MASTER THESIS

Assessing Life Cycle Costs over increasing Building Circularity Levels

Ing. L. Braakman

University of Twente
Construction Management and Engineering (CME)

Supervisors
Dr. Ir. R. S. de Graaf
Dr. S. Bhochhibhoya

Company supervisor
Ir. N. Nielen

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L. Braakman[1]

[1]*Construction Management and Engineering, University of Twente, Enschede, The Netherlands*
E-mail: lindabraakman@gmail.com

In the last couple of years, actors in the construction industry have demonstrated an increasing willingness to move towards circular businesses. However, many consider circular construction to be more expensive, which makes actors reluctant for investing in circularity. This study contributes to existing literature by relating the building's circularity level to its Life Cycle Costs. Using design-oriented research, scenarios with a gradually increasing circularity level are designed on the basis of a standard one-family house. The scenarios are then related to their Life Cycle Costs. The results revealed that it is possible to double the current building design's circularity level while keeping the Life Cycle Costs equal. At the highest circular scenario, the Life Cycle Costs increase sharply due to almost doubled purchasing costs. Increasing the lifespan of the building revealed an increasing difference in the operational and End of Life costs between low and high circular building scenarios. The turning point of which the Life Cycle Costs are lower for buildings with the highest reachable circularity level (of 0,49) is around 85 years of lifespan. Although, it is more economic attractive to double in circularity level as it directly decreases the Life Cycle costs. Incentives of the government should encourage the industry to invest and collaborate with chain partners to develop better circular building materials and decrease the purchasing costs.

Keywords: Building Circularity Indicator (BCI), Circular Construction, Level of Circularity (LoC), Life Cycle Costing (LCC), Residual Value.

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1. Introduction

The circular economy (CE) is presented as the alternative for the current, essentially linear, economy. The linear economy is characterized by a 'take-make-dispose' pattern, which economic growth depends on selling products (Alizadeh, 2016). The CE, in contrast, refers to an industrial economy that is restorative (Ellen Macarthur Foundation, 2013). It replaces the End of Life (EoL) phase by the high-quality circular loop of nutrients for reuse, remanufacturing and recycling. The current global concerns about resource scarcity will especially impact the construction industry. The construction industry depends for more than 90% on raw materials such as iron, aluminum, copper, sand, clay, limestone and wood (Alizadeh, 2016; Van Odijk & Van Bovene, 2014). Bringing these materials back in the loop decreases the dependency on these resources. In addition, CE aims to bring economic prosperity by value retention. The European Commission (2018) states that the construction industry generates the heaviest and most voluminous waste stream in the European Union. They underline the high potential for recycling and reuse of this waste stream, since some of its components have a high resource value. About 70-80% of the discarded construction materials have potential for retention by applying it in another application (Ellen Macarthur Foundation, 2013).

Both aspects make companies increased their willingness to move towards more circular businesses. These industrial actors, who are non-experts in the CE, require support in applying circular principles in an economically feasible manner. However, the Dutch construction industry is made reluctant for investing in circular projects due to multiple sources claiming CE to be more expensive. A circular house increase in costs with 10.000 euro (Doodeman, 2019). Circular construction is more expensive by higher product and labour costs (Copper8 & Alba Concepts, 2017). The product costs in circular projects increase due to applying more expensive biodynamic products, required to replace main elements, such as steel, glass and cement (James Brueton, 2018). The labour costs increase using alternative construction techniques that are more expensive compared to the traditional ones (Surgenor, Winch, Moodey, & Mant, 2019). However, in none of the statements there is attention for the operating and End of Life costs during a long period of lifespan. Considering the costs in all life cycle phases, using Life Cycle Costing (LCC), is important to balance the initial costs and expected future operational costs during a long period of lifespan.

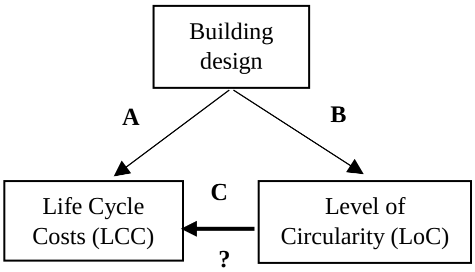


Figure 1: Influence of building design on Life Cycle Costs (A) and Level of Circularity (B). Unknown relationship between Life Cycle Costs and Level of Circularity (C).

Figure 1 shows the relation of building design, LCC and Level of Circularity (LoC). When selecting materials in the building design, some materials are primarily attractive in initial costs, but can have adverse effects on quality, reliability and performance during the lifespan of the building (Al Ghonamy, Esam, Aichouni, Abdulwahab, Ashraf, & Subhi, 2015). Buildings that are designed and constructed to reduce life-cycle environmental impacts deliver direct economic benefits such as lower operational and maintenance costs, slower depreciation and higher asset value (European Commission, 2014). 'A' shows the relationship how the building design impacts the LCC due to material selection and construction method. The material resources, the connection types and function integrated into the building design at 'B' influence the LoC (Ellen Macarthur Foundation, Granta Design, & LIFE, 2015). Yet, it is unknown how the building's LoC influences the LCC, represented by relationship 'C'. Construction companies are struggling to evaluate the Level of Circularity (LoC) and its relationship with the project LCC. Investigating this is important to stimulate the construction industry towards a CE. Firstly, by showing the potential to improve circularity in the current building design and secondly, to set ambitions regarding circularity level by discussing the feasibility to invest in circular projects. Finally, to provide a context for the speculations about increased costs for circular construction by delivering scientific evidence.

2. Theoretical background

2.1 Circular design strategies in construction

Circular construction is defined as the development of a building that during construction, operation and reuse utilises available and renewable resources. The building components are prepared for value retention by lifespan extension or returning materials in future cycles. With the aim of minimizing the impact on the environment by reducing the virgin material demand through the reuse of resources and keep materials into the chain by applying regenerative (circular) solutions.

Several circularity strategies exist to reduce the consumption of natural resources, and minimise the production of waste (Potting, Hekkert, Worrell, & Hanemaaijer, 2017). The existing strategies, often called as the R's, are prioritized according a varying number of circularity levels (Ellen Macarthur Foundation, 2013; Kirchherr, Reike, & Hekkert, 2017; Potting et al., 2017; Reike, Vermeulen, & Witjes, 2018). The R-imperatives that best fit the construction industry are reuse, remanufacture and recycle. These are therefore considered to fit the waste scenarios for the LoC and LCC assessments.

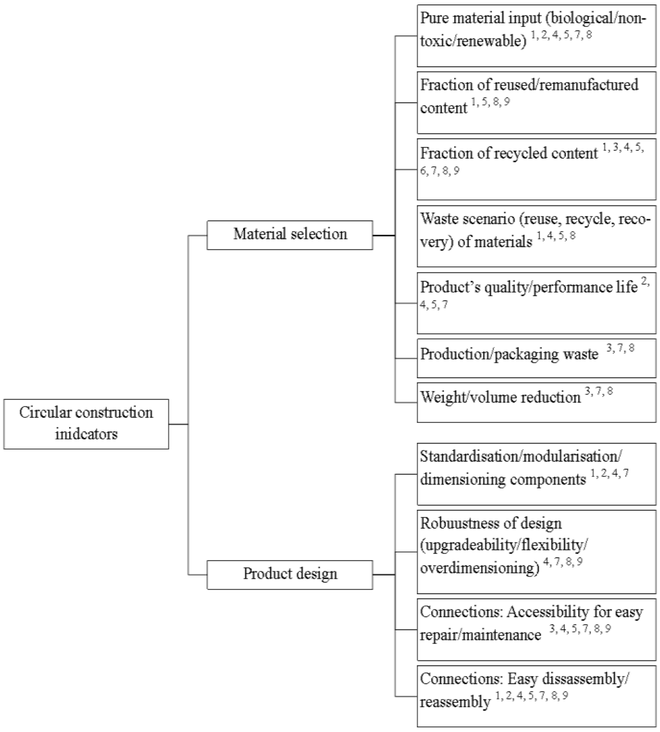


Figure 2: Circular construction indicators [1](Ellen Macarthur Foundation et al., 2015), [2](Geldermans, 2016), [3](Braungart, Mcdonough, & Bollinger, 2006), [4](Bocken, Pauw, De Bakker, & Van der Grinten, 2016), [5](Verberne, 2016), [6](Nelissen, Van de Griendt, Van Oppen, Pallada, Wiedenhoff, Van de Waal, & Bögl, 2018), [7](Mestre & Cooper, 2017), [8](Kubbinga, Bamberger, Van Noort, Van de Reek, Blok, Roemers, & Faes, 2018), [9](Bovea, Quemades-Beltrán, Pérez-Belis, Juan, Braulio-Gonzalo, & Ibáñez-Forés, 2018).

Circularity assessment tool	Sources	Indicators (fit to product circularity indicator, figure 2)	Input	Output
Circular Economy Toolkit	(WBCSD, 2018; Walker, 2018; Saidani, 2017)	Material selection: Recycled content, packaging waste, weight reduction, energy for production. Product design: life time extension (upgradability), design for repair, design for reuse.	Qualitative: yes/no questions	Qualitative: 3 levels
Circular Economy Indicator Prototype	(WBCSD, 2018; Walker, 2018; Saidani, 2017)	Material selection: Recycled/reused content, packaging waste. Product design: life time extension (high quality), design for repair, design for reuse.	Qualitative: yes/no questions	Quantitative: Score (%)
Material Circularity Indicator	(EMF, 2013; Linder, 2017; Walker, 2018)	Material selection: Recycled/reused content, waste scenario, lifespan, weight reduction.	Quantitative: percentages	Quantitative: Score (from 0- 1)
Building Circularity Indicator	(Verberne, 2016)	Material selection: Recycled/reused content, waste scenario, lifespan, weight reduction. Product design: connections, accessibility of fixings, function integration.	Quantitative: percentages + Qualitative: point	Quantitative: Score (from 0- 1)
Input-output balance sheet	(Capellini, 2017; Saidani, 2017)	Material selection: Pure material input, recycled content, waste scenario, lifespan.	Quantitative: multiple units	Quantitative: Economic evaluation
Eco-costs	(Linder, 2017; Walker, 2018)	N/A.	Quantitative: numerical data	Quantitative: numerical
Circulariteit Prestatie Gebouw	(Jonge Honden, 2018; Bouwfysisch maandblad, 2018)	Material selection: Recycled/reused content, biological content, packaging waste. Product design: upgradability design solutions.	Qualitative: point score + yes/no questions	Quantitative: Score (from 1-10)
BREEAM circularity indicators	(Circle Economy et al., 2018)	Material selection: Pure input, recycled/reused content, waste scenario, Product design: Connections, accessibility of fixings.	Quantitative + qualitative	Not clear yet

Table 1: Characteristics of suitable tools available in literature for assessing building's level of circularity.

2.2 Tools for assessing the level of circularity

In this study, indicators for circular construction are selected and an inventory is made of available tools to select the most appropriate tool to assess the building's circularity level.

2.2.1 Circular construction indicators

A circularity metric at the product level should focus exclusively on measuring circularity, which is the material fraction of used products (Niero & Kalbar, 2019). This excludes the assessment of environmental performance or other energy consumption issues. Therefore, the circular construction indicators focus on the material input and waste scenario. Also, the designs opportunities to extend the building's and materials' lifespan are taken into account.

Geldermans (2016) distinguishes product value based on specific intrinsic (material origin) and relational properties (building design and use). Similarly the Ellen Macarthur Foundation (2013) defines circular design as improvements in material selection and product design. Circular product indicators collected from different fields of scientific literature are structured in figure 2.

2.2.2 Selection of circularity assessment tool

Multiple tools exist in both academic and grey literature to assess the LoC on macro, meso and micro level (Niero & Kalbar, 2019; Saidani, Yannou, Leroy, & Cluzel, 2017; Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). Table 1 shows an inventory of tools, the most suited is selected for product circularity assessments. The 'Building Circularity Indicator' (BCI) of Verberne (2016) is considered as the most appropriate tool off this research's point of view. As table 1 indicates, the selected tool reflects the circularity by a quantitative score on both building and component level. The other tools have been considered but were not regarded as suitable because they rely on qualitative data or focus only on building or component LoC.

2.2.3 Explanation of the BCI

Verberne (2016) developed the BCI as a decision-making instrument for circularity within the construction industry. The BCI enables building circularity assessment on multiple levels (figure 3). The basis of the BCI (Verberne, 2016) is the Material Circularity Indicator (MCI) of the Ellen Macarthur Foundation et al. (2015). The MCI considers the material's origin, waste scenario and lifespan. The MCI is complemented by the Disassembly Determining Factors (DFF) index of Durmisevic (2006), which result in the Product Circularity Indicator (PCI). These DFF factors identify the possibility for disassembly in the product design by focussing on function integration and connection types. For instance, applying recycled tiles result in a high MCI score. In contrast, a low PCI score is achieved for this application as the chemical connection type could not be easily disassembled

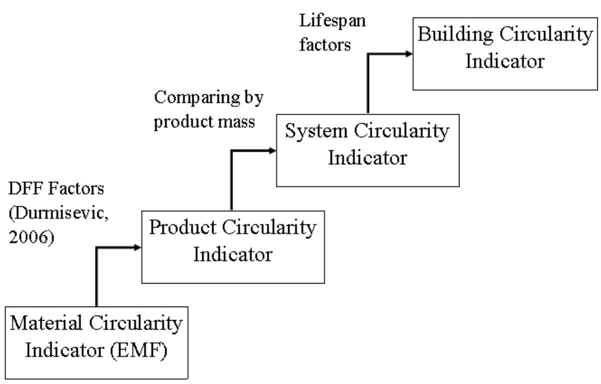


Figure 3: Structure of the levels in the BCI assessment

without damage. The products are categorized in systems by the building system layers of Brand (1995). The relative amount of each product within the system is determined by its mass. The System Circularity Indicators (SCI) are multiplied by a lifespan factor resulting in the BCI score.

