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Exploring the relationship between the level of circularity and the life cycle costs of a one-family house

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ABSTRACT

In the last couple of years, actors in the construction industry have shown an increasing willingness to move towards circular businesses. However, many consider circular construction to be a more expensive option, which makes actors reluctant to invest in circularity. This study contributes to the existing literature by relating the Level of Circularity (LoC) for a one-family house to its Life Cycle Costs (LCC). Using design-orientated research, the design of the one-family house was altered to gradually increase its LoC. The results revealed that it is possible to double the LoC to 0.41 compared to the initial design (LoC = 0.20) without increasing the LCC. Furthermore, the measures do not require radical changes to the design and construction process. Rather, it only requires replacing virgin materials with recycled or biological materials, and using building products that can be disassembled relatively easily. The results also revealed that increasing the circularity level further resulted in a sharp increase in product costs, and therefore an increase in LCC. This makes it less economically attractive for construction companies. Therefore, we suggest starting with relatively easy measures, which can already double the current circularity level of typical one-family houses.

1. Introduction

The building industry is responsible for the highest amount of resource use (Ness and Xing, 2017; Wouterszoon Jansen et al., 2020) and has a considerable environmental impact worldwide (Bhochhibhoya et al., 2020). The construction and demolition of buildings account for around one-third of global materials consumption and waste generation (Ellen Macarthur Foundation, 2019). Policies worldwide recognise that the building industry has to take urgent action to reduce emissions, climate change and resource depletion (Ghaffar et al., 2020).

Reacting to this, several studies have sought solutions for a more sustainable use of construction materials (Bocken et al., 2016). The circular economy (CE) concept provides ideas for resource decoupling (Giorgi et al., 2019; UNEP, 2011) that offer resource efficiency and effectiveness, and the reduction of resource use and waste production (Wouterszoon Jansen et al., 2020). A circular economy is one that is restorative and regenerative by design and maintains materials at their highest utility and value at all times (Ellen Macarthur Foundation, 2013). Many have adopted the circular economy model by replacing the ‘end-of-life’ concept with effective and smart reuse strategies that reduce the use of virgin materials and negative environmental impacts (Ghaffar et al., 2020).

The CE function in closing material loops through technological innovation, including recycling and reuse, relies on sale-and-take-back or lease contracts as well as the introduction of new business models, (Ellen MacArthur Foundation, 2015). The CE offers two main benefits for the building industry. First, it decreases the dependency on new resources (Ellen Macarthur Foundation, 2013; Potting et al., 2018; Verberne, 2016). Second, it can bring the economic benefit of infinite resources through value retention (Ellen Macarthur Foundation, 2013). The building industry is particularly relevant to the CE as it generates the heaviest and most voluminous waste stream in the European Union (European Commission, 2014) and is responsible for the depletion of valuable resources (Durmisevic, 2019). The circular economy has achieved widespread interest through its aim of generating economic and environmental prosperity (Buyle et al., 2019; Kirchherr et al., 2017). Circular construction is seen by Ghaffar et al. (2019) as increasing the industry's competitiveness by protecting the business against a shortage of resources and unstainable prices.

However, the implementation of a CE way of thinking within the construction industry is still in an early stage despite the efforts of multiple CE-related research projects within the industry. It is often limited to minimising waste and maximising recycling (Buyle et al., 2019; European Commission, 2014; Ghaffar et al., 2020). However, rather than only focusing on recycling, the industry should also pay

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more attention to reuse, remanufacturing and future use scenarios (Reike et al., 2018). On a note of caution, Buyle et al. (2019) highlighted that increasing circularity does not always result in more sustainable products and buildings. Furthermore, the study by Zink and Geyer (2017) emphasised that reusing construction products after the end-of-life phase in other production processes does not necessarily guarantee a reduction in the related environmental and economic impacts.

Therefore, it is important to evaluate the economic and environmental impacts of products from a lifecycle perspective in decision-making. The Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approaches provide an overview and a methodological basis to evaluate design, construction and material choices and provide a justification for selection (Buyle et al., 2019).

A quantitative analysis of circularity performance is important to evaluate how well a product performs in the context of the CE (Ellen Macarthur Foundation, 2015, Gregson et al., 2015) and in supporting decision-making when evaluating the performance of products. However, evaluating the economic impact of circular products is equally important for companies in determining the economic feasibility of circular solutions. Companies are still undecided whether circular measures are financially viable and an acceptable solution for their customers (Kambanou and Sakao, 2020). In the construction industry, there is a reluctance to invest in circular construction, in part because multiple sources state that circular construction is more expensive. For example, Brueton (2018) claimed that product costs increase by applying more expensive biodynamic products to replace major materials involving steel, glass and cement. Furthermore, labour costs increase because alternative construction techniques are needed that are more expensive than traditional ones (Surgenor et al., 2019). However, these claims focus on the cost increasing factors in the short term, and there is often little attention to the possibilities that a CE approach might lower operating and end-of-life costs in the longer term. One should therefore use Life Cycle Costing (LCC), which has great potential in supporting decision-making by evaluating different circular scenarios (Giorgi et al., 2019). LCC is a widely used tool that can support decision-making regarding economic friendly building technologies and materials and can help reduce the total cost of buildings (Ashraf et al., 2015; Zabalza Bribián et al., 2011).

As the name suggests, LCC has a lifecycle perspective, and this is crucial to the CE approach (Kambanou and Sakao, 2020). It not only considers the investment costs but also operating costs during the product's expected lifetime (Gluch and Baumann, 2004). By using the LCC approach, all the initial cost increases are balanced against expected future cost savings (Giorgi et al., 2019). Comparing the LCC of multiple scenarios is useful in identifying cost barriers and changes in the cost structure and thus forms a basis for determining pricing strategy (Kambanou and Sakao, 2020). Despite its advantages, the adoption and application of LCC in the building sector remains limited (Gluch and Baumann, 2004). Which may be due to the difficulties in conducting a LCC and in interpreting the results. Expert support is needed as well as training to fully understand the concept.

There are numerous publications on LCC in the building sector but only a limited number of studies on the economic impact of circular buildings. Giorgi et al. (2019) analysed the application of lifecycle tools to evaluate circular strategies in decision-making. The study shows that most lifecycle tools are applied only to consider construction, demolition and waste management, and overlook the design approach. In contrast, the study by Kambanou and Sakao (2020) focused on the selection of circular measures in the design phase through LCC-informed choices. The study found the LCC approach relevant in providing information on financial consequences while also providing some information on resource efficiency/circularity aspects. Buyle et al. (2019) carried out a more elaborate study on LCA and LCC analyses to justify possible choices based on sustainability and the financial feasibility of various types of wall assemblies. The study, which incorporated the basic principles of end-of-life scenarios within LCC, reveals the product-level environmental and economic impacts for a range of end-of-life scenarios. Another study, by Wouterszoon Jansen et al. (2020), emphasises the CE-LCC model in incorporating different end-of-life scenarios in the LCC calculation. The CE-LCC model can be used to compare the economic performance of circular product designs (Wouterszoon Jansen et al., 2020). However, no research findings have been published that compare LCC and circularity levels in different circular design scenarios. Such knowledge, on how the LCC evolves over multiple circularity levels, is important to be able to assess the profitability of a circular measure. In order for businesses to adopt CE ideas in reality, they need to understand the financial outcomes of circular solutions. Therefore, in this research, multiple tools are integrated to illustrate the potential environmental benefits and financial feasibility of multiple circular scenarios. The focus is on the relationship between a building's circularity level and its LCC.

