ↑
2B	€ -	€ 17.650 ↑	€ 4.167 ↑	€ 344 ↓	€ 22.161 ↑
3	€ -	€ 17.070 ↑	€ 4.762 ↑	€ 1.175 ↑	€ 23.007 ↑
4	€ -	€ 14.961 ↓	€ 4.473 ↑	€ 657 ↓	€ 20.091 ↓
5	€ -	€ 13.807 ↓	€ 5.035 ↑	€ 1.088 ↑	€ 19.931 ↓
6	€ -	€ 18.958 ↑	€ 4.858 ↑	€ 646 ↓	€ 24.462 ↑
7	€ -	€ 15.460 ↓	€ 5.130 ↑	€ 657 ↓	€ 21.247 ↓

Table 43: Results LCCA phase C. End of Life costs

	Labour & Equipment	Inspection	Transport	Disposal	Total
Base	€ 2.416	€ 789	€ 815	€ 386	€ 4.406
1A	€ 2.791 ↑	€ 789 -	€ 330 ↓	€ 381 ↓	€ 4.291 ↓
1B	€ 3.351 ↑	€ 789 -	€ 373 ↓	€ 479 ↑	€ 4.992 ↑
2A	€ 2.464 ↑	€ 789 -	€ 766 ↓	€ 365 ↓	€ 4.384 ↓
2B	€ 2.458 ↑	€ 789 -	€ 789 ↓	€ 379 ↓	€ 4.327 ↓
3	€ 2.751 ↑	€ 789 -	€ 772 ↓	€ 343 ↓	€ 4.537 ↑
4	€ 2.839 ↑	€ 789 -	€ 253 ↓	€ 276 ↓	€ 4.158 ↓
5	€ 3.116 ↑	€ 789 -	€ 319 ↓	€ 370 ↓	€ 4.594 ↑
6	€ 2.798 ↑	€ 789 -	€ 749 ↓	€ 336 ↓	€ 4.672 ↑
7	€ 3.163 ↑	€ 789 -	€ 270 ↓	€ 348 ↓	€ 4.570 ↑