3. Materials and methods

3.1 Research methodology

The research strategy that is used in this study is design-oriented. This method enables to analyse the deviation in LCC over the multiple designed scenarios with increasing LoC. The research starts by determining the LoC of the baseline. This is a common building design of one-family terraced house of 140 m^2 in the Netherlands with a prefabricated concrete structure and traditional finishing materials (Appendix III). Housing corporations usually consider an investment period of around 50 years for these project types. The functional unit are the building components, consisting of the systems structure, skin and space plan. In the design process circular building components, available in the Dutch construction market, are applied as alternatives in the baseline. First the best circular scenario is designed and assessed on its circularity level to determine for this research the maximum feasible circular level, called the final scenario. The design process is followed by the design of multiple scenarios with gradually increasing LoC between the baseline and final scenario. Finally, the baseline and scenarios are assessed on their LCC to analyse how costs vary over an increasing LoC.

A requirement during the design of the scenarios is that each scenario must fulfil the same conditions as those of the baseline. Therefore, the building insulation (RC) value and acoustic performance must remain the same. In addition, corrections for a low weight structure are made in the foundation design. The functional unit excluded the building services.

3.2 Modification of the BCI tool

The BCI tool is validated by Verberne (2016) and has been further elaborated towards its PCI factors by Van Vliet (2018). However, it still contains some practical issues to measure the circularity level for houses. Therefore, the BCI had to be modified to fit the case and to solve some practical issues beforehand.

Materials with a high utility factor are too optimistically evaluated in the MCI assessment at their virgin material use and waste production. In practice, materials with a high utility factor require more virgin materials and more waste is generated during their lifespan. In the modified BCI version is proposed to balance this score by multiplying the utility factor with the virgin materials used and waste generated (see figure 4).

Besides, the biological or natural material input is not mentioned in the MCI of the Ellen Macarthur Foundation et al. (2015) and Verberne (2016). Considering this type of material input separately reduces the amount of virgin material input. Therefore, the biobased input is proposed to be included in the modified BCI tool (figure 4). Furthermore, Verberne (2016) excluded the recycling process efficiency. Van Vliet explained in an interview (06-03-2019) the complexity of this assessment and preferred to use a standard score of 1. However, the waste processor's competence and the integration of multiple functions in an object, for instance pipes in concrete walls, determine if the whole product could be fully recycled. Therefore, in the modified tool it is proposed to include the recycling efficiency rate by Ellen Macarthur Foundation et al. (2015) and to reduce this rate by factors as explained in appendix VII.

<u>Input information</u>

X =	Utility of a product (technical/functional lifespan)
V =	Fraction Virgin foodstock
W =	Fraction unrecoverable waste
Fr, Fu, Fb =	Fraction from non-virgin (recycled, reused, biobased) sources
Cr, Cu, Cc =	Recoverable waste after use-phase by recycling, reuse or composting
(Wf+Wc)/2 =	Efficiency of recycling process (Ellen Macarthur Foundation, Granta Design, & LIFE, 2015)

Formulas BCI (Verberne, 2016)		**Formulas modified BCI**	
V =	1 - Fr - Fu	X ≤ 1; V	= 1 - Fr - Fu - Fb
		X > 1; V	= (1 - Fr - Fu - Fb) * X
W =	1 - Cr - Cu	X ≤ 1; W	= (1 - Cr - Cu - Cc) + ((Wf+Wc)/2)
		X > 1; W	= ((1 - Cr - Cu - Cc) + ((Wf+Wc)/2)) * X

* Mass is excluded for overview

Figure 4: Comparison formulas BCI and modified BCI

Within the BCI's material circularity assessment, Verberne (2016) replaced the product lifespan evaluation by a comparison between the products' technical and building layers' functional lifespan. This functional lifespan is considered following the building layers theory of Brand (1995). However, Brand considered these lifespans for commercial buildings, which are subject to marketing and image. This means that these lifespans are less applicable for residential buildings. Therefore, the functional lifespan for the structure, skin and space plan are rephrased to respectively 100, 50 and 30 years according to practice.

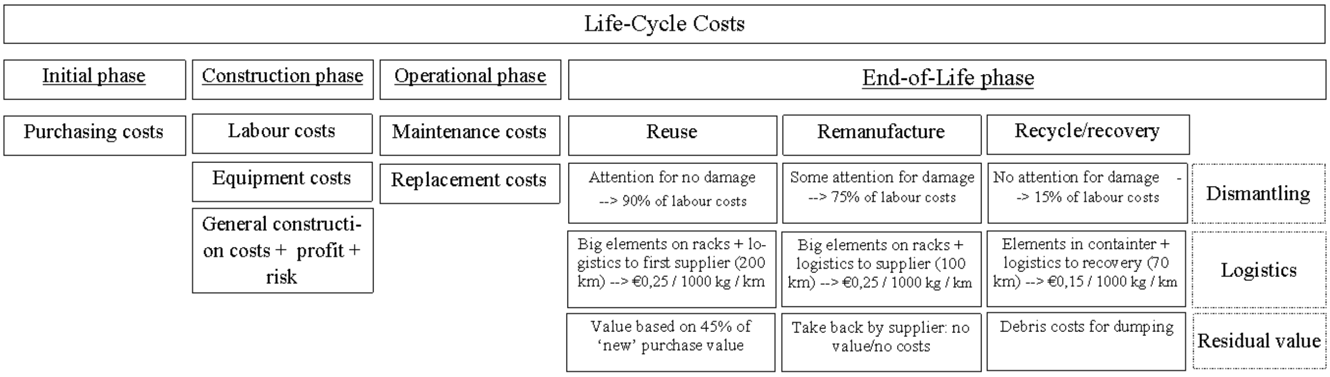


Figure 5: Cost breakdown structure of LCC

Besides is incorporated that the functional lifespan is subject to the individual building components' functional requirements, like their thermal condition. In Appendix I the formulas of the modified BCI are shown.

3.3 Assessing the BCI

The data source about the materials origin, waste scenario and lifespan are initially gathered by the databases 'Nederlands Instituut voor Bouwbiologie en Ecologie' (NIBE) and 'Nationale Milieudatabase' (NMD). In addition, current and circular building component suppliers are requested to provide data about the materials origin and waste scenario. This data is used when the situation in practice deviates from the theoretical data.

3.4 Assessing LCC within the CE

LCC is considered with accounting all the product's economic costs next to its lifespan costs to compare the cost-effectiveness of alternatives within the whole lifecycle (Di Maria, Eyckmans, & Van Acker, 2018). LCC was applied to compare different building designs both in terms of initial costs and expected future operational costs (Bhochhibhoya, Pizzol, Achten, Maskey, Zanetti, & Cavalli, 2017; Ristimäki, Säynäjoki, Heinonen, & Junnila, 2013). In this study, the initial costs are all the costs incurred in the material supply and the construction of the building. Whereas future costs, are costs for the building's operation over 50 years of lifespan and to remove the building after its lifespan. The costs break down of each phase are shown in figure 5. The functional unit of this study are the structure, skin and space plan of the building in different scenarios. The system boundaries for each scenario were from raw material input in the initial phase, product manufacturing (construction phase), use (operational) phase towards the disposal, recycling, remanufacturing or reuse at the End-of-Life phase. The costs per phase are explained below.

3.4.1 Initial phase

The costs in the initial phase contain the costs to purchase the building components for material supply on site. The current case's building components costs are based on the budget plan of the contractor. The costs of the alternative building components are collected by requesting purchase price from suppliers and the database of Cobouw.

3.4.2 Construction phase

The costs for labour and equipment to construct the building are known as the construction phase costs. Besides, general construction costs are calculated for risks and profit. The baseline components construction costs are based on the budget plan of the contractor. Basically, the alternative components are considered by the same data and adapted when changes in construction time and equipment are required.

3.4.3 Operational phase

Costs for building operation include only the maintenance and replacement of building components during their lifespan. The indirect influence of the building components on water and energy consumption costs are excluded. The building maintenance includes mostly the costs for labour by inspections, repairing, cleaning or painting the visible building components. The operational costs consider also costs for the replacement of the (non-)visual components when these exceed in technical or functional lifespan. This includes the purchasing and labour costs for disassembly and reassembly of the component. In addition, the components' residual value or their costs for dumping debris are concerned.

Maintenance experts and suppliers were asked about the maintenance and replacement cycles of building components. Both costs are per building component plot on a yearly schedule in order to calculate the present value according to the matching operational year.

The present value of all life cycle phases' costs during the building's lifespan was calculated by:

$$LCC = C_0 + \sum C_t / (1+i-j-k)^t$$

Where,

C_0 = initial costs (initial and construction phase)
C_t = present value of all recurring costs (operational and EoL cost) at year t
t = year of cash flow
i = discount rate
j = inflation rate
k = escalation rate of materials

3.4.4 End of Life phase within a CE

Costs for removing the building after its lifespan are considered in the EoL costs. It contains the costs for dismantling, logistics and reutilization of the building components. The last one is better known in the current linear economy as debris costs. Where materials are depreciated to no value and costs remain when dumping the materials. Within a CE, materials contain a residual value after their lifespan. More original value is captured in closer loops by a priority order of reuse, remanufacture and recycling (McKinsey & Company, 2016). Incorporating this value in the EoL phase result in lower LCC for circular buildings.

The evaluation of the residual value is the most complex part. No academic research has determined how to calculate the residual value for building components or products. In practice, Madaster[1] and TNO[2] started developing their own tool to determine the building components' residual value. Both tools' exact formulas are not published. It is too extensive and will go beyond the scope of this research to develop a scientifically based tool to consider the residual value for the building components. By desk research and interviews, a tool is developed by incorporating the basics of these currently available tools.

Incorporating the type of waste scenario (allocated as reuse, remanufacture or recycling of section 2.1) is important to distinguish the amount of value which could be retained in the building component. The tools of TNO and Madaster do not incorporate the differences in waste scenario. Madaster (2018) depreciates the product value on a linear basis by comparing the current to its technical lifespan. However, this is inconsistent with the CE idea of value retention. TNO in contrast stated that a building component should be appraised on the craftsmanship, technology and machine utilization of the initial product manufacturing (Van der Werf, 2019). Therefore, the building components are evaluated by comparing their 'new' purchase prices with resold ones of platforms that offer building components for reuse. Components with no guarantee for reuse, are considered as remanufacturable when the initial suppliers offer the guarantee to take the materials back for free to reutilize them in a new product. Their component value is considered as zero by no value and even no dumping costs after lifespan. When recycling the product, costs are included for material dump after their lifespan. This results in a negative value. Assumptions in these residual values of figure 5 are explained in appendix VII. In appendix II the LCC formulas are shown.

4. Results

4.1 Design of the scenarios

A standard one-family house (the baseline) scores a circularity level of 0,20 within a range of 0 (not circular) and 1 (circular). Applying the best circular building components in the final scenario resulted in a score of 0,49. This result is considered as the highest reachable circularity level of the building design within this research, but this score still seems quite low. A higher circularity level is technically difficult to reach. The results of both scenarios (appendix III) show a relatively higher MCI score compared to the PCI. First, due to the chemical connections which are still used for assembling recycled or biobased materials available in market. Secondly, by function integration in a lot of materials of the building design. Besides, the modified factors in the BCI are being more critical on the material circularity assessment. The PCI score is downgraded by function integration and use of chemical connection types in materials. As a result, the final scenario BCI score does not approach the ultimate circularity score of 1. The scenarios in between the baseline and final scenario are designed by gradually increasing the LoC. In table 2, the replaced components are visualised in comparison to the prior scenario.

[1] Madaster is a building component registration platform for material passports.

[2] TNO is an independent research organisation in the technique and environment, established in the Netherlands.