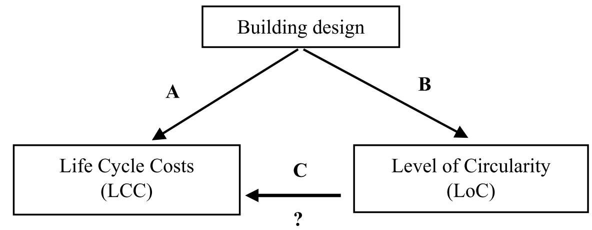

Fig. 1. Influence of building design on Life Cycle Costs (A) and Level of Circularity (B). Unknown relationship between Life Cycle Costs and Level of Circularity (C).

Fig. 1 shows the influence of building design on both Life Cycle Costs (LCC) and the Level of Circularity (LoC). Arrow 'A' reflects how the building design impacts the LCC due to material selection and construction methods. When selecting materials in the building design stage, some materials are primarily attractive for their low initial costs but can have adverse effects on the quality, reliability and performance of the building over its lifespan (Al Ghonamy et al., 2015). Moreover, the residual value within the end-of-life phase is barely considered in LCC research.

Similarly, the material resources, the connection types and the functions integrated into the building design influence (Arrow 'B') the LoC (Ellen Macarthur Foundation, 2015). Buildings that are designed and constructed to reduce lifecycle environmental impacts often deliver direct economic benefits such as lower operational and maintenance costs, slower depreciation and higher asset value (European Commission, 2014). Nevertheless, it is unknown how a building's LoC influences the LCC, as represented by arrow 'C'. Understanding this is important in order to stimulate the construction industry to move towards a CE: first, by showing the potential to improve circularity in current building design and, second, to set targets regarding the circularity level by discussing the feasibility of investing in circular projects.

2. Theoretical background

2.1. Circular design strategies in construction

Circular construction is defined as the development of a building that utilises available and renewable resources during construction, operation and reuse. The building components are designed and prepared for value retention by lifespan extension, or by returning the materials for reuse in future cycles. The aim is to minimise the impact on the environment by reducing the demand for virgin materials through the reuse of resources and keeping them in the material loop by applying regenerative (circular) solutions. As such, the CE significantly changes the concept of a building. In circular construction, the building becomes a stock of resources to be maintained for as long as possible

Table 1
Different building design scenarios.

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Final scenario
	changes in:	Compared to the baseline	Compared to scenario 1	Compared to scenario 2	Compared to scenario 3	Compared to scenario 4	Compared to scenario 5
Structure	Prefabricated concrete, no recyclable content					Prefab wood 1st/2nd floor + walls + roof + no foundation piles	Prefab wood ground floor + recycled conc. found. beams
Skin	Brickwork, Glass fibre insulation, concrete roof tiles	Clay roof tiles	Recycled wood frames + biobased windowsill		Flax insulation + dry brickwork		
Space plan	Gypsum block wall, anhydrite- finished floor, ceramic tiles		Sand-lime wall blocks + biobased doorsill	Dry finished floor (EPS)	Recycled wood frame + wood sills + recycled tiles	Dry fin. floor (wood) + Reused wall panels (flax)	Wall and floor panels (rather than tiles)

and to be reused or recycled at the end of their life (Giorgi et al., 2019).

Several circularity strategies exist to reduce the consumption of natural resources and minimise the production of waste (Potting et al., 2017). The existing strategies, often called the R-imperatives, are prioritised based on a varying number of circularity levels (Ellen Macarthur Foundation, 2013; Kirchherr et al., 2017; Potting et al., 2017; Reike et al., 2018). The R-imperatives that best fit the construction industry are reuse, remanufacture and recycle. These are therefore considered in the waste scenarios for the LoC and LCC assessments in this study.

2.2. *Tools for assessing the level of circularity*

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

2.2.1. *Circular construction indicators*

An appropriate circularity metric at the product level should focus exclusively on measuring material circularity. This excludes the assessment of environmental performance, or other energy consumption issues. As such, the circular construction indicators focus on the material input and waste scenarios. Further, the design opportunities to extend the building's and materials' lifespans should be taken into account.

Geldermans (2016) distinguishes a product's value based on specific intrinsic (material origin) and relational properties (building design and use). Similarly, the Ellen Macarthur Foundation (2013) defines circular design in terms of improvements in material selection and product design. This research sees these ideas as an essential element in the selection of an appropriate circularity assessment tool.

2.2.2. *Selection of circularity assessment tool*

Several tools exist in both the academic and the grey literature to assess the LoC on macro-, meso- and micro-levels (Niero and Kalbar, 2019; Saidani et al., 2019, 2017). From an inventory of product circularity assessments, the 'Building Circularity Indicator' (BCI) of Verberne (2016) is considered as the most appropriate tool for this research since the BCI tool represents circularity with a quantitative score on both building and component levels. Other tools were considered but were seen as less appropriate because they relied on qualitative data, or focussed 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 to be assessed on multiple levels. The basis of the BCI is the Material Circularity Indicator (MCI) of the Ellen Macarthur Foundation (2015). The MCI considers a material's origin, waste scenario and lifespan. The MCI is complemented by the Disassembly Determining Factors (DFF) index of Durmisevic (2006), which together establish the Product Circularity Indicator (PCI).

The DFF factors identify possibilities for independent disassembly of materials in the product design by focussing on function integration and connection types. For example, the potentially high MCI score of recycled wall tiles will be decreased significantly as the chemical connections cannot easily be disassembled without damage. The products are also categorised in systems based on 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

This study uses a design-orientated research strategy. This method enables one to analyse the differences in LCC for different design scenarios. Each scenario has a corresponding LoC and LCC, and we have explored if and how the LoC scores were related to the corresponding LCC.

The research starts by determining the LoC of a baseline building. This is a conventional building design for a one-family terraced house of 140 m^2 in the Netherlands with a prefabricated concrete structure, brick façade, anhydrite-finished floor, gypsum walls and other traditional finishing materials (Table C.1). Housing corporations usually adopt an investment period of around 50 years for these housing types. The functional unit is the building components consisting of the system's structure, skin and space plan. In the research process, circular building components, available on the Dutch construction market, are applied as alternatives to the baseline (Table 1). First, the best possible circular scenario was determined and assessed on its circularity level to determine the maximum feasible circular level, labelled the final scenario. The research process follows the design of multiple scenarios with gradually increasing LoCs between the baseline and final scenarios. Following this, the baseline and the other scenarios are assessed on their LCC to analyse how costs vary with increasing LoC.

3.2. Building design scenarios

The circular building design scenarios were developed by considering the impact that the use of alternative (reused, recycled, biological or demountable) materials would have on the circularity level. The principle was to start by applying alternatives that have a high impact on the circularity level and low impact on product and construction costs. Before selecting alternative materials for the design scenarios, some background understanding is required about the factors that have a large impact on the building circularity assessment tool.

In circularity assessments, and particularly in a BCI assessment, the lifespan of a building layer has a large impact on the building's circularity score. Building materials in the space plan or skin will be replaced more often (shorter functional lifespan) than materials in the structure (longer lifespan), so their impact will be greater on the total building circularity score. Another important factor is the mass of the building material. The mass of an applied material relative to the total mass of the building layer determines its impact on the circularity level within the building layer. As a consequence, stone materials have a larger impact than, for instance, insulation materials and wood products such as window frames and stairs.

A critical criterion is the profitability of a circular measure, as an alternative needs to be functionally equivalent and of equal value to the client (Kambanou and Sakao, 2020). Therefore, each design scenario must meet the same conditions as those of the baseline. For example, the building insulation value (RC) and acoustic performance must remain the same.

These aspects are considered when designing the scenarios. In each scenario, additional material changes are added and compared to the previous scenario, until the final scenario is reached.