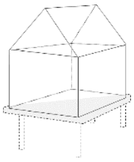
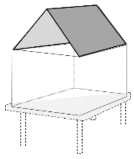
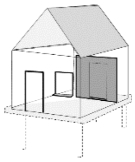
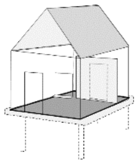
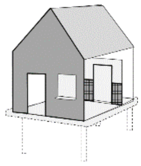
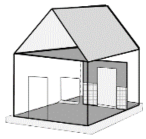
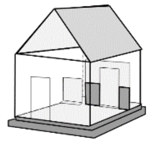
	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Final scenario
BCI	0,20	0,28	0,31	0,38	0,41	0,49	0,49
Changes in:		 Compared to baseline	 Compared to sc. 1	 Compared to sc. 2	 Compared to sc. 3	 Compared to sc. 4	 Compared to sc. 5
Structure						Prefab wood 1st/2nd floor + walls + roof + no found. piles	Prefab wood ground floor + recycled conc. found. beams
Skin		Roof clay tiles	Recycled wood frames + Biobased sill		Flax insulation + Dry brickwork		
Space plan			Sand-lime wall blocks + Biobased sill	Dry finishing floor (EPS)	Recycled wood frame + Wood sills + Recycled tiles	Dry fin. floor (wood) + Reused wall panels (flax)	Wall and floor panels (instead of tiles)

Table 2: Description of changes in building design of scenarios.

Appendix IV gives a total overview of the building design and circularity assessment of each scenario. The high mass building components of the systems skin and space plan are replaced first. These components have a higher impact on the BCI score because of their relative high systems' weight and higher system dependency factor. Finally, the components in the building structure are replaced.

4.2 Influence of the LoC on the LCC of the building

The scenarios' LCC (figure 6) reveal that it is possible to double the circularity level of the baseline till 0,41, while keeping the LCC equal. Applying high mass building components in the skin and space plan has the most effect on the LoC. In this study is proposed to start implementing recycled or biobased materials, which show the smallest increase in purchasing costs. Subsequently, materials should be assembled by dry connections, which demand a higher increase in purchasing costs which could stil be balanced by a decrease in the EoL costs.

Beyond a circularity level of 0,41, it is required to apply circular design principles in the building structure. This is less preferred because of their low impact in LoC and sharp increase in purchasing costs. This increase could no longer be balanced by the EoL costs which results in an increase in LCC from 0,41 of circularity level.

5. Analysis

5.1 The influence of the building design on the LoC

Replacing the high mass components in the skin and space plan has a significant impact on the LoC. Whereas lower mass components, as insulation materials, have hardly any impact. Therefore, it is suggested to first replace the high mass building components in the skin and space plan.

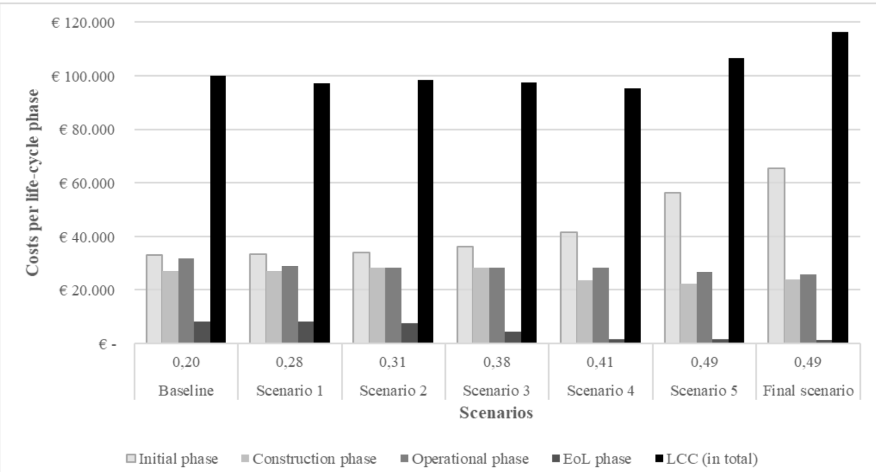


Figure 6: Costs per life cycle phase plotted over the designed scenarios with an increasing LoC.

Building components from virgin materials should be replaced by biobased and recycled content. Replacing for instance the concrete roof tiles of scenario 1 by clay increases the building circularity level with 0,07 point. Some other available circular building components are gypsum walls, sand-based walls, recycled tiles and flax, cellulose and recycled jeans insulation. Already many suppliers offer a biobased or recycled variant in addition to their common building components. In contrast, few suppliers focus on product design by developing alternative, dry connected assemblies, instead of the current used chemical connections. It is recommended to focus on the assemblies, as they have high impact on the circularity assessment. Replacing for instance the solid in-situation poured finishing floor into a dry floor results in an increase in circularity level of 0,07 point. Other dry connected building components are available, for instance click-based brickwork, inner-walls and tile panels. Applying circular design principles in the building structure are recommended as last option because of their low impact in LoC and high increase in purchasing costs. No difference in the LoCs between the fifth and final scenario indicate the low impact of the changes in the building structure on the assessment.

5.2 The influence of the building design on the LCC

As indicated in the results, the LCC remain the same when slowly increasing the LoC until 0,41. Beyond this level, the LCC increase as a result of almost doubled purchasing costs. This is due to applying more expensive and less common components within building designs at higher circular scenarios. The circular components are less common and subject to market effects. Suppliers indicate to determine their prices by supply and demand. The market volume of circular components is lower. Therefore, suppliers ask a higher margin for products labelled as 'circular'. The suppliers hardly relate the increase of material or labour time to higher purchasing costs.

The construction costs vary over the LoC by different type of building components applied in the designs of the scenarios. In general, recycled materials demand for similar construction techniques and result in comparable costs. However, there is no common standard in labour costs when assembling materials using dry connections. Some building components are less labour intensive (dry brickwork), where others are more intensive (dry finishing floor). At the highest LoCs, the costs drop by applying a low weight (prefabricated wood) structure.

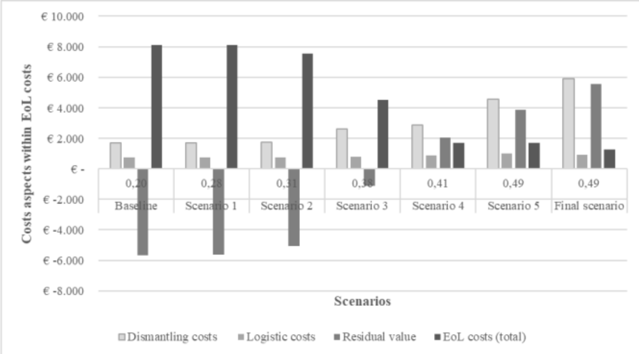


Figure 7: Costs aspects within the EoL over the designed scenarios.

In theory, high circular scenarios result in lower operational costs. This is due to the incorporation of dry connections and better accessibility of fixings resulting in undamaged components with possibilities for reuse. This is reflected in the results by a slight decrease in operational phase costs in the scenarios with a higher LoC. It could be discussed if the difference in operational costs between the low and high circular scenarios becomes higher when increasing the lifespan (section 5.3).

Considering (circular) principles of disassembly and reuse in building design, it possible to achieve a positive residual value (Allen, Beverley, Carter, Cheshire, Frater, Howe, & Rees, 2017). A circular building can better maintain in value compared to a traditional building. Figure 7 shows that scenarios with a higher LoC retain in value whereas the residual value is negative for low circular scenarios. This negative residual value is due to costs for dumping materials after their lifespan. These costs are prevented when applying circular alternative components intended for reuse or with the guarantee to be taken back by the supplier after their lifespan. However, the costs for dismantling the components without damage increases at the higher circularity scenarios. Therefore, certain costs remain within the EoL phase.

5.3 The effect of lifespan on the LCC

The amount of costs in the operational and EoL phase are dependent on the lifespan. Incorporating the investment perspectives of investors and corporations, the lifespans of 30, 70 and 100 years are most sensible to consider in the sensitivity analysis.

At 30 years of lifespan, figure 8 shows hardly any difference in the operational costs between the baseline and more circular scenarios. From 50 years of lifespan, the differences in operational costs between the scenarios increase. The reassembly of building components at scenarios with a higher LoC make it

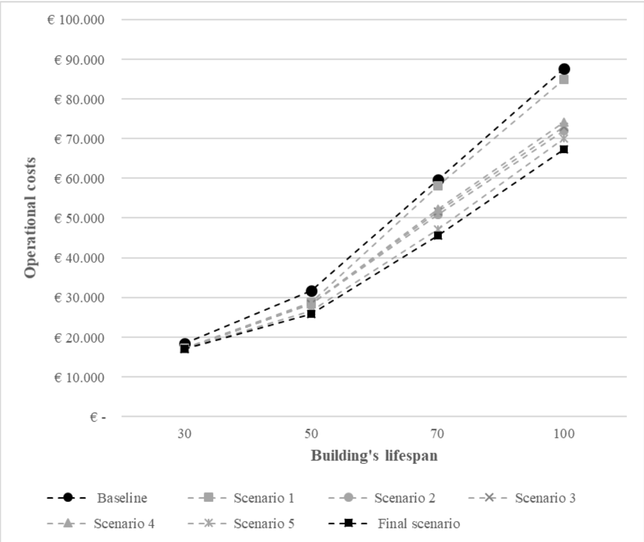


Figure 8: Trend in operational costs of scenarios over an increasing building’s lifespan.

possible to reach the materials ultimate lifespan, which results in a decrease of the operational costs. While the EoL costs for low circular scenarios in figure 9 increase, from a circularity level above 0,38 the EoL costs decreases over lifespan. Extending the lifespan results in more economic value due to value retention at circular buildings from a circularity level of 0,41 (see figure A in appendix VI). This results in a turning point at around 85 years of lifespan, where the LCC are lower for the highest reachable circular building (figure 10). However, this long investment period does not makes it economically attractive to design a highest reachable circularity level. The sharp increase in purchasing costs are too high compared to the small increase in circularity level (from 0,41 towards 0,49).

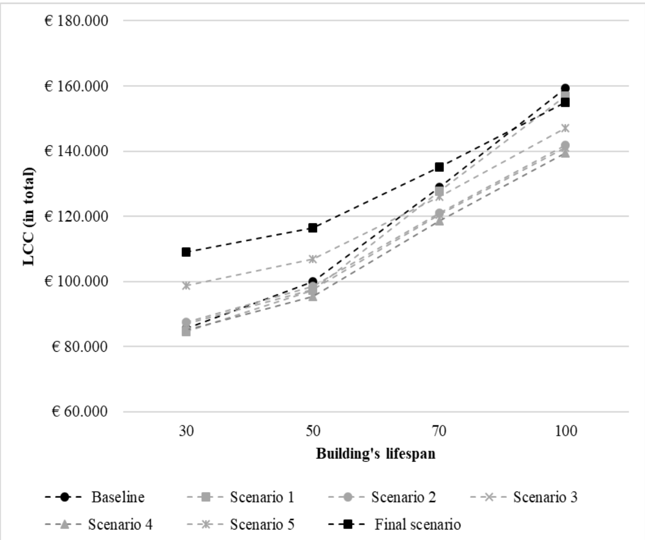


Figure 10: Trend in LCC of the scenarios over an increasing building’s lifespan.

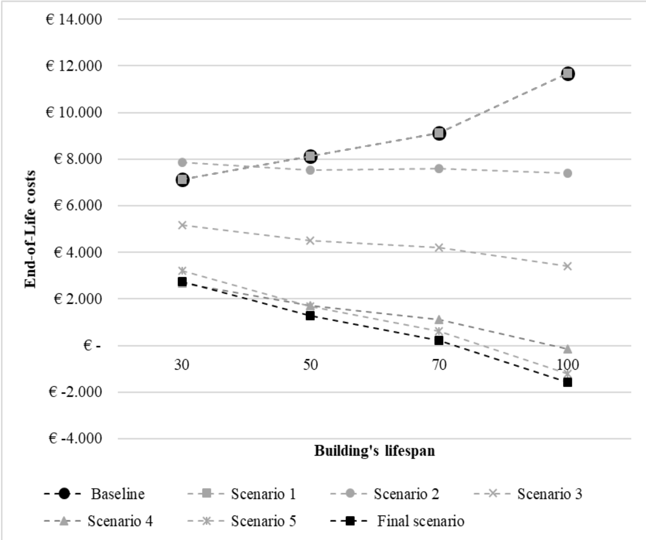


Figure 9: Trend in EoL costs of scenarios over an increasing building’s lifespan.

6. Discussion

6.1 Scientific contribution of relating LoC to LCC

LCC is important to discuss the economic feasibility of circular project investments by incorporating the costs of all life cycle phases. This makes sure that the initial costs will be balanced with the expected future operational costs. Only in that case the value of the CE becomes visible. However, architectural and engineering firms concentrate their efforts on the initial investment (purchasing and construction) costs. Aspects as replacement and EoL costs are rarely considered (Lowres & Hobbs, 2017). When including these costs, more economic value could be reached when increasing the LoC. The residual value of high circular scenarios remains stable over an increased lifespan. However, there are several debatable aspects in future calculation due to uncertainty about the discount, inflation and material escalation rates act on future increase of material scarcity. In addition, governmental regulations have an influence on pushing the purchase of materials or making their reuse attractive by more expensive dump. These aspects are not considered in the research, but probably have more influence on the purchase and residual value of buildings than the incorporated rates.

The research supports the statement of Fischer (2019) that circular construction increases the residual value of products. The value of flexibility and lifetime extension can be expressed as the existing building value plus its future potential (Fischer, 2019). In this research, only the components’ lifespan extension is included.

However, the influence of building flexibility through future add-ons and open space plans should also be included. Coenen (2019) introduced circularity assessment factors to assess the design adaptability for lifespan extension and reusability of components by standardized sizes. Future research should focus how to incorporate these factors in the BCI besides the factors of the PCI. However, applying these factors in LCC is not introduced yet. Hermans, Geraedts, Van Rijn, & Groep (2014) did come up with a tool that incorporates these factors to determine future buildings value. However, they expressed the building value by a score and not in economic value. The tool was therefore not considered as applicable.

Meanwhile, the research contributed to another relevant topic in the academic field by assessing the BCI tool of Verberne (2016) on its practicability. Next to the proposed modifications in section 3.2 and the above-proposed add-ons for the PCI factors, two other aspects are identified that expose the current lacks in the BCI model. Section 5.1 expresses the high influence of building components' mass on the LoC. It could be discussed if the factor mass is the best way to express the amount of material incorporated in the system. Verberne (2016) also concluded that the current BCI assessment is too dependent on the material mass. Applying high volume, but low mass materials, like insulation and roof elements, barely impact the BCI outcome in most situations. Future research should determine if a factor, such as volume, would be better. Furthermore, the BCI tool lacks the distinction between the priority order of the R-imperatives (of section 2.1). The type of material input or waste scenario has not been weighted by being more or less preferred. Incorporating this will forge the highest deployment of the component's values. Despite these remarks, the BCI tool could still be considered as a reliable tool as it incorporates the most important aspects to assess the building's LoC.

During the research, it appeared that the input for circularity and LCC assessment is highly dependent on collaboration between chain partners to create a closed loop supply chain (Leising, Quist, & Bocken, 2018). Arrangements with suppliers about guaranteed building component take back and value after lifespan, influences the components waste scenario and residual value. Besides, collaboration in the supply chain is important to make more efficient use of materials. Most circular materials will be remanufactured after their lifespan whereas reuse is more preferred. Arrangements with suppliers and clients for material reuse within sequential projects could result in better value retention of materials. The research was not able to influence this collaboration, therefore, some general assumptions are made (Appendix VII). In practice, it is possible to further increase the building's circularity level when clients, contractors and suppliers start with co-development of circular products. Most suppliers focus currently on the input of recycled content in their products. According to the research results there should be more focus on circular product design by developments in dry connection types and less on function integration.

6.2 Limitations in the LCC and LoC assessment

The research scope was to design scenarios with an increasing LoC by replacing circular alternative building components in the layers structure, skin and space plan. The functional unit excludes the building services, which contribute to a significant part of the operational costs in the LCC. Besides, the energy and water consumption during the lifespan is not incorporated. Favourable effects of applying other material types, like the thermal circulation of a wood structure, are not included. Furthermore, the design strategy of replacing alternative building components make that the LoC is limited by the building architecture. In addition, only materials available in the construction supply chain are included. Other material types could have resulted in a higher LoC, but it is unsure if these materials could be certificated as safe for construction and be reliable in price. On the other hand, the research certainty is limited by the current knowledge available about the material and labour costs. In the future, these costs could vary due to developments in new techniques for reutilization of materials and governmental pressure due to raised taxes. Furthermore, the research is limited by generating scenarios manually and not by a computer algorithm. Other beneficial scenarios could exist and might give other insights into the results. The last point of uncertainty is that the circularity assessment is only considered by the BCI tool of Verberne (2016). The researcher is fully aware of the existence of other assessment tools and the possibility of changes in the circularity level when applying other tools.

Another considerable aspect for future research is the influence of circular business models on LCC. In this research, the circular supplier business model is considered by applying circular materials and product design. However, this does not guarantee to generate profit by value retention, which is required to earn money in a CE. Other circular business models, focussed on product remanufacturing, reuse and reselling, could enhance value retention. The influence of these business models on the LCC should be incorporated to improve the insight into the economic feasibility of circular projects. This asks for a new perspective on how to integrate the costs and earnings of these models in LCC.

7. Conclusions and recommendations

A circularity level of 0,49 (on a scale of 0 (not circular) and 1 (circular)) was maximal feasible when applying circular alternative building component in the design of a standard one-family house. A higher circularity level is technically difficult to reach by the low circularity level of in the market available building components and the critically modified BCI tool.

In construction LCC is important to balance the initial costs with the expected future operational costs. The results show that it is possible for a standard one-family house to double the circularity level (till 0,41) while keeping the LCC equal. Higher circularity buildings are more expensive in purchasing costs through a market effect of over-pricing circular building components. In contrast, the residual value remains stable for high circular buildings at an increasing lifespan. This results in a turning point around 85 years of lifespan, where buildings with the highest reachable circularity level of 0,49 are lower in LCC. This long investment period does not makes it economically attractive to design a building with the highest reachable circularity level. This due to a sharp increase in purchasing costs compared to the small increase in circularity level (from 0,41 towards 0,49).

Circular construction involves the entire supply chain. Therefore, recommendations are considered for each partner as well for the overall chain.

- As the purchase price of circular building components seems to be subject to over-pricing due to a market-effect, government incentives are recommended to support the application of circular building components in construction. Besides, tax on material dump should encourage lifespan extension and prevention of dump.
- Collaboration within the supply chain is crucial in the CE. First to encourage co-development between contractor and supplier regarding circular product design to improve dry connection types and prevent function integration. Secondly, arrangements between parties could result in efficient material (re)use or guarantees regarding material take back by suppliers.
- Future research of academics and the industry is required to determine what economic value could be achieved when focussing on circular business models within LCC. Probably remanufacturing and reuse models provide more future potentials for value creation due to maintenance incomes and resale of already financial depreciated materials. In addition, it diminishes the chance of being affected by resource scarcity in the future.

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Experts in the construction industry of investing, costing, maintaining and supplying current and circular building components are thanked to share their information and to brainstorm about circular construction solutions. Being grateful at Dr. R. S. De Graaf, Dr. S. Bhochhibhoya and ir. N. Nielen for their time, effort and support during the research.

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Appendix I Formulas for the modified BCI assessment

Circularity Assessment

Material Circularity Indicator

Input information

M	Fraction mass [kg]
V	Fraction volume [m1/m2/m3/piece]
Fr	Fraction form recycled sources
Fu	Fraction from reused sources
Fb	Fraction biological material
Cr	Fraction of mass for recycling process
Cu	Fraction of mass for reuse
Cc	Fraction of mass for composting
Ef	Effiency of recycling process used to produced recycled foodstock
Ec	Effiency of recycling process used for product for recycling
Lt	Product technical lifetime
Lf	Product functional lifetime (according layers of Brand)

Formulas

V	Virgin foodstock	$X \leq 1$; V	= 1 - Fr - Fu - Fb
		$X > 1$; V	= (1 - Fr - Fu - Fb) * X
W0	Unrecoverable waste after use-phase		= 1 - Cr - Cu - Cc
Wf	Unrecoverable waste when producing recycled foodstock for product		= (1 - Ef) * Fr / Ef
Wc	Unrecoverable waste when proecessing recycling parts of a product		= (1 - Ec) * Cr
W	(Total) Mass of unrecoverable waste	$X \leq 1$; W	= W0 + (Wf/Wc)/2
		$X > 1$; W	= (W0 + (Wf/Wc)/2) * X
X	Utility of a product		= Lt / Lf
LFI			= 0,9 / X
MCI	Material Circularity Indicator		= max (0, (1 - LFI * F (X)))
if X>1	Virgin foodstock will be multiplied by utility of product as replacement factor		= (1 - Fr - Fu - Fb) * X
if X>1	Unrecoverable waste will be multiplied by utility of product as replacement factor		= (1 - Fr - Fu - Fb) * X

Product Circularity Indicator

Input information

Fi One of the DFF factors

Table 7: Fuzzy variables for DDF (E. Durmisevic et al. 2006)

Functional separation	separation of functions	1.0
	integration of function with same lifecycle into one element	0.6
	integration of function with different lifecycle into one element	0.1
Functional dependence	modular zoning	1.0
	planed interpenetrating for different solutions (overcapacity)	0.8
	planed for one solution	0.4
	unplanned interpenetrating	0.2
	total dependence	0.1
Technical life cycle / coordination	long (1) / long (2) or short (1) / short (2) or long (1) / short (2)	1.0
	medium (1) / long (2)	0.5
	short (1) / medium (2)	0.3
	short (1) / long (2)	0.1
Geometry of product edge	open linear	1.0
	symmetrical overlapping	0.8
	overlapping on one side	0.7
	unsymmetrical overlapping	0.4
	insert on one side	0.2
	insert on two sides	0.1
Standardisation of product edge	pre-made geometry	1.0
	half standardised geometry	0.5
	geometry made on the construction site	0.1
Type of connections	accessory external connection or connection system	1.0
	direct connection with additional fixing devices	0.8
	direct integral connection with inserts (pin)	0.6
	direct integral connection	0.5
	accessory internal connection	0.4
	filled soft chemical connection	0.2
	filled hard chemical connection	0.1
	direct chemical connection	0.1
Accessibility to fixings and intermediary	accessible	1.0
	accessible with additional operation with causes no damage	0.8
	accessible with additional operation which is reparable damage	0.6
	accessible with additional operation which causes damage	0.4
	not accessible – total damage of bought elements	0.1

Formulas

Fd	Summation of the DFF factors	= ∑ Fi
PCI	Product circularity Indicator	= 1/(max Fd) * Fd * MCI
		= 1/7 * Fd * MCI

System Circularity Indicator

Formulas

M total	Total product mass of the product range within the system (structure/skin/spaceplan)	= ∑ M
SCI (t)	Theoretical system circulularity indicator (based on the MCI compared to systems total weight)	= ∑ (M * MCI) / M total
SCI (p)	Practical system circulularity indicator (based on the PCI compared to systems total weight)	= ∑ (M * PCI) / M total

Building Circularity Indicator

Input information

LK Factor for system dependency (distinguish more relevant systems with longer lifetime (Verberne 2016))

Stuff	1	Skin	0,7
Spaceplan	0,9	Structure	0,2
Services	0,8	Site	0,1

Formulas

LK total	Summation of the system dependencies	= ∑ LK
		= 0,9 + 0,7 + 0,2
BCI (t)	Theoretical Building Circularity Indicator (based on the theoretical SCI)	= 1 / LK total * ∑ (SCI (t) * LK)
BCI (p)	Practical Building Circularity Indicator (based on the practical SCI)	= 1 / LK total * ∑ (SCI (p) * LK)

Appendix II Formulas for LCC

Life-Cycle Costing

Product costs
Purchase products (excluding VAT (BTW))

Construction costs

Labour	Labour for construction of the building (including subcontractor)	= h/m2 * m2 * hourly wage
Equipment		= wage/m2 * m2
Risk & profit margin	12% margin for risks, profit, general construction site and indirect costs	
Construction costs	Total of labour and equipment including percentages for risk & profit	= (labour + equipment) * 1,12

For example

Operating costs
Maintenance and replacement of building components, required to operate the building in good conditions.

Maintenance costs	Costs mostly man-hours (for cleaning, inspection and repairing)	
Replacement costs	Costs for new product, man-hours (for removing + placing new product) and dump of removed product	
	The same products with the same conditions will be replaced.	
Replacement costs includes:		
Product costs	Purchase costs of the product, converted with the NPV incl. escalation rate of material.	= Costs/m2 * m2 / NPV
NPV	Present value of the cash flow over a period of the building's lifespan	= (1 + i - j - k) ^ (years / 2)
i	Discount rate = 3% (government interest 0,7%, risk 2%, profit 0,3%)	= 0,03
j	Inflation (1,81%)	= 0,0181
k	Escalation rate of the material	
Years	Years of lifespan of building	= Lifespan of building in relevant year
Construction costs	Costs for labour (man-hours) and equipment, converted with the NPV.	= (Labour * 2 + equipment) / NPV
	Labour costs are multiplied by two for both removing and placing the product.	

Example of maintenance costs	('3 Material costs'!T21*'5 LCC 50y'!F21)/((1+$E$4-$F$4)^'5 LCC 50y'!R7)	Source: '5 LCC 50y [R21]
	(Maintenance costs/m2 * m2)/((1+i-j)^years))	
Example of replacement costs	(('3 Material costs'!G21*'5 LCC 50y'!F21)/((1+$E$4-$F$4-'3 Material costs'!AA21)^'5 LCC 50y'!X7))+((L21*2+M21)/((1+$E$4-$F$4)^X7))+(-BD21)	Source: '5 LCC 50y [X21]
	(Product costs/m2 * m2)/((1+i-j-k)^years)) + ((labour*2+equipment)/((1+i-j)^years)) + Dump costs	

End-of-Life costs
Costs for the client at the End-of-Life of a building (costs to remove the building).
Costs consist of labour to dismantle the building and costs for logistics of the components. Besides there are costs when dumping the materials or a residual value when reusing it.
Cost breakdown structure is categorized in the waste scenarios: reuse, remanufacture and recycling.