3.2.1. Scenario 1

First, the concrete roof tiles are replaced by clay ones. These represent a large mass within the building layer skin. Changing the roof tiles, have no impact on the building design and construction process.

3.2.2. Scenario 2

In the second scenario, other materials are replaced with circular versions of those materials. So, the window frames, sills, and block walls are replaced by recycled or bio-based alternative materials. Again, this does not affect the design and construction process.

3.2.3. Scenario 3

In scenario 3, the floor finishing, which significantly influences the circularity level (78% of the circularity level of the space plan), is replaced by a demountable alternative. This impacts on the design and construction process, as it changes the floor thickness, increases the amount of labour required and, therefore, also the construction costs.

3.2.4. Scenario 4

In the fourth scenario, more expensive materials are applied. In the building skin, the insulation has been replaced with flax, a biological alternative. Further, the brickwork has been replaced by a demountable variant, which is more expensive in product costs but less labour intensive. In the space plan, materials have been replaced with more expensive biological or recycled options.

3.2.5. Scenario 5

In scenario 5, the building structure has been replaced by a wooden structure. This has a large impact on the design process, as the connections, foundations and building physics will be completely changed. Further, it has an impact on product costs as prefabricated wood structures are more expensive. However, it is possible that product costs could decrease if wood sales increase in the coming years. The construction process will be easier because of the low weight of the wooden building components and simpler connections.

3.2.6. Final scenario

In the final scenario, the replacement materials tend to be expensive and have a limited impact on the circularity level. In particular, the demountable wall and floor panels, compared to recycled tiles, have hardly any impact due to their low mass. Given that the profitability of circular measures is important, this scenario is unlikely to contribute to a shift towards circular construction due to the high costs. Rather, this scenario gives an idea of what the maximum achievable circularity level might be.

3.3. Modification of the BCI tool

The BCI tool was developed by Verberne (2016) and its PCI factors further elaborated on by Van Vliet (2018). However, there are still some practical issues when it comes to measuring the circularity level of houses. For instance, the theoretical BCI model only determines the circularity level during the initial construction phase. The circularity level over the lifespan when it comes to replacing building components has not been considered. From a practical perspective, it seems necessary to incorporate such activities over a certain lifespan. This is especially the case since the impact of circular product design on product remanufacturing and reuse only then becomes evident at the circularity level. Therefore, the BCI tool had to be modified to fit our purpose and to resolve some practical issues.

The MCI assessment focuses only on the material input at the start of manufacturing a product and does not consider the materials required over the entire lifespan of a product. Materials with a high utility factor require more virgin materials, and more waste is generated during their lifespan. In the modified BCI assessment, the MCI score is adjusted by multiplying it by the utility factor for the virgin materials used and waste generated (see Fig. 2). Moreover, the biological or natural material input is not considered in the MCI of the Ellen Macarthur Foundation (2015) and Verberne (2016). Considering this type of material input separately reduces the amount of virgin material used. Therefore, bio-based input is included in the modified BCI tool. Furthermore, Verberne (2016) excluded the recycling process's efficiency. Van Vliet (2018), who critically analysed the model of Verberne, explained [in an interview of 06–03–2019] the complexity of this assessment and preferred to use a standard score of 1. However, the waste

Input information

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

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

Fig. 2. BCI and modified BCI formulas.

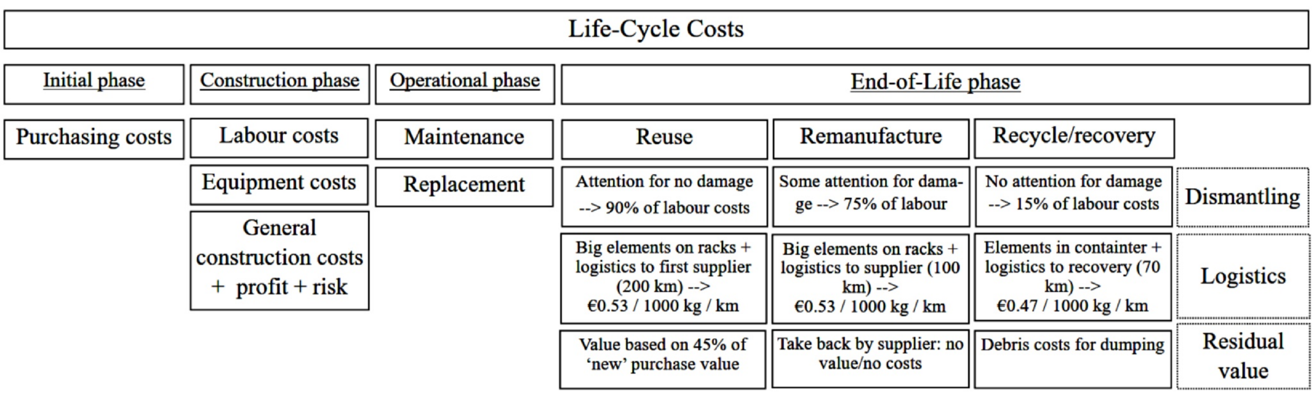

Fig. 3. Cost breakdown structure of LCC.

processor's competence in material separation and how many functions are integrated in an object determine if an entire product can be fully recycled. Therefore, in the modified tool, the recycling efficiency rate of the Ellen Macarthur Foundation (2015) is incorporated, but reduced by making certain assumptions as explained in Appendix Table G.1.

Within the BCI's material circularity assessment, Verberne (2016) replaced the product lifespan evaluation with a comparison of the functional lifespans of the products' technical and building layers. This functional lifespan is determined by following the building layers theory of Brand (1995). However, Brand considered the lifespans of commercial buildings, which are subjected to marketing and image issues, and might not be applicable to residential buildings. Therefore, the functional lifespan for the structure, skin and space plan are taken as 100, 50 and 30 years respectively, reflecting current housing practice. Further, it is taken into account that the functional lifespan is subject to the individual building components meeting their functional requirements, such as their thermal insulation. The formulas for the modified BCI are shown in the equations of Appendix A.1.

3.4. Assessing the BCI

The data on the origins of the materials, waste scenarios and lifespans were taken from databases prepared by the 'Nederlands Instituut voor Bouwbiologie en Ecologie' (NIBE, 2019) and 'Nationale Milieudatabase' (Milieudatabase, 2019). In addition, current and circular building component suppliers were asked to provide data on material origins and waste scenarios.

3.5. Assessing LCC within the CE

LCC are determined by accounting for all a product's economic costs and lifespan costs in order to compare the cost-effectiveness of alternatives over the entire lifecycle. The LCC approach has been applied to compare different building designs, both in terms of initial costs and expected future operational costs (Bhochhibhoya et al., 2017; Ristimäki et al., al.,2013; Glunch and Baumann, 2004). In this study, the initial costs cover all the costs incurred in the material supply and the construction of the building. Future costs are those for the building's operation over a 50-year lifespan and those incurred in its end-of-life phase. The functional unit of this study is the structure, skin, and space plan of the building under the different scenarios. The system boundaries for each scenario range from raw material input in the initial phase, product manufacturing in the construction phase, maintenance and replacement in the operational phase, through to the disposal, recycling, remanufacturing, or reuse in the end-of-life phase (shown in Fig. 3). The costs for each phase are explained below and in the equations of Appendix B.1–5.

3.5.1. Initial phase

The costs in the initial phase are the costs of purchasing the building components for supply onsite. The current case's building component costs are based on the budget plan of a consulted contractor. The costs of the alternative building components were obtained by requesting purchase prices from suppliers and by accessing a database assembled by Cobouw. Cobouw is a newspaper dedicated to the construction industry but the organisation also gathers and maintains relevant construction industry-related data, such as purchasing costs.