	Reuse	**Remanufacture**	**Recycling/recovery**
Dismantling costs	High attention for causing damage	Some attention for causing damage	No attention for causing damage
	90% of construction man-hours	*75% of construction man-hours*	*15% of construction man-hours.*
Logistic costs	(Big) elements on racks or pallets	Elements on racks or pallets.	Elements in container
	€ 0,25 / 1000kg / km	€ 0,25 / 1000kg / km	€ 0,15 / 1000kg / km
	Distance to (first) supplier is 200 km.	*Distance to supplier is 100 km.*	*Distance to waste processor is 70 km.*
Residual value	Component level	Material level	Rubbish level
	Value based 45% of normal component pric	*Costs for dumping debris*	*Costs for dumping debris*
	Additional: escalation rate materials	*Non costs, when take back materials by suppl*	*Additional: escalation rate at steel + aluminium*

Debris costs

Material	**Category**	**€/tonne**
Concrete	Clean dump	€ 2,50
	Elements 50cmx50cm	€ 4,00
Ceramic	Clean dump	€ 2,50
Sand-lime/anhydrite	Construction and demolition waste	€ 175,00
Wood unpainted	Wood class A	€ 75,00
Wood painted/boards	Wood class B	€ 85,00
Insulation material	Construction and demolition waste	€ 175,00
	Take back materials by supplier	€ -
	Cotton 40kg	€ *0,75* per kg

Value scarce materials

Material	**Category**	**€/tonne**
Lintel	Steel	€ 900,00
Frames	Aluminium	€ 700,00

Distmantling

Example of percentage man-hours for dismantling	ALS(AC21="Recycle";0,15;(ALS(AC21="Remanufacture";0,75;(ALS(AC21="Reuse";0,9;0,15)))))	Source: '3 Material costs [AE21]
	ALS(Waste scenario=Recycling = 15% man-hours;(ALS(Waste scenario=Remanufacture = 75% of man-hours;(ALS(Waste scenario = Reuse = 90% of man-hours; Others = 15% man	
Example of dismantling costs	('3 Material costs'!AE21*L22)/((1+$E$4-$F$4)^$A$7)	Source: '5 LCC 50y [BB22]
	(Percentage man-hours for dismantling (above)*Labour (man-hours))/((1+i-j)^years))	

Logistics

Example of km for logistics	ALS(AC21="Recycle";70;(ALS(AC21="Remanufacture";100;(ALS(AC21="Reuse";200;70)))))	Source: '3 Material costs [AF21]
	ALS(Waste scenario ="Recycle = 70 km;(ALS(Waste scenario ="Remanufacture = 100 km;(ALS(Waste scenario ="Reuse = 200km;Others = 70km)))))	
Example of size for logistics	ALS(AC21="Recycle";0,15;(ALS(AC21="Remanufacture";0,25;(ALS(AC21="Reuse";0,25;0,15)))))	Source: '3 Material costs [AG21]
	ALS(Waste scenario ="Recycle = €0,15/kg/tonne;(ALS(Waste scenario ="Remanufacture = €0,25/kg/tonne;(ALS(Waste scenario ="Reuse = €0,25/kg/tonne;Others = €0,15/kg/tonn	
Example of logistic costs	(E22*'3 Material costs'!AF21*'3 Material costs'!AG21/1000)/((1+$E$4-$F$4)^$A$7)	Source: '5 LCC 50y [BC22]
	(Mass*Km for logistics*Size for logistics/per tonne)/((1+i-j)^years))	

Residual value

	The residual value of components could be distinguished by costs for dumping the materials after lifespan or value when these will be reused.	
Example of costs	Debris costs per tonne (see above)	Source: '3 Material costs [AI21]
Example of residual value (costs)	(- E22/1000*'3 Material costs'!AI21/((1+$E$4-$F$4-'3 Material costs'!AA21)^$A$7)	Source: '5 LCC 50y [BD22]
	(minus for costs) Mass per tonne* Debris costs per tonne /((1+i-j-k)^years))	
Example of value	0,45*G84	Source: '3 Material costs [AH84]
	45% * product costs per m2	
Example of residual value (value)	(F68*'3 Material costs'!AH84)/((1+$E$4-$F$4-'3 Material costs'!AA21)^$A$7)	Source: '5 LCC 50y [BD68]
	Area in m2 * Value per m2 /((1+i-j-k)^years))	
EoL costs	(BB22+BC22-BD22)	Source: '5 LCC 50y [BE22]
	Distmantling costs + Logistic costs - Residual value	

Life-Cycle Costs
Costs of all life cycle phases (initial-, construction-, operational- and EoL-phase).

Example of LCC	K22+N22+AZ22+BF22	Source: '5 LCC 50y [BH22]
	Initial phase + Construction phase + Operational phase + EoL phase.	

Appendix III Building design and LoC of baseline and final scenario

Elements	Current	MCI	PCI/SCI	Full circular	MCI	PCI/SCI
Structure						
Walls	Prefabricated concrete	0,63	0,36	Wood elements (services not integrated)	0,40	0,33
Ground floor	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Prefabricated - wood elements	1,00	0,87
First and second floor	Precast concrete slabs (kanaalplaatvloer	0,57	0,21	Prefabricated - wood elements	1,00	0,87
Roof	Prefabricated roofelements Isover syste	0,38	0,26	Prefabricated - flax elements	1,00	0,81
Foundation beams	Concrete beams prefabricated	0,59	0,53	Recycled concrete 100%	0,78	0,70
Foundation piles	Prefabricated concrete piles 250x250mm	0,59	0,47			
Stairs	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout) (take ba	1,00	0,91
			0,42			**0,65**
Skin						
Roofcovering	Concrete tiles	0,25	0,25	Clay tiles (reuse)	1,00	1,00
Insulation (wall)	Glass wool Rc 4,7	0,15	0,08	Flax Rc 4,7 (160mm)	0,94	0,54
Wall cladding	Brickwork (chemical connections)	1,00	0,54	Brickwork (dry connections)	1,00	0,71
Front/back door	Hard wood door	0,58	0,49	Recycled hard wood door	1,00	0,86
Window/doorframes	Hard wood frame	0,55	0,45	Recycled wood window/door frame	1,00	0,81
Door + window glass	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23
Lintel	Steel	0,98	0,54	Steel	0,98	0,54
Gutter	Aluminum	0,71	0,58	Aluminum	0,71	0,58
Window sill (outside)	Ceramic	0,94	0,54	Composite biobased	0,96	0,55
			0,36			**0,65**
Spaceplan						
Finishing floor ground floor	Anhydride	0,12	0,02	Dry floor (egalisation pearls + wood insul	0,64	0,34
Finishing floor first/second floor	Anhydride	0,12	0,02	Dry floor (egalisation pearls + wood insul	0,29	0,15
Pre-wall (services)				Agricultural fibres	0,91	0,43
Inner walls	Gypsum blocks 70mm	0,12	0,02	Reused and recycled gypsum + flax (meta	0,95	0,45
Inner door frames	Steel	0,68	0,59	Recycled wood door frame	1,00	0,87
Inner doors	Wood including honeycomb structure	0,54	0,49	Wood including honeycomb structure	0,44	0,41
Inner door sills	Artificial stone (kunststeen)	0,12	0,07	Composite biobased	0,96	0,53
Windowsill (vensterbank)	Composite (Bianco Wit composiet)	0,11	0,05	Wood	0,44	0,20
Wall tiles (toilet + bathroom)	Ceramic tile in cement	0,50	0,23	PVC Panells (dry connections)	0,46	0,46
Floor tiles (toilet)	Ceramic tile in cement	0,34	0,16	PVC Panells (dry connections)	0,46	0,46
Floor tiles (bathroom)	Ceramic tile in cement	0,34	0,16	PVC Panells (dry connections)	0,46	0,46
			0,03			**0,34**
Building circularity indicator			**0,20**			**0,49**

Appendix IV Results LoCs per scenario

Dark grey: modification in comparison to previous scenario
Light grey: modification in comparison to baseline.

Elements	Current	MCI	PCI/SCI	Scenario 1	MCI	PCI/SCI	Scenario 2	MCI	PCI/SCI	Scenario 3	MCI	PCI/SCI
										Structure		
Walls	Prefabricated concrete	0,63	0,36	Prefabricated concrete	0,63	0,36	Prefabricated concrete	0,63	0,36	Prefabricated concrete	0,63	0,36
Ground floor	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34
First and second floor	Precast concrete slabs (kanaalplaatvloer)	0,57	0,21	Precast concrete slabs (kanaalplaatvloer)	0,57	0,21	Precast concrete slabs (kanaalplaatvloer)	0,57	0,21	Precast concrete slabs (kanaalplaatvloer)	0,57	0,21
Roof	Prefabricated roofelements Isover syste	0,38	0,26	Prefabricated roofelements Isover syster	0,38	0,26	Prefabricated roofelements Isover syster	0,38	0,26	Prefabricated roofelements Isover syster	0,38	0,26
Foundation beams	Concrete beams prefabricated	0,59	0,53	Concrete beams prefabricated	0,59	0,53	Concrete beams prefabricated	0,59	0,53	Concrete beams prefabricated	0,59	0,53
Foundation piles	Prefabricated concrete piles 250x250mm	0,59	0,47	Prefabricated concrete piles 250x250mm	0,59	0,47	Prefabricated concrete piles 250x250mm	0,59	0,47	Prefabricated concrete piles 250x250mm	0,59	0,47
Stairs	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout)	0,41	0,37
			0,42			**0,36**			**0,36**			**0,36**
										Skin		
Roofcovering	Concrete tiles	0,25	0,25	Clay tiles (recycle)	1,00	1,00	Clay tiles (recycle)	1,00	1,00	Clay tiles (recycle)	1,00	1,00
Insulation (wall)	Glass wool Rc 4,7	0,15	0,08	Glass wool Rc 4,7	0,15	0,08	Glass wool Rc 4,7	0,15	0,08	Glass wool Rc 4,7	0,15	0,08
Wall cladding	Brickwork (chemical connections)	1,00	0,54	Brickwork (chemical connections)	1,00	0,54	Brickwork (chemical connections)	1,00	0,54	Brickwork (chemical connections)	1,00	0,54
Front/back door	Hard wood door	0,58	0,49	Hard wood door	0,58	0,49	Recycled hard wood door	1,00	0,86	Recycled hard wood door	1,00	0,86
Window/doorframes	Hard wood frame	0,55	0,45	Hard wood frame	0,55	0,45	Recycled wood window/door frame	1,00	0,81	Recycled wood window/door frame	1,00	0,81
Door + window glass	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23
Lintel	Steel	0,98	0,54	Steel	0,98	0,54	Steel	0,98	0,54	Steel	0,98	0,54
Gutter	Aluminum	0,71	0,58	Aluminum	0,71	0,58	Aluminum	0,71	0,58	Aluminum	0,71	0,58
Window sill (outside)	Ceramic	0,94	0,54	Ceramic	0,94	0,54	Composite biobased	0,96	0,55	Composite biobased	0,96	0,55
			0,36			**0,56**			**0,57**			**0,57**
										Spaceplan		
Finishing floor ground floor	Anhydride	0,12	0,02	Anhydride	0,12	0,02	Wet floor (anhydrite + foil)	0,12	0,03	Dry floor (egalisation pearls + EPS insulat	0,50	0,26
Finishing floor first/second floor	Anhydride	0,12	0,02	Anhydride	0,12	0,02	Wet floor (anhydrite + foil)	0,12	0,03	Dry floor (egalisation pearls + EPS insulat	0,50	0,26
Pre-wall (services)												
Inner walls	Gypsum blocks 70mm	0,12	0,02	Gypsum blocks 70mm	0,12	0,02	Sand lime blocks (eco-element)	0,98	0,20	Sand lime blocks (eco-element)	0,98	0,20
Inner door frames	Steel	0,68	0,59	Steel	0,68	0,59	Steel	0,68	0,59	Steel	0,68	0,59
Inner doors	Wood including honeycomb structure	0,54	0,49	Wood including honeycomb structure	0,54	0,49	Wood including honeycomb structure	0,44	0,41	Wood including honeycomb structure	0,44	0,41
Inner door sills	Artificial stone (kunststeen)	0,12	0,07	Artificial stone (kunststeen)	0,12	0,07	Composite biobased	0,96	0,53	Composite biobased	0,96	0,53
Windowsill (vensterbank)	Composite (Bianco Wit composiet)	0,11	0,05	Composite (Bianco Wit composiet)	0,11	0,05	Composite (Bianco Wit composiet)	0,11	0,05	Composite (Bianco Wit composiet)	0,11	0,05
Wall tiles (toilet + bathroom)	Ceramic tile in cement	0,50	0,23	Ceramic tile in cement	0,50	0,23	Ceramic tile in cement	0,50	0,23	Ceramic tile in cement	0,50	0,23
Floor tiles (toilet)	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16
Floor tiles (bathroom)	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16	Ceramic tile in cement	0,34	0,16
			0,03			**0,03**			**0,08**			**0,08**
Building circularity indicator			**0,20**			**0,28**			**0,31**			**0,38**