3.5.2. Construction phase

The costs for labour and equipment to construct the building are referred to as the construction phase costs. In addition to general construction costs, these also include allowances for risks and profit. In our study, the baseline construction costs are based on the budget plan of the contractor. The costs for the alternative components are based on the same data but adapted when changes in construction time and equipment are required.

3.5.3. Operational phase

Costs in the operational phase cover 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 in this study as the circularity assessment only focuses on the building materials. Moreover, data on water and energy consumption are difficult to retrieve and are related to the user's behaviour. The building maintenance costs are primarily the costs of labour for inspections, repairs, cleaning or painting the visible building components. The operational costs also consider costs of replacing the (non-)visual components when these exceed their technical or functional lifespan. This includes the purchasing and labour costs for disassembly and reassembly of a component. In addition, the components' residual value and the costs for disposal of debris are determined.

Maintenance experts and suppliers were consulted about the maintenance and replacement cycles of building components. For each building component, these costs were plotted on a yearly schedule in order to calculate the present value given the operational year concerned.

3.5.4. End- of-life phase (EoL) within a CE

The costs for removing a building after its lifespan are considered in calculating EoL costs. This includes the costs for dismantling and reutilisation of the building components and logistics. The reutilisation element is more commonly referred to as debris costs in the current linear economy literature. In effect, the materials have depreciated to zero value. In most cases, there are costs for dumping the materials. Within a CE, materials have a residual value after their lifespan, as there is the intention to reutilise them after their initial lifespans. The condition of the product determines its residual value. The better the condition, the more the material loop can be closed, and the more the original value of the material can be recaptured (McKinsey and Company, 2016). In a CE, the nearest to a closed loop is achieved thorough reuse, followed by remanufacturing and recycling. Incorporating this value in the EoL phase results in a lower LCC for circular buildings.

The residual value is not computed in this study because evaluating the residual value is the most complex part of calculating LCC within the CE, and no academic research has developed a tool for it. Developing such a scientifically based tool is also beyond the scope of this research. Instead, estimates of the residual value of building components are determined by desk research and interviews with experts in the construction industry.

Incorporating the type of waste scenario (either as reuse, remanufacture or recycling, see Section 2.1) is important in distinguishing the value that could be recovered from a building component. Therefore, the residual value of a reusable building component is evaluated by comparing 'new' purchase prices with used ones on platforms that offer building components for reuse. In general, it can be stated that reusable materials retain 45% of their value after their functional lifespan. Components with no guarantee of reuse, are only considered as remanufacturable when the initial suppliers guarantee to take the materials back without cost, i.e. to reutilise them in a new product. The value of these components is considered as zero as there are no costs for dumping and no income from them being taken back by the supplier. Finally, when recycling a product, disposal costs are included for dumping the material after its lifespan. This results in a negative value.

In addition to the residual value of building components at their EoL, there will also be costs for removing the component from the rest of the building and for logistics. These costs are also influenced by the waste scenario. The dismantling costs used are based on the initial construction costs, specifically the assembly time for the components. The disassembly time for a reusable component is considered to be broadly similar to the assembly time, although no time will be required for finishing, such as ensuring airtightness or adjusting hinges. Remanufacturable components require less careful handling of the materials to avoid damage. Recyclable components can be disassembled by crane, with less attention given to the separation of materials. Based on a calculation of all these scenarios, the overall result is that the dismantling costs of reusable, remanufacturable and recyclable components are estimated at 90%, 75% and 15% respectively of the construction costs.

The logistics for reutilisation of the building components are, again, based on the waste scenarios. Reusable and remanufacturable building components are assumed to have higher logistical costs due to transporting larger elements. In contrast, recycled components have lower transport costs as these are smaller elements transported in high volume containers. Some research has recently been carried out on generalised transport costs of intermodal freight transport. Hanssen et al. (2012) indicated, based on a case study, a total marginal generalised costs of €0.43[1] per tonne per km. Similarly, Gleissner and Möller (2011) indicated transport costs of about €0.54[2] per tonne per kilometre. These figures are consistent with current practice (based on 2020 prices) of €0.50[3] per tonne per kilometre. Based on these numbers the logistic costs of recycled components are assumed on €0.47 and the reusable and remanufacturable components assumed on €0.53 per tonne per kilometre.

Reusable components are likely to be transported over longer distances as they have to be returned to specific suppliers for repair and resell, and an average of 200 km is assumed. For remanufacturing, it is assumed that there are more potential users of the released materials and so distances will be less (150 km). Recycling could be carried out by local processors (70 km).

The EoL costs are calculated by summing the (positive) residual values and the (negative) dismantling and logistic costs.

The present value of all the lifecycle phases' costs over a building's lifespan is 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

4. Results

4.1. Scenario designs

A standard one-family house (the baseline case) achieved a circularity level (BCI) of 0.20 within a range of 0 (non- circular) and 1 (fully circular). This is a reasonable score for a traditional house with a

[1] Based on €4.61 per truck km and 10.64 tonne in one truck.

[2] Based on €538.90 per 200 km and 5 tonne in one truck.

[3] Based on €800 per 200 km and 8 tonne in one truck.

prefabricated structure and dry connections. The subsequent scenarios (scenario 2 onwards) have been developed by applying better circular building components. First, the high mass building components of the system's skin and space plan were replaced. These components have a significant impact on the BCI because of their relatively high mass and high system dependency factor. In later scenarios, the components in the structure that are replaced have a relatively high impact on the construction process and a relatively low impact on the circularity level.

Applying the best imagined circular building components (the final scenario) resulted in a score of 0.49. Within this research, this is considered the highest achievable circularity level given the basic building design. Although this score might seem quite low it can be explained. It was seen that a higher circularity level would be difficult to achieve. Primarily, this is due to the chemical-based connections that are still used for assembling the recycled or bio-based materials available on the market. Second, the functional integration seen in many components of the building design makes them difficult to fit within a circular concept. As a result, the final scenario's BCI score is some distant from the ultimate circularity score of 1. The scenarios between the baseline and final scenarios were developed by gradually increasing the LoC. The building materials applied and circularity scores are shown in Appendix Table D.1.

4.2. The LoC'S influence on the LCC of the building

Fig. 4 shows the relation between the LCC per phase and the LoC in the different scenarios. The results show that the circularity level can be doubled from the baseline to 0.41 without increasing the LCC. Replacing the high-mass components in the building's skin and interior space plan has a greater effect on the circularity level than adopting circular materials in the building structure.

In scenarios 1 and 2, building components were replaced with materials with a recycled or bio-based component. This had little impact on the purchasing costs and no impact on the LCC. In scenarios 3 and 4, building components were chosen that could be assembled with dry connections. The increase in initial purchasing costs was balanced by a decrease in the end-of-life costs, and this made it possible to double the circularity level without increasing the LCC.

To go beyond a circularity level of 0.41 requires the application of circular design principles to the structure of the building. This is less attractive because of the relatively low impact on the circularity level coupled with a sharp increase in the purchasing costs. This increase cannot be balanced by reduced EoL costs and, thus, results in an increase in LCC.

4.3. The influence of building design on the LoC

Many Dutch construction companies have already started implementing biobased or recycled construction materials in place of virgin ones. Table 2 illustrates that the use of clay rather than concrete roof tiles already increases the circularity level by ~0.07. Replacing the glass wool insulation by flax has little impact (~0.01) due to the relatively low mass of the product. The use of a wood structure increases the circularity level but also has a significant impact on the construction process, indicated by the increased LCC. Many solutions based on circular materials are available in the circular supply chain. However, few suppliers focus on product designs that involve dry-connected assemblies in place of the current chemical connections. We would encourage a focus on the connections as they have a large impact on circularity. For instance, replacing the in-situation poured solid floor finishing with a dry floor increases the circularity level by ~0.07. Other dry-connected building components include click-based brickwork, dry panel inner-walls and tile panels. Applying circular design principles in the structure can have a large impact on the product and the construction process, but less impact on the circularity level and is therefore seen as less attractive although this nevertheless resulted in an increase in the building circularity level of ~0.05.

4. The influence of the building design on the LCC

The building design scenarios (Table 1) were designed to use the above-mentioned circular alternatives in terms of material and product design. The scenarios were then assessed for their LCC based on the initial and future costs. As indicated in Fig. 4, the LCC remains broadly unchanged when steadily increasing the LoC to 0.41. However, beyond this level, the LCC increases because of an almost doubling of purchasing costs. This is due to the necessity of applying more expensive and less common components to achieve higher circularity scores. However, these circular components are less common and therefore their price is subject to market effects. Suppliers indicated that they determine their prices by supply and demand. The market volume of circular components is lower and, therefore, suppliers seek a higher margin on products labelled as 'circular'.

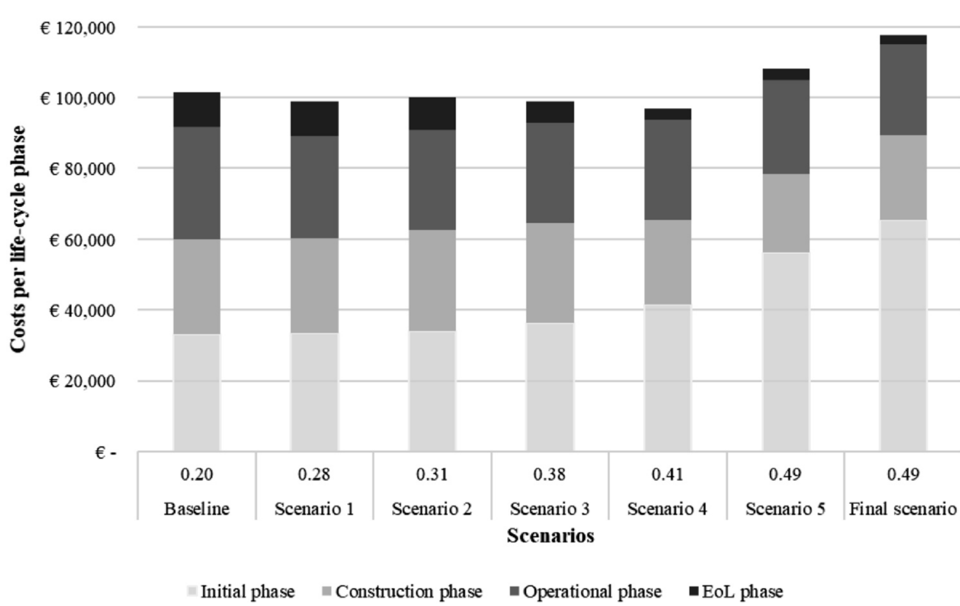

Fig 4. Costs per life cycle phase for design scenarios with increasing LoC (Table D.1 shows the costs in detail).

Table 2
Impact of better circular alternatives in materials and product design on the circularity level and LCC.

Focus on:	Building components	Virgin materials	Better circular alternatives	Circularity level	Overall LCC (50 yr)[1]
Materials	Skin - Roof tiles	Concrete	Clay	+0.07	−47%
	Skin - Insulation	Glass fibre insulation	Flax	+0.01	+11%
	Structure - Walls and floors	Prefabricated concrete structure	Prefabricated wood structure	+0.05	+89%
Product design	Spaceplan - Finishing floor	Solid in-situation poured	Dry floor of levelling granules and plates	+0.07	+8%
	Spaceplan – Inner walls	Gypsum lime-based block wall	Recycled gypsum plates metal stud or flax panels	+0.03	−35%
	Spaceplan - Tiles	Limed tiles	Click-based tile panels	+0.01	−35%
	Skin - Façade	Limed brickwork	Click-based brickwork	+0.02	−26%

[1]LCC (initial and future costs) of the circular alternative compared to the virgin material.

The construction costs vary as the LoC changes because different types of building components are used in the scenarios. In general, recycled materials require similar construction techniques and result in comparable costs to new materials. However, there is no simple relationship when it comes to labour costs when assembling materials using dry connections. Some building components are less labour intensive (e.g. dry brickwork), while others are more intensive (dry floor finishing). With the highest LoC designs, the costs drop through applying a lightweight prefabricated wood structure.

In theory, highly circular scenarios result in lower operational costs. This is due to the incorporation of dry connections and more accessible fixings, making it possible to remove undamaged components with possibilities for reuse. This is reflected in the results shown by a slight decrease in operational costs in the scenarios with a higher LoC. It could be argued that the difference in operational costs between the low and high circular scenarios will become higher with an increasing lifespan (Section 4.5).

Considering circular principles for disassembly and reuse in building design, it is possible to achieve a positive residual value (Allen et al., 2017). A circular building can achieve better value than a traditional building. Scenarios with a higher LoC retain value at the end of a building's life, whereas the residual value is negative for low circular scenarios. This negative residual value is due to the costs incurred in disposing of materials after their lifespan. These costs are avoided by using alternative circular components intended for reuse, or with a guarantee to be taken back by the supplier after their lifespan. However, the costs for dismantling and removing components without damage increase at the higher circularity scenarios. That is why certain costs remain in the EoL phase.

4.5. *The effect of lifespan on the LCC*

The costs in the operational and EoL phases depend on the lifespan. Given the investment perspectives of investors and corporations, lifespans of 30, 70,and 100 years are the most relevant to consider. The sensitivity analysis in Fig. 5 shows that with a 30-year lifespan there is hardly any difference in the operational costs between the baseline and the more circular scenarios. Only the initial (product and construction) costs influence the difference between the costs. With a lifespan of 50 years or above, the differences in operational costs between the scenarios increase. The reassembling of building components in scenarios with higher circularity levels makes it possible to utilise the materials' ultimate lifespans, resulting in a decrease in operational costs.

The final scenario has the lowest increase in operational costs. However, as indicated in Fig. 4, the final scenario is not attractive in terms of LCC due to the significantly higher initial costs. The baseline scenario shown in Fig. 5 has the largest increase in operational costs, especially when increasing the lifespan beyond 50 years. Overall, the most cost-efficient scenario is Scenario 4, which combines relatively low initial and EoL costs (Fig. 4) with relatively low operational costs over an increasing lifespan (Fig. 5).

Fig. 6 shows that, at a lifespan of around 85 years, there is a crossover point, and the final scenario has a lower LCC than the baseline scenario. This is the result of two factors related to operational and EoL costs in the high circular scenarios (a circularity level of 0.41 and above) compared to the baseline case. First, when increasing the lifespan, the EoL costs of highly circular scenarios increase more slowly than the baseline (shown in the Appendix Fig. F.1). Second, extending the lifespan increases the economic value of highly circular buildings due to their better value retention (Appendix Fig. F.2) than the baseline design. This results in a crossover point at around 85 years of lifespan, where the LCC becomes lower for the highest achievable circular building (Fig. 6). Nevertheless, even with this long lifespan, it is still not economically attractive to adopt very high levels of circularity. The large increase in initial purchasing costs required is simply too high to justify the small increase in the circularity level from 0.41 to 0.49.