Elements	Scenario 4	MCI	PCI/SCI	Scenario 5	MCI	PCI/SCI	Full circular	MCI	PCI/SCI	Current + 4 alternatives	MCI	PCI/SCI
Walls	Prefabricated concrete	0,63	0,36	Wood elements (services integrated)	0,40	0,31	Wood elements (services not integrated)	0,40	0,33	Prefabricated concrete	0,73	0,41
Ground floor	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Ribbed floor (ribcassettevloer) incl. insula	0,59	0,34	Prefabricated - wood elements	1,00	0,87	Ribbed floor (ribcassettevloer) incl. insulatio	0,59	0,34
First and second floor	Precast concrete slabs (kanaalplaatvloer)	0,57	0,21	Prefabricated - wood elements	1,00	0,79	Prefabricated - wood elements	1,00	0,87	Precast concrete slabs (kanaalplaatvloer)	0,68	0,25
Roof	Prefabricated roofelements Isover syster	0,38	0,26	Prefabricated - flax elements	1,00	0,69	Prefabricated - flax elements	1,00	0,81	Prefabricated roofelements Isover systemro	0,38	0,26
Foundation beams	Concrete beams prefabricated	0,59	0,53	Concrete beams prefabricated	0,59	0,53	Recycled concrete 100%	0,78	0,70	Concrete beams prefabricated	0,59	0,53
Foundation piles	Prefabricated concrete piles 250x250mm	0,59	0,47							Prefabricated concrete piles 250x250mm (5	0,59	0,47
Stairs	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout)	0,41	0,37	Pine wood/plywood (vurenhout) (take back for	1,00	0,91	Pine wood/plywood (vurenhout)	0,41	0,37
			0,36			**0,48**			**0,65**			**0,42**
Roofcovering	Clay tiles (recycle)	1,00	1,00	Clay tiles (recycle)	1,00	1,00	Clay tiles (reuse)	1,00	1,00	Clay tiles (recycle)	1,00	1,00
Insulation (wall)	Flax Rc 4,7 (160mm)	0,94	0,54	Flax Rc 4,7 (160mm)	0,94	0,54	Flax Rc 4,7 (160mm)	0,94	0,54	Glass wool Rc 4,7	0,15	0,08
Wall cladding	Brickwork (dry connections)	1,00	0,71	Brickwork (dry connections)	1,00	0,71	Brickwork (dry connections)	1,00	0,71	Brickwork (dry connections)	1,00	0,71
Front/back door	Recycled hard wood door	1,00	0,86	Recycled hard wood door	1,00	0,86	Recycled hard wood door	1,00	0,86	Hard wood door	0,58	0,49
Window/doorframes	Recycled wood window/door frame	1,00	0,81	Recycled wood window/door frame	1,00	0,81	Recycled wood window/door frame	1,00	0,81	Hard wood frame	0,55	0,45
Door + window glass	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23	HR++ glass	0,42	0,23
Lintel	Steel	0,98	0,54	Steel	0,98	0,54	Steel	0,98	0,54	Steel	0,98	0,54
Gutter	Aluminum	0,71	0,58	Aluminum	0,71	0,58	Aluminum	0,71	0,58	Aluminum	0,71	0,58
Window sill (outside)	Composite biobased	0,96	0,55	Composite biobased	0,96	0,55	Composite biobased	0,96	0,55	Ceramic	0,94	0,54
			0,65			**0,65**			**0,65**			**0,62**
Finishing floor ground floor	Dry floor (egalisation pearls + EPS insulat	0,50	0,26	Dry floor (egalisation pearls + wood insul	0,64	0,34	Dry floor (egalisation pearls + wood insulation)	0,64	0,34	Dry floor (egalisation pearls + wood insulatic	0,64	0,34
Finishing floor first/second floor	Dry floor (egalisation pearls + EPS insulat	0,50	0,26	Dry floor (egalisation pearls + wood insul	0,64	0,34	Dry floor (egalisation pearls + wood insulation)	0,29	0,15	Dry floor (egalisation pearls + wood insulatic	0,64	0,34
Pre-wall (services)							Agricultural fibres	0,91	0,43			
Inner walls	Sand lime blocks (eco-element)	0,98	0,20	Reused and recycled gypsum + flax (meta	0,95	0,45	Reused and recycled gypsum + flax (metalstud)	0,95	0,45	Reused and recycled gypsum + flax (metalstu	0,95	0,45
Inner door frames	Recycled wood door frame	1,00	0,87	Recycled wood door frame	1,00	0,87	Recycled wood door frame	1,00	0,87	Steel	0,68	0,59
Inner doors	Wood including honeycomb structure	0,44	0,41	Wood including honeycomb structure	0,44	0,41	Wood including honeycomb structure	0,44	0,41	Wood including honeycomb structure	0,54	0,49
Inner door sills	Composite biobased	0,96	0,53	Composite biobased	0,96	0,53	Composite biobased	0,96	0,53	Artificial stone (kunststeen)	0,12	0,07
Windowsill (vensterbank)	Wood	0,44	0,20	Wood	0,44	0,20	Wood	0,44	0,20	Composite (Bianco Wit composiet)	0,11	0,05
Wall tiles (toilet + bathroom)	Ceramic recycled tiles in cement	0,58	0,27	Ceramic recycled tiles in cement	0,58	0,27	PVC Panells (dry connections)	0,46	0,46	Ceramic tile in cement	0,50	0,23
Floor tiles (toilet)	Ceramic recycled tiles in cement	0,58	0,27	Ceramic recycled tiles in cement	0,58	0,27	PVC Panells (dry connections)	0,46	0,46	Ceramic tile in cement	0,34	0,16
Floor tiles (bathroom)	Ceramic recycled tiles in cement	0,58	0,27	Ceramic recycled tiles in cement	0,58	0,27	PVC Panells (dry connections)	0,46	0,46	Ceramic tile in cement	0,34	0,16
			0,23			**0,36**			**0,34**			**0,35**
Building circularity indicator			**0,41**			**0,49**			**0,49**			**0,46**

Appendix V Results LCC per scenario

Elements	Current	Initial	Construction	Operational	End-of-Life	LCC	Scenario 1	Initial	Construction	Operational	End-of-Life	LCC
Walls	Prefabricated concrete	€ 8.783,46	2070,01	€ -	€ 428,63	€ 11.282,10	Prefabricated concrete	€ 8.783,46	€ 2.070,01	€ -	€ 428,63	€ 11.282,10
Ground floor	Ribbed floor (ribcassettevloer) incl. insula	€ 1.714,77	503,13	€ -	€ 100,08	2317,99	Ribbed floor (ribcassettevloer) incl. insulati	€ 1.714,77	€ 503,13	€ -	€ 100,08	€ 2.317,99
First and second floor	Precast concrete slabs (kanaalplaatvloer	€ 4.041,64	858,08	€ -	€ 243,12	5142,84	Precast concrete slabs (kanaalplaatvloer)	€ 4.041,64	€ 858,08	€ -	€ 243,12	€ 5.142,84
Roof	Prefabricated roofelements Isover syste	€ 3.723,90	1168,73	€ -	€ 252,70	5145,34	Prefabricated roofelements Isover systemr	€ 3.723,90	€ 1.168,73	€ -	€ 252,70	€ 5.145,34
Foundation beams	Concrete beams prefabricated	€ 1.408,40	1938,49	€ -	€ 284,41	3631,31	Concrete beams prefabricated	€ 1.408,40	€ 1.938,49	€ -	€ 284,41	€ 3.631,31
Foundation piles	Prefabricated concrete piles 250x250mm	€ 620,75	1771,28	€ -	€ 158,31	2550,34	Prefabricated concrete piles 250x250mm (5	€ 620,75	€ 1.771,28	€ -	€ 158,31	€ 2.550,34
Stairs	Pine wood/plywood (vurenhout)	€ 1.600,00	4385,38	€ -	€ 299,35	6284,73	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73
	Structure	**€ 21.892,92**	**€ 12.695,11**	**€ -**	**€ 1.766,60**	**36354,63**	**Structure**	**€ 21.892,92**	**€ 12.695,11**	**€ -**	**€ 1.766,60**	**€ 36.354,63**
Roofcovering	Concrete tiles	€ 422,75	€ 1.552,05	€ 2.908,30	€ 94,27	€ 4.977,37	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 90,66	€ 2.330,98
Insulation (wall)	Glass wool Rc 4,7	€ 560,34	€ 965,07	€ -	€ 64,91	€ 1.590,32	Glass wool Rc 4,7	€ 560,34	€ 965,07	€ -	€ 64,91	€ 1.590,32
Wall cladding	Brickwork (chemical connections)	€ 1.291,73	€ 5.021,87	€ 1.404,41	€ 354,93	€ 8.072,94	Brickwork (chemical connections)	€ 1.291,73	€ 5.021,87	€ 1.404,41	€ 354,93	€ 8.072,94
Front/back door	Hard wood door	€ 2.420,00	€ 608,19	€ 5.032,44	€ 49,31	€ 8.109,95	Hard wood door	€ 2.420,00	€ 608,19	€ 5.032,44	€ 49,31	€ 8.109,95
Window/doorframes	Hard wood frame	€ 2.830,00	€ 576,54	€ 16.923,59	€ 65,49	€ 20.395,62	Hard wood frame	€ 2.830,00	€ 576,54	€ 16.923,59	€ 65,49	€ 20.395,62
Door + window glass	HR++ glass	€ -	€ -	€ -	€ -	€ -	HR++ glass	€ -	€ -	€ -	€ -	€ -
Lintel	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02
Gutter	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54
Window sill (outside)	Ceramic	€ 79,80	€ 236,14	€ 181,62	€ 13,92	€ 511,49	Ceramic	€ 79,80	€ 236,14	€ 181,62	€ 13,92	€ 511,49
	Skin	**€ 8.183,46**	**€ 9.933,08**	**€ 26.450,37**	**€ 647,35**	**€ 45.214,25**	**Skin**	**€ 8.448,98**	**€ 9.933,08**	**€ 23.542,07**	**€ 643,73**	**€ 42.567,86**
Finishing floor ground floor	Anhydride	€ 272,00	€ 387,52	€ -	€ 632,45	€ 1.291,97	Anhydride	€ 272,00	€ 387,52	€ -	€ 632,45	€ 1.291,97
Finishing floor first/second floor	Anhydride	€ 408,27	€ 440,24	€ 306,87	€ 938,23	€ 2.093,60	Anhydride	€ 408,27	€ 440,24	€ 306,87	€ 938,23	€ 2.093,60
Pre-wall (services)			€ -	€ -	€ -	€ -			€ -	€ -	€ -	€ -
Inner walls	Gypsum blocks 70mm	€ 869,94	€ 1.947,04	€ 1.870,61	€ 476,81	€ 5.164,40	Gypsum blocks 70mm	€ 869,94	€ 1.947,04	€ 1.870,61	€ 476,81	€ 5.164,40
Inner door frames	Steel	€ 356,72	€ 188,71	€ -	€ 7,24	€ 552,67	Steel	€ 356,72	€ 188,71	€ -	€ 7,24	€ 552,67
Inner doors	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92
Inner door sills	Artificial stone (kunststeen)	€ 30,99	€ 36,96	€ -	€ 4,53	€ 72,48	Artificial stone (kunststeen)	€ 30,99	€ 36,96	€ -	€ 4,53	€ 72,48
Windowsill (vensterbank)	Composite (Bianco Wit composiet)	€ 122,17	€ 141,22	€ 291,51	€ 17,67	€ 572,57	Composite (Bianco Wit composiet)	€ 122,17	€ 141,22	€ 291,51	€ 17,67	€ 572,57
Wall tiles (toilet + bathroom)	Ceramic tile in cement	€ 278,58	€ 857,86	€ 1.438,78	€ 111,23	€ 2.686,45	Ceramic tile in cement	€ 278,58	€ 857,86	€ 1.438,78	€ 111,23	€ 2.686,45
Floor tiles (toilet)	Ceramic tile in cement	€ 45,24	€ 52,35	€ 110,84	€ 8,94	€ 217,36	Ceramic tile in cement	€ 45,24	€ 52,35	€ 110,84	€ 8,94	€ 217,36
Floor tiles (bathroom)	Ceramic tile in cement	€ 182,21	€ 204,08	€ 441,14	€ 37,35	€ 864,78	Ceramic tile in cement	€ 182,21	€ 204,08	€ 441,14	€ 37,35	€ 864,78
	Spaceplan	**€ 2.958,61**	**€ 4.426,81**	**€ 5.022,71**	**€ 2.255,09**	**€ 14.663,22**	**Spaceplan**	**€ 2.958,61**	**€ 4.426,81**	**€ 5.022,71**	**€ 2.255,09**	**€ 14.663,22**
		€ 33.034,99	**€ 27.055,00**	**€ 31.473,08**	**€ 4.669,04**	**€ 96.232,10**		**€ 33.300,51**	**€ 27.055,00**	**€ 28.564,78**	**€ 4.665,42**	**€ 93.585,71**