6. Discussion

6.1. *Scientific contribution of relating LoC to LCC*

The research reveals that within CE it is important to evaluate LCC when assessing the economic feasibility of circular project investments as LCC incorporates the costs of all the lifecycle phases. This enables the initial costs to be combined with the expected future operational costs. Only then, will the value of the CE become visible. However, clients of architectural and engineering firms often focus only on the initial purchasing and construction costs. Aspects such as replacement and EoL costs are barely considered (Lowres and Hobbs, 2017).

In this research, the costs of all the lifecycle stages are considered: from product investment through to EoL, and even potential new lifecycles through reuse, remanufacturing or recycling. Fig. 4 showed the costs in all the lifecycle phases for a range of circular scenarios. These results show a relatively small increase[4] in initial costs for some circular building designs compared to the baseline. Moreover, Fig. 5 showed a more than compensatory decrease of 11% in operational costs[5] of such circular building designs over current building designs.

Further, it is interesting to consider the decrease in the EoL costs when increasing the circularity level of building designs (Fig. 7). The EoL costs of highly circular scenarios can be 79% lower than the baseline design. This decrease in EoL costs appears to be particularly the result of a higher residual value in the products at the end of the building's life. Further, the EoL costs of circular buildings can remain stable over an increased lifespan (Appendix. F.2) although this would require construction industry clients to invest 8%[5] more initially, primarily to meet the higher costs of circular materials.

During this research, it became clear that supply chain collaboration

[4] Research result: Investment costs of scenario 4 are €65,295 compared to €60,090 in the baseline.

[5] Research result: Operational costs of scenario 4 are €28,345 compared to €31,703 in the baseline.

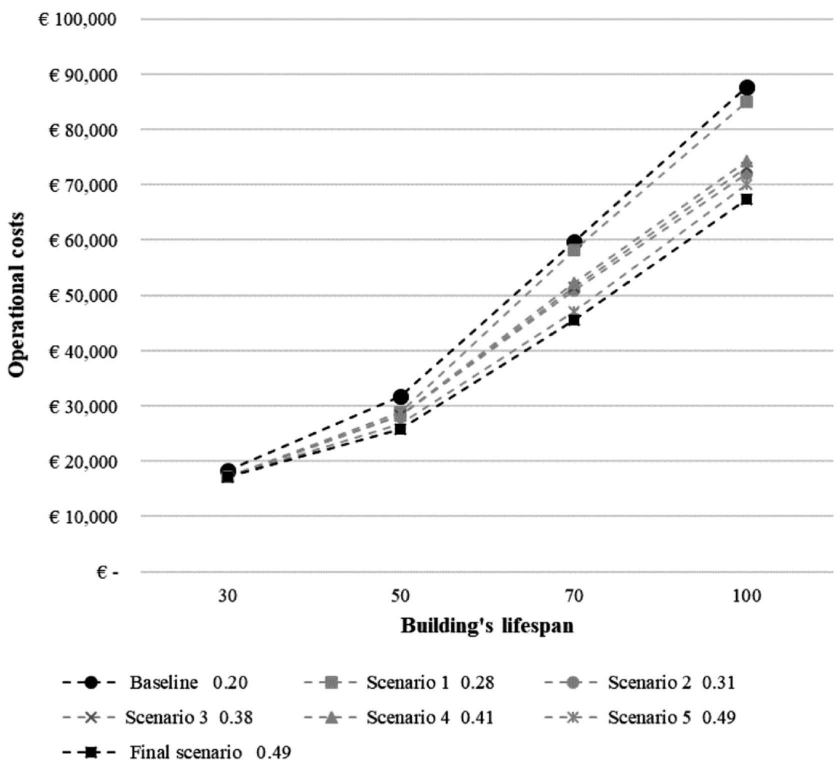

Fig. 5. Trend in operational costs of the scenarios over an increasing building's lifespan.

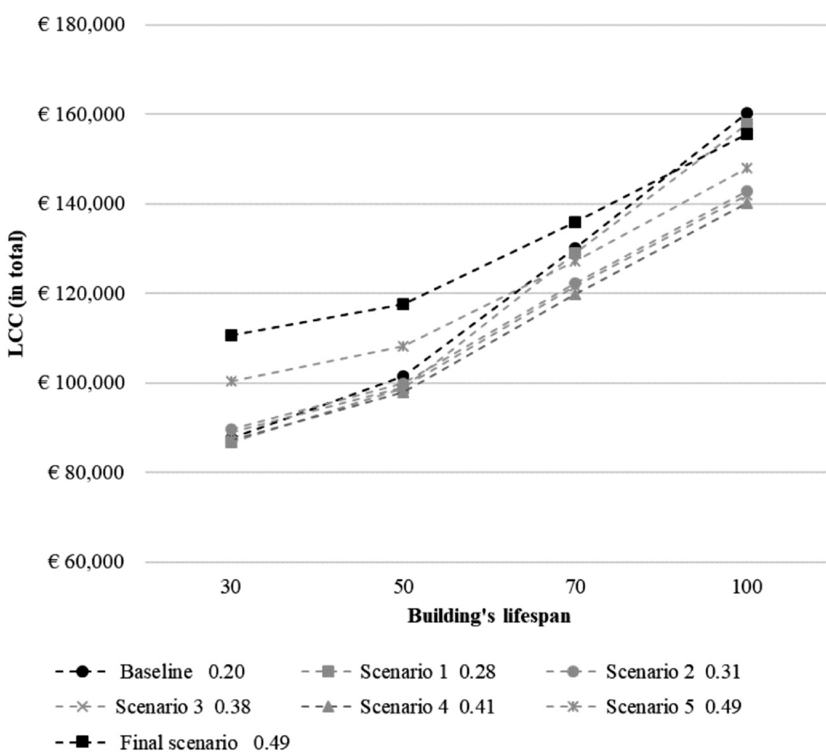

Fig. 6. LCC trends of the various scenarios with increasing building lifespan.

is important to create a closed-loop supply chain to make more efficient use of materials (Leising et al., 2018). Arrangements with suppliers about guaranteed building component take-back and value after a building's lifespan can influence the components' waste scenarios and residual values. These, in turn, have an impact on the LoC and LCC calculations. Arrangements with suppliers and clients to stimulate material reuse within sequential projects could result in materials having a better value retention (the general assumptions made are listed in Appendix Table G.2). Governments could encourage circular construction with incentives to support the application of circular building components. Furthermore, policymakers could tax waste material disposal to encourage lifespan extension and reduce the dumping

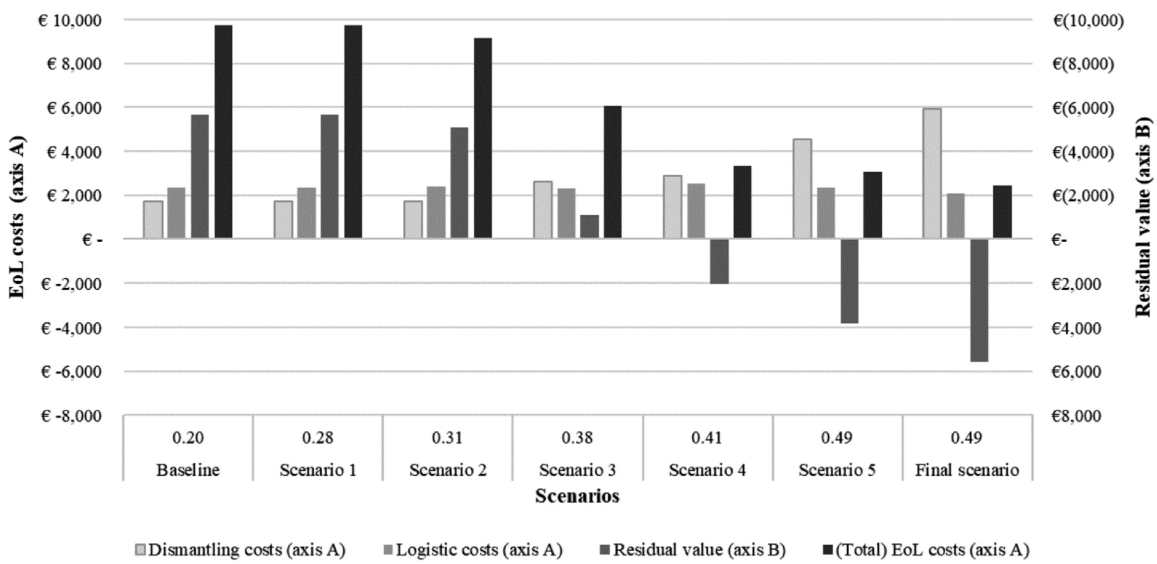

Fig. 7. Trend in End-of-Life costs with increasing circularity over a lifespan of 50 years.

of materials.

Moreover, this study contributed to another relevant topic in the academic field by assessing the practicality of the BCI tool developed by Verberne (2016). In this design-orientated research, this BCI tool has been critically reviewed for practice. The outcomes of the circularity assessment have been analysed and the model has been reviewed and modified to make it more suitable for practice. Some modifications to the BCI model were proposed in Section 3.2. Another point for attention is the large influence of the mass of building components on the LoC calculation. It could be fruitful to discuss if 'mass' is the best way to express the amount of material incorporated in the system. Verberne (2016) himself concluded that the current BCI assessment is too dependant on the material mass. High volume but low mass materials, such as insulation and roof elements, generally have very little impact on the BCI outcomes. Future research should determine if an alternative factor, such as 'volume', could be better. Furthermore, the BCI tool fails to distinguish between the priorities of the R-imperatives (Section 2.1). The types of material input and the waste scenarios are not weighted in terms of being more or less preferable. Incorporating this would encourage the deployment of a component's ongoing value. Despite these remarks, the BCI tool can still be considered as a reliable tool since it incorporates the most important aspects in assessing a building's LoC.

By combining the BCI and LCC tools, the importance of flexibility in building design for the building's circularity becomes clear. The value of flexibility and lifetime extension can be expressed in terms of the existing building's value plus its future potential (Fischer, 2019). In this research, only extending the components' lifespans is included. However, the influence of building flexibility through future add-ons and internal space plan flexibility should also be included. Coenen (2019) introduced circularity assessment factors to assess design adaptability for lifespan extension and reusability of components through standardised sizes. Future research should focus on how to incorporate these factors, in addition to the factors of the PCI, in the BCI since these factors have yet to be applied in LCC calculations. Although Hermans et al. (2014) have developed a tool that incorporates these factors to determine a building's future value, this only expresses the building value as a score and not in terms of economic value. The tool was therefore not considered applicable for our research.

6.2. Limitations in the LCC and LoC assessment and future research

In this section, we acknowledge some limitations of our research to place the findings in the right perspective. First, the research scope was to develop scenarios with increasing LoCs by replacing standard components in the structure, skin and space plan using circular components. However, the range of possible LoCs is limited by the existing building architecture and by the building materials available in the construction supply chain. Other material types could result in a higher LoC, but these were not considered as we could not be sure that these materials could be certified as safe for construction or be confident of a realistic price.

Second, the research was limited by current knowledge on material and labour costs. In the future, these costs could alter due to the development of new techniques for reutilisation of materials and through government pressure (e.g. raised taxes).

Third, the scenarios were manually generated rather than by a computer algorithm. Other scenarios could have been found by using an algorithm and might have provided additional insights. Further, the circularity levels found might change if these were assessed using other tools. There are other assessment tools, and there is the possibility of changes in the circularity levels when applying these other tools.

Future research could decrease these uncertainties by carrying out similar research for a range of projects to validate the relationship between building circularity level and LCC. This study has contributed to the research field of building circularity by introducing a method for assessing the LCC of circular building designs and validating this assessment approach with a first case. The next step is to identify comparable cases and develop scenarios with increasing circularity. All these should then be assessed for their circularity level and LCC. Based on comparisons of their LoC and LCC results, it can be assessed whether there is a consistent optimum in terms of circularity level and if the relationship between an increase in circularity level and LCC is consistent. If there is a relationship, and some uniformity in the optimum circularity level and LCC, some principles could be developed for circular design strategies based on economic feasibility.

Fourth, a critical aspect when comparing the profitability of circular material alternatives is that the comparison is only sensible when the alternatives are functionally equivalent and of equal value for a client (Kambanou and Sakao, 2020). In our study, the scenarios were designed in such a way that the structural, physical and quality levels were similar in all the scenarios.

Fifth, building services are excluded because energy and water consumption patterns over the 50-year lifespan assumed in this research would be highly speculative. Incorporating these aspects in future research on lifecycle assessments could make it possible to elaborate further on the environmental impact of circular scenarios for building design. It is important to determine the impact of circular building design in the broader context of energy consumption for production through to the recycling of materials.

The final point related to uncertainty concerns the several debatable aspects in future calculations due to uncertainty about discount rates, inflation and material escalation rates and on future material scarcity. In addition, governmental regulations could be influential by encouraging the purchase of certain materials, or through making their reuse attractive by making disposal more expensive. These aspects are not considered in the research but could easily have more influence on the purchase and residual values of buildings than the incorporated rates. Residual value calculation is an important aspect within the LCC approach. This includes the quality of a product for future reuse since this can make it more economically attractive by retaining more value. Future research could usefully study the principles of residual value calculation and how to include this in LCC approaches. This will support the application of circular materials and design principles, by decreasing the associated costs over the lifecycle of a building. In addition, the impact of adopting other circular business models on the LCC requires further research. By applying circular materials and product designs, a circular supplier business model was considered in our research. However, this did not fully guarantee profit through value retention, which is an element of a CE. Other circular business models that focus more on product remanufacturing, reuse and reselling could identify ways to enhance value retention. The influence of these business models on the LCC should be addressed to improve our understanding of the economic feasibility of circular projects. This demands a new perspective on how to integrate the costs and earnings of these models in LCC analyses.

7. Conclusions

LoC and LCC analyses were performed to assess the increase or decrease in costs of adopting circular building designs. The research outcomes contribute by showing that circular building design measures are financially valuable for a client. In the study, a circularity level of 0.49 (on a scale of 0 (not circular) to 1 (circular)) was the maximum achievable when replacing currently used components with more circular alternatives in the design of a standard one-family house. Higher circularity levels are difficult to achieve as circular building components are still scarce and are subject to cost premiums. Further, more radical building designs may be required.

The results show that, for a standard one-family house, replacing traditional materials with circular alternatives can double the circularity level (to 0.41) without impacting the LCC. Buildings with a higher circularity level (up to 0.49) are possible but require more radical changes in product design and construction processes. However, such novel products are far more expensive through a market effect of price premiums on circular building components. Furthermore, we saw that extending the buildings lifespan (up to 100 years) delivers significantly lower LCC for buildings with a circularity level of 0.41, compared to the baseline (0.20) and also the final scenario (0.49). This is a consequence of the combination of the relatively small increase in initial costs (product and construction) and the lower future costs (operational and EoL). Overall, the required changes to achieve a circularity level of 0.41 appear the most economically attractive as these result in lower LCC, even with a building lifespan of only 30 years. For clients in the construction industry this will require an 8% increase in initial investment but this will be more than offset by a 25% reduction in future costs.