Elements	Scenario 2	Initial	Construction	Operational	End-of-Life	LCC	Scenario 3	Initial	Construction	Operational	End-of-Life	LCC
												Layer: Structure
Walls	Prefabricated concrete	€ 8.783,46	€ 2.070,01	€ -	€ 428,63	€ 11.282,10	Prefabricated concrete	€ 8.783,46	€ 2.070,01	€ -	€ 428,63	€ 11.282,10
Ground floor	Ribbed floor (ribcassettevloer) incl. insulati	€ 1.714,77	€ 503,13	€ -	€ 100,08	€ 2.317,99	Ribbed floor (ribcassettevloer) incl. insulati	€ 1.714,77	€ 503,13	€ -	€ 100,08	€ 2.317,99
First and second floor	Precast concrete slabs (kanaalplaatvloer)	€ 4.041,64	€ 858,08	€ -	€ 243,12	€ 5.142,84	Precast concrete slabs (kanaalplaatvloer)	€ 4.041,64	€ 858,08	€ -	€ 243,12	€ 5.142,84
Roof	Prefabricated roofelements Isover systemr	€ 3.723,90	€ 1.168,73	€ -	€ 252,70	€ 5.145,34	Prefabricated roofelements Isover systemr	€ 3.723,90	€ 1.168,73	€ -	€ 252,70	€ 5.145,34
Foundation beams	Concrete beams prefabricated	€ 1.408,40	€ 1.938,49	€ -	€ 284,41	€ 3.631,31	Concrete beams prefabricated	€ 1.408,40	€ 1.938,49	€ -	€ 284,41	€ 3.631,31
Foundation piles	Prefabricated concrete piles 250x250mm (5	€ 620,75	€ 1.771,28	€ -	€ 158,31	€ 2.550,34	Prefabricated concrete piles 250x250mm (5	€ 620,75	€ 1.771,28	€ -	€ 158,31	€ 2.550,34
Stairs	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73
	Structure	**€ 21.892,92**	**€ 12.695,11**	**€ -**	**€ 1.766,60**	**€ 36.354,63**	**Structure**	**€ 21.892,92**	**€ 12.695,11**	**€ -**	**€ 1.766,60**	**€ 36.354,63**
							Layer: Skin					
Roofcovering	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 90,66	€ 2.330,98	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 90,66	€ 2.330,98
Insulation (wall)	Glass wool Rc 4,7	€ 560,34	€ 965,07	€ -	€ 64,91	€ 1.590,32	Glass wool Rc 4,7	€ 560,34	€ 965,07	€ -	€ 64,91	€ 1.590,32
Wall cladding	Brickwork (chemical connections)	€ 1.291,73	€ 5.021,87	€ 1.404,41	€ 354,93	€ 8.072,94	Brickwork (chemical connections)	€ 1.291,73	€ 5.021,87	€ 1.404,41	€ 354,93	€ 8.072,94
Front/back door	Recycled hard wood door	€ 2.710,40	€ 608,19	€ 5.062,58	€ 45,55	€ 8.426,73	Recycled hard wood door	€ 2.710,40	€ 608,19	€ 5.062,58	€ 45,55	€ 8.426,73
Window/doorframes	Recycled wood window/door frame	€ 3.169,60	€ 576,54	€ 16.939,32	€ 45,24	€ 20.730,70	Recycled wood window/door frame	€ 3.169,60	€ 576,54	€ 16.939,32	€ 45,24	€ 20.730,70
Door + window glass	HR++ glass	€ -	€ -	€ -	€ -	€ -	HR++ glass	€ -	€ -	€ -	€ -	€ -
Lintel	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02
Gutter	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54
Window sill (outside)	Composite biobased	€ 155,61	€ 180,04	€ 45,09	€ 13,81	€ 394,55	Composite biobased	€ 155,61	€ 180,04	€ 45,09	€ 13,81	€ 394,55
	Skin	**€ 9.154,79**	**€ 9.876,98**	**€ 23.451,40**	**€ 619,60**	**€ 43.102,77**	**Skin**	**€ 9.154,79**	**€ 9.876,98**	**€ 23.451,40**	**€ 619,60**	**€ 43.102,77**
							Layer: Spaceplan					
Finishing floor ground floor	Wet floor (anhydrite + foil)	€ 276,00	€ 945,90	€ -	€ 632,45	€ 1.854,35	Dry floor (egalisation pearls + EPS insulatio	€ 1.152,80	€ 866,88	€ -	€ 137,29	€ 2.156,97
Finishing floor first/second floor	Wet floor (anhydrite + foil)	€ 414,28	€ 1.278,36	€ 306,87	€ 938,23	€ 2.937,73	Dry floor (egalisation pearls + EPS insulatio	€ 1.730,35	€ 1.301,19	€ 291,19	€ 206,07	€ 3.528,81
Pre-wall (services)		€ -	€ -	€ -	€ -	€ -		€ -	€ -	€ -	€ -	€ -
Inner walls	Sand lime blocks (eco-element)	€ 952,10	€ 1.947,04	€ 1.681,70	€ 734,84	€ 5.315,68	Sand lime blocks (eco-element)	€ 952,10	€ 1.947,04	€ 1.681,70	€ 734,84	€ 5.315,68
Inner door frames	Steel	€ 356,72	€ 188,71	€ -	€ 7,24	€ 552,67	Steel	€ 356,72	€ 188,71	€ -	€ 7,24	€ 552,67
Inner doors	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92
Inner door sills	Composite biobased	€ 44,04	€ 50,96	€ -	€ 3,88	€ 98,88	Composite biobased	€ 44,04	€ 50,96	€ -	€ 3,88	€ 98,88
Windowsill (vensterbank)	Composite (Bianco Wit composiet)	€ 122,17	€ 141,22	€ 291,51	€ 17,67	€ 572,57	Composite (Bianco Wit composiet)	€ 122,17	€ 141,22	€ 291,51	€ 17,67	€ 572,57
Wall tiles (toilet + bathroom)	Ceramic tile in cement	€ 278,58	€ 857,86	€ 1.438,78	€ 111,23	€ 2.686,45	Ceramic tile in cement	€ 278,58	€ 857,86	€ 1.438,78	€ 111,23	€ 2.686,45
Floor tiles (toilet)	Ceramic tile in cement	€ 45,24	€ 52,35	€ 110,84	€ 8,94	€ 217,36	Ceramic tile in cement	€ 45,24	€ 52,35	€ 110,84	€ 8,94	€ 217,36
Floor tiles (bathroom)	Ceramic tile in cement	€ 182,21	€ 204,08	€ 441,14	€ 37,35	€ 864,78	Ceramic tile in cement	€ 182,21	€ 204,08	€ 441,14	€ 37,35	€ 864,78
	Spaceplan	**€ 3.063,82**	**€ 5.837,31**	**€ 4.833,79**	**€ 2.512,47**	**€ 16.247,40**	**Spaceplan**	**€ 5.256,70**	**€ 5.781,12**	**€ 4.818,12**	**€ 1.285,15**	**€ 17.141,09**
		€ 34.111,53	**€ 28.409,40**	**€ 28.285,19**	**€ 4.898,67**	**€ 95.704,80**		**€ 36.304,41**	**€ 28.353,21**	**€ 28.269,52**	**€ 3.671,36**	**€ 96.598,50**

Elements	Scenario 4	Initial	Construction	Operational	End-of-Life	LCC	Scenario 5	Initial	Construction	Operational	End-of-Life	LCC
Walls	Prefabricated concrete	€ 8.783,46	€ 2.070,01	€ -	€ 428,63	€ 11.282,10	Wood elements (services integrated)	€ 14.682,60	€ 1.871,02	€ -	€ 885,38	€ 17.439,00
Ground floor	Ribbed floor (ribcassettevloer) incl. insulati	€ 1.714,77	€ 503,13	€ -	€ 100,08	€ 2.317,99	Ribbed floor (ribcassettevloer) incl. insulati	€ 1.714,77	€ 503,13	€ -	€ 100,08	€ 2.317,99
First and second floor	Precast concrete slabs (kanaalplaatvloer)	€ 4.041,64	€ 858,08	€ -	€ 243,12	€ 5.142,84	Prefabricated - wood elements	€ 7.998,00	€ 917,27	€ -	€ 345,52	€ 9.260,80
Roof	Prefabricated roofelements Isover systemr	€ 3.723,90	€ 1.168,73	€ -	€ 252,70	€ 5.145,34	Prefabricated - flax elements	€ 8.085,18	€ 1.598,96	€ -	€ 601,83	€ 10.285,97
Foundation beams	Concrete beams prefabricated	€ 1.408,40	€ 1.938,49	€ -	€ 284,41	€ 3.631,31	Concrete beams prefabricated	€ 1.408,40	€ 1.938,49	€ -	€ 284,41	€ 3.631,31
Foundation piles	Prefabricated concrete piles 250x250mm (5	€ 620,75	€ 1.771,28	€ -	€ 158,31	€ 2.550,34		€ -	€ -	€ -	€ 158,31	€ 158,31
Stairs	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73
	Structure	**€ 21.892,92**	**€ 12.695,11**	**€ -**	**€ 1.766,60**	**€ 36.354,63**	**Structure**	**€ 35.488,95**	**€ 11.214,27**	**€ -**	**€ 2.674,87**	**€ 49.378,09**
				Layer: Skin								
Roofcovering	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 90,66	€ 2.330,98	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 90,66	€ 2.330,98
Insulation (wall)	Flax Rc 4,7 (160mm)	€ 822,37	€ -	€ -	€ 14,82	€ 837,18	Flax Rc 4,7 (160mm)	€ 822,37	€ -	€ -	€ 14,82	€ 837,18
Wall cladding	Brickwork (dry connections)	€ 5.462,74	€ 1.364,87	€ 1.404,41	€ -650,37	€ 7.581,65	Brickwork (dry connections)	€ 5.462,74	€ 1.364,87	€ 1.404,41	€ -650,37	€ 7.581,65
Front/back door	Recycled hard wood door	€ 2.710,40	€ 608,19	€ 5.062,58	€ 45,55	€ 8.426,73	Recycled hard wood door	€ 2.710,40	€ 608,19	€ 5.062,58	€ 45,55	€ 8.426,73
Window/doorframes	Recycled wood window/door frame	€ 3.169,60	€ 576,54	€ 16.939,32	€ 45,24	€ 20.730,70	Recycled wood window/door frame	€ 3.169,60	€ 576,54	€ 16.939,32	€ 45,24	€ 20.730,70
Door + window glass	HR++ glass	€ -	€ -	€ -	€ -	€ -	HR++ glass	€ -	€ -	€ -	€ -	€ -
Lintel	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02
Gutter	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54
Window sill (outside)	Composite biobased	€ 155,61	€ 180,04	€ 45,09	€ 13,81	€ 394,55	Composite biobased	€ 155,61	€ 180,04	€ 45,09	€ 13,81	€ 394,55
	Skin	**€ 13.587,82**	**€ 5.254,91**	**€ 23.451,40**	**€ -435,79**	**€ 41.858,35**	**Skin**	**€ 13.587,82**	**€ 5.254,91**	**€ 23.451,40**	**€ -435,79**	**€ 41.858,35**
				Layer: Spaceplan								
Finishing floor ground floor	Dry floor (egalisation pearls + EPS insulatio	€ 1.152,80	€ 866,88	€ -	€ 137,29	€ 2.156,97	Dry floor (egalisation pearls + wood insulat	€ 1.260,80	€ 866,88	€ -	€ 129,49	€ 2.257,17
Finishing floor first/second floor	Dry floor (egalisation pearls + EPS insulatio	€ 1.730,35	€ 1.301,19	€ 291,19	€ 206,07	€ 3.528,81	Dry floor (egalisation pearls + wood insulat	€ 1.892,46	€ 1.301,19	€ 166,90	€ 194,36	€ 3.554,91
Pre-wall (services)		€ -	€ -	€ -	€ -	€ -		€ -	€ -	€ -	€ -	€ -
Inner walls	Sand lime blocks (eco-element)	€ 952,10	€ 1.947,04	€ 1.681,70	€ 734,84	€ 5.315,68	Reused and recycled gypsum + flax (metalst	€ 1.719,10	€ 1.885,33	€ 204,41	€ 725,55	€ 4.534,39
Inner door frames	Recycled wood door frame	€ 980,00	€ 188,71	€ -	€ 14,05	€ 1.182,76	Recycled wood door frame	€ 980,00	€ 188,71	€ -	€ 14,05	€ 1.182,76
Inner doors	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92
Inner door sills	Composite biobased	€ 44,04	€ 50,96	€ -	€ 3,88	€ 98,88	Composite biobased	€ 44,04	€ 50,96	€ -	€ 3,88	€ 98,88
Windowsill (vensterbank)	Wood	€ 321,50	€ 130,57	€ 434,01	€ 10,32	€ 896,39	Wood	€ 321,50	€ 130,57	€ 434,01	€ 10,32	€ 896,39
Wall tiles (toilet + bathroom)	Ceramic recycled tiles in cement	€ 324,16	€ 857,86	€ 1.395,70	€ 66,93	€ 2.644,66	Ceramic recycled tiles in cement	€ 324,16	€ 857,86	€ 1.395,70	€ 66,93	€ 2.644,66
Floor tiles (toilet)	Ceramic recycled tiles in cement	€ 36,48	€ 52,35	€ 95,25	€ 4,23	€ 188,31	Ceramic recycled tiles in cement	€ 36,48	€ 52,35	€ 95,25	€ 4,23	€ 188,31
Floor tiles (bathroom)	Ceramic recycled tiles in cement	€ 160,32	€ 204,08	€ 386,05	€ 16,69	€ 767,14	Ceramic recycled tiles in cement	€ 160,32	€ 204,08	€ 386,05	€ 16,69	€ 767,14
	Spaceplan	**€ 6.094,25**	**€ 5.770,46**	**€ 4.846,86**	**€ 1.214,95**	**€ 17.926,52**	**Spaceplan**	**€ 7.131,35**	**€ 5.708,76**	**€ 3.245,29**	**€ 1.186,13**	**€ 17.271,53**
		€ 41.574,99	**€ 23.720,49**	**€ 28.298,26**	**€ 2.545,76**	**€ 96.139,50**		**€ 56.208,13**	**€ 22.177,93**	**€ 26.696,69**	**€ 3.425,22**	**€ 108.507,96**