On the basis of the results of our analyses, it is concluded that it is possible to decrease LCC while increasing the circularity. To boost the circularity of houses with financially viable alternatives requires investors to invest more in the initial phase. Further, our research shows that increasing a building's lifespan lowers the overall cost of the building. Having shown the basic feasibility of adopting circular designs, the supply chain should be encouraged to develop circular alternatives to existing materials and to collaborate with contractors that want to incorporate circular product design and efficient use of materials in their businesses.

Credit author statement

Linda Braakma: Conceptualization, Methodology, Writing, data collection, Formal analysis, visualization

Silu Bhochhibhoya: Conceptualization, Methodology, Reviewing and Editing, visualization

Robin de Graaf: Conceptualization, Reviewing and Editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105149.

References

Allen, P., Beverley, K., Carter, C., Cheshire, D., Frater, L., Howe, S., Kreißig, J., Radway, C., Rees, A., 2017. Circular economy: opportunity for the welsh built environment. Cardiff.

Ashraf, N., Al Ghonamy, A., Esam, M., Aichouni, M., Abdulwahab, M., Subhi, O., 2015. Significance of Life Cycle Costing for Selection of Building Construction Materials, in: second Intl. Conf. on Advances in Civil, Structural and Construction Engineering - CSCE 2015 94–98. https://doi.org/10.15224/978-1-63248-042-2-97.

Bhochhibhoya, S., Pizzol, M., Achten, W.M.J., Maskey, R.K., Zanetti, M., Cavalli, R., 2017. Comparative life cycle assessment and life cycle costing of lodging in the Himalaya. Int. J. Life Cycle Assess. 22, 1851–1863. https://doi.org/10.1007/s11367-016-1212-8.

Bhochhibhoya, S., Pizzol, M., Marinello, F., Cavalli, R., 2020. Sustainability performance of hotel buildings in the Himalayan region. J. Clean. Prod. 250, 119538. https://doi.org/10.1016/j.jclepro.2019.119538.

Bocken, N.M.P., Pauw, I.De, Bakker, C., Grinten, B.Van Der, Bocken, N.M.P., Pauw, I.De, Bakker, C., Grinten, B.Van Der, 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Brand, S., 1995. Sharing layers, in: How Buildings Learn: What Happens After They're Built. Penguin, London, pp. 252.

Brueton, J., 2018. Sustainable building products: the factors to consider [WWW Document]. Envirobuild URL. https://www.governmenteuropa.eu/sustainable-building-products-circular-economy/89564/ 5/6 (accessed 7.20.19).

Buyle, M., Galle, W., Debacker, W., Audenaert, A., 2019. Sustainability assessment of circular building alternatives: consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. J. Clean. Prod. 218, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306.

Coenen, T., 2019. Circulaire bruggen en viaducten - Een notitie met de kernpunten. Univ. Twente; Rijkswaterstaat, Enschede.

Durmisevic, E., 2019. Circular economy in construction: design strategies for reversible buildings.

Durmisevic, E., 2006. Transformable building structures: design for disassembly as a way to introduce sustainable engineering to building design & construction. Delft.

Ellen Macarthur Foundation, 2019. Making buildings with new techniques that eliminate waste.

Ellen Macarthur Foundation, 2015. Circularity indicators - an approach to measuring circularity - methodology.

Ellen Macarthur Foundation, 2013. Towards the circular economy - economic and business rationale for an accelerated transition. 10.1162/108819806775545321.

European Commission, 2014. Resource efficiency opportunities in the buildign sector. COM 445 Final. Brussels.

Fischer, A., 2019. Building value - a pathway to circular construction finance, Circle

Economy, Sustainable finanance lab. Nederland Circulair.
Geldermans, R.J., 2016. Design for change and circularity – accommodating circular material & product flows in construction. Energy Procedia 96, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153.
Ghaffar, S.H., Burman, M., Braimah, N., 2020. Pathways to circular construction: an integrated management of construction and demolition waste for resource recovery. J. Clean. Prod. 244, 9.
Giorgi, S., Lavagna, M., Campioli, A., 2019. LCA and LCC as decision-making tools for a sustainable circular building process. IOP Conf. Ser. Earth Environ. Sci. 296. https://doi.org/10.1088/1755-1315/296/1/012027.
Gleissner, H., Möller, K., 2011. Case Studies in Logistics, 1st ed. Springer.
Gluch, P., Baumann, H., 2004. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Build. Environ. 39, 571–580. https://doi.org/10.1016/j.buildenv.2003.10.008.
Hanssen, T.-E.S., Mathisen, T.A., Jørgensen, F., 2012. Generalized Transport Costs in Intermodal Freight Transport. Procedia - Soc. Behav. Sci. 54, 189–200. https://doi.org/10.1016/j.sbspro.2012.09.738.
Hermans, M., Geraedts, R., Rijn, E.Van, Romoy, H., 2014. Gebouwen met toekomstwaarde! Het beaplenvan de toekomstwaarde van gebouwen vanuit het perspectiefvan adaptief vermogen, financieel rendement en duurzaamheid: eindrapport. 10.13140/2.1.1947.4561.
Kambanou, M.L., Sakao, T., 2020. Using life cycle costing (LCC) to select circular measures: a discussion and practical approach. Resour. Conserv. Recycl. 155. https://doi.org/10.1016/j.resconrec.2019.104650.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Leising, E., Quist, J., Bocken, N., 2018. Circular Economy in the building sector: three cases and a collaboration tool. J. Clean. Prod. 176, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010.
Lowres, F., Hobbs, G., 2017. Challenging the current approach to end of life of buildings using a life cycle assessment (LCA) approach, in: challenging the Current Approach to End of Life of Buildings Using a Life Cycle Assessment (LCA) Approach. International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste, pp. 247–250.
McKinsey&Company, 2016. Why the circular economy is all about retaining value [WWW Document]. Podcast URL. https://www.mckinsey.com/business-functions/sustainability/our-insights/why-the-circular-economy-is-all-about-retaining-value.
Ness, D.A., Xing, K., 2017. Toward a resource-efficient built environment: a literature review and conceptual model. J. Ind. Ecol. 21, 572–592. https://doi.org/10.1111/jiec.12586.
Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002.
Potting, J., Hanemaaijer, A., Delahaye, R., Hoekstra, R., Ganzevles, J., Lijzen, J., 2018. Circular economy: what we want to know and can measure. Hague.
Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product chain. Hague.
Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.
Ristimäki, M., Säynäjoki, A., Heinonen, J., Junnila, S., 2013. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. Energy 63, 168–179. https://doi.org/10.1016/j.energy.2013.10.030.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? proposed requirements for the design of a circularity measurement framework. Recycl. MDPI 2. https://doi.org/10.3390/recycling2010006.
Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.
Surgenor, A., Winch, R., Moodey, L., Mant, A., 2019. Circular economy guidance for construction clients: how to practically apply circular economy at the project brief stage. London.
UNEP, 2011. Pathways to sustainable development and poverty eradication - a synthesis for policy makers. Toward GREEN Econ. 52.
Van Vliet, M., 2018. Disassembling the steps towards building circularity. Eindhoven Univ. Technol. Eindhoven.
Verberne, J.J.H., 2016. Building circularity indicators-An approach for measuring circularity of a building. Eindhoven Univ. Technol.
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., van Bortel, G., 2020. A circular economy life cycle costing model (CE-LCC) for building components. Resour. Conserv. Recycl. 161, 104857. https://doi.org/10.1016/j.resconrec.2020.104857.
Zabalza Bribián, I., Valero Capilla, A., Aranda Usón, A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140. https://doi.org/10.1016/j.buildenv.2010.12.002.
Zink, T., Geyer, R., 2017. Circular Economy Rebound. J. Ind. Ecol. 21, 593–602. https://doi.org/10.1111/jiec.12545.