Elements	Full circular	Initial	Construction	Operational	End-of-Life	LCC
Walls	Prefabricated concrete	€ 14.682,60	€ 1.871,02	€ -	€ 704,78	€ 17.258,40
Ground floor	Ribbed floor (ribcassettevloer) incl. insulati	€ 7.998,00	€ 917,27	€ -	€ 345,52	€ 9.260,80
First and second floor	Precast concrete slabs (kanaalplaatvloer)	€ 7.998,00	€ 917,27	€ -	€ 345,52	€ 9.260,80
Roof	Prefabricated roofelements Isover systemr	€ 8.085,18	€ 1.598,96	€ -	€ 601,83	€ 10.285,97
Foundation beams	Concrete beams prefabricated	€ 1.521,08	€ 1.938,49	€ -	€ 284,41	€ 3.743,98
Foundation piles	Prefabricated concrete piles 250x250mm (5	€ -	€ -	€ -	€ -	€ -
Stairs	Pine wood/plywood (vurenhout)	€ 1.600,00	€ 4.385,38	€ -	€ 299,35	€ 6.284,73
	Structure	**€ 41.884,85**	**€ 11.628,41**	**€ -**	**€ 2.581,41**	**€ 56.094,67**
Roofcovering	Clay tiles (recycle)	€ 688,28	€ 1.552,05	€ -	€ 353,71	€ 2.594,04
Insulation (wall)	Glass wool Rc 4,7	€ 822,37	€ -	€ -	€ 14,82	€ 837,18
Wall cladding	Brickwork (chemical connections)	€ 5.462,74	€ 1.364,87	€ 1.404,41	€ -650,37	€ 7.581,65
Front/back door	Hard wood door	€ 2.710,40	€ 608,19	€ 5.062,58	€ 45,55	€ 8.426,73
Window/doorframes	Hard wood frame	€ 3.169,60	€ 576,54	€ 16.939,32	€ 45,24	€ 20.730,70
Door + window glass	HR++ glass	€ -	€ -	€ -	€ -	€ -
Lintel	Steel	€ 308,84	€ 313,61	€ -	€ -29,43	€ 593,02
Gutter	Aluminum	€ 270,00	€ 659,60	€ -	€ 33,94	€ 963,54
Window sill (outside)	Ceramic	€ 155,61	€ 180,04	€ 45,09	€ 13,81	€ 394,55
	Skin	**€ 13.587,82**	**€ 5.254,91**	**€ 23.451,40**	**€ -172,73**	**€ 42.121,40**
Finishing floor ground floor	Anhydride	€ 1.260,80	€ 866,88	€ -	€ 129,49	€ 2.257,17
Finishing floor first/second floor	Anhydride	€ 1.892,46	€ 1.301,19	€ 166,90	€ 194,36	€ 3.554,91
Pre-wall (services)		€ 2.489,52	€ 1.964,21	€ -	€ -403,54	€ 4.050,18
Inner walls	Gypsum blocks 70mm	€ 1.719,10	€ 1.885,33	€ 204,41	€ 725,55	€ 4.534,39
Inner door frames	Steel	€ 980,00	€ 188,71	€ -	€ 14,05	€ 1.182,76
Inner doors	Wood including honeycomb structure	€ 392,49	€ 170,83	€ 562,95	€ 20,64	€ 1.146,92
Inner door sills	Artificial stone (kunststeen)	€ 34,09	€ 36,96	€ -	€ 2,84	€ 73,89
Windowsill (vensterbank)	Composite (Bianco Wit composiet)	€ 321,50	€ 130,57	€ 434,01	€ 10,32	€ 896,39
Wall tiles (toilet + bathroom)	Ceramic tile in cement	€ 565,25	€ 390,29	€ 667,68	€ 46,82	€ 1.670,04
Floor tiles (toilet)	Ceramic tile in cement	€ 44,46	€ 16,47	€ 34,70	€ -2,39	€ 93,25
Floor tiles (bathroom)	Ceramic tile in cement	€ 195,39	€ 72,38	€ 152,50	€ -10,49	€ 409,78
	Spaceplan	**€ 9.895,06**	**€ 7.023,81**	**€ 2.223,15**	**€ 727,64**	**€ 19.869,67**
		€ 65.367,74	**€ 23.907,13**	**€ 25.674,56**	**€ 3.136,32**	**€ 118.085,74**

Appendix VI Remaining results LCC over increasing lifespan

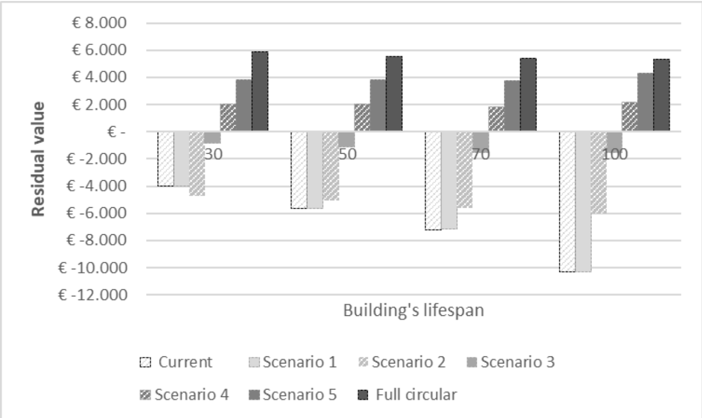

Figure A(left): Residual value of scenarios over lifespan.

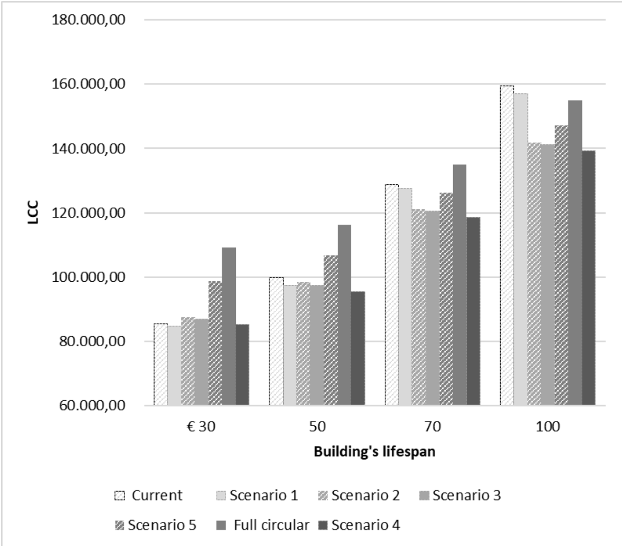

Figure B(right): LCC of scenarios over lifespan.

Appendix VII List of assumptions

During the research, assumptions have been made regarding the information as input for the BCI assessment and the LCC. In some cases, not all information was available, in others there must be concerned in about 30-50 years a circular economy has been developed in the Netherlands. Therefore, it must be expected there is a more positive attitude towards the reuse or remanufacturing of qualitative and non-toxic elements. However, the progress of technical development to facilitate the design and remanufacturing of components on a better way could not be estimated. Therefore, there has no assumptions made regarding this.

Assumptions regarding the BCI assessment

Origin of materials	The origin of materials has been requested at suppliers and validated with NIBE. If there was no information available of these inconsistences, the information of NIBE has been assumed as most reliable.
Waste scenario of materials	The waste scenario has been requested at suppliers and validated with data of NIBE. However, when the supplier guarantee takes back, it is assumed that the material will be recycled, instead of incinerated.
Efficiency of recycling process	The two factors Ef and Ec determine the efficiency of the recycling process. Ec, as efficiency after use phase, has been assumed as 1. Ef, as efficiency to result as recycled material in new product, is assumed to be 100%. However, the efficiency could be depreciated by some factors. First, if functions are integrated in a component → assumed to be a decrease of efficiency by 20%. Second, if the material has been recycled by a professional. If there is take back guarantee → best change for reuse or remanufacturing of product, otherwise assumed of decrease of efficiency by 20%.
Technical lifespan of materials	The maximal lifespan is by NIBE stated as 75 years. However, when supplier guarantee a longer lifespan, this will be incorporated.

Assumptions regarding the LCC

Purchasing phase (product costs)	The product costs of the circular alternative building components are request at suppliers in the Dutch construction market. When volume discounts are not observed, a discount of 5% are assumed. This percentage is based on the price difference for a contractor when purchasing materials on the regular market in comparison to having price agreements for volumes. Besides, it is assumed that a lightweight construction (like wood) does not need a heavy foundation. The foundation piles are cancelled.
Construction phase (labour costs)	For light weight construction, the time for labour is assumed to reduce by 20% through more easily placing of the elements.
Construction phase (equipment costs)	The costs for scaffolding and crane (truck) are both incorporated in as one cost aspect in the budget plan of the case. Therefore, for both type of equipment, the building components are selected who use the type of equipment and the total costs are balanced as costs per component. These costs same costs are incorporated for the alternative building components. When using a lightweight construction (like wood), the costs for the crane are lowered for a less heavy crane.
Operational phase (replacement costs)	It is assumed that about 30 years, there is more attention for the use of materials. When replacing functions (like services) behind the wall cladding or finishing floor. It is assumed these wall and floor panels will not be replaced but reused when these have not reached their technical lifespan. Labour costs for replacing the products are assumed as twice the man-hours for placing the element. In order to cover also the careful dismantling of the product.
Net Present Value (NPV)	The discount rate and inflation have been assumed based on suggested rates by Alba Concepts. They include the discount rate of 3%, by a government interest of 0,7%, risk of 2% and profit of 0,3%. The inflation is by them considered as 1,81%.

Escalation rate materials	It is difficult to predict how the current escalation rate of materials for the coming two years, by economic circumstance and pressure on supply of prefabricated materials and labour, will continue in the future. Besides, it is not known for sure how-to market will react on material scarcity and how this will influence the escalation rate of the materials. By uncertainties in this, it is assumed the escalation rate will follow the same trend as last couple years. Therefore, the escalation rate of the last years from commodity indexes are considered.
Escalation rate labour	The costs for labour are assumed to increase by the same rate as the inflation. Therefore, these are not incorporated in the NPV.
End of Life phase (dismantling costs)	The demolishing time for building components of the structure and space plan are ones considered for a project where components will be recycled and reused. The results are compared with the construction of the components. Based on these results is assumed to generalize the time for dismantling the building components by a percentage of the construction time. For each waste scenario, of reuse, remanufacture and recycle, a separate percentage is considered.
End of Life phase (logistic costs)	It is assumed that the costs for logistics of building components, which will be reused and remanufactured will be higher, by transporting whole components. The costs for components that will be recycled will be lower by smaller elements in higher volume transported in containers. Besides, it is assumed that the distance for the transport of reusable components will be higher through to specific suppliers who take back the materials for repair and resell. 200 km distance has been considered by, a circle this diameter reaches most parts of the Netherlands. For remanufacturing is assumed the there is more potential for more suppliers to make use of the released materials. Therefore, 100 km distance has been considered, which cover a fourth of the Netherlands. For recycling are more companies able to process the materials. Madaster take for general materials 150 km, for stone 40 km and for wood 20 km into account. These distances are generalized to assumed distance of 70 km.
End of Life phase (residual value)	Determining the residual value of building components for the future (about 50 years) is highly complex, but many uncertainties in regulations, material costs and attitude towards the reuse or remanufacturing of materials. It is assumed the difference in price for a new and reused product will currently be the same as these is in future. Therefore, the prices for resold and new products are compared from two platforms. The platforms clarify that to determine to price by offer and demand. However, the difference in price of the platforms do not correspond for the same type of component. Therefore, is chosen to generalize the price difference of the components per platform. One had a difference in price of 42%, the other of 48%. The difference in price for reused materials in comparison to the new price is assumed as 45%. This value is considered for reused materials over the initial product price to determine its residual value. When remanufacturing the elements, it is assumed the supplier will take back for free the components. It is assumed for most suppliers who have the incentive for taking back materials, they have organized in a couple of years. When recycling the materials, costs are incorporated for the dump of materials. Through to uncertainties in the future about the deployment of the dumped materials, it is uncertain how their cost for dumping will develop. Most accurate are the current costs for dumping materials, which will be included for the future.