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Full length article

A circular economy life cycle costing model (CE-LCC) for building components



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ABSTRACT

The building industry is responsible for the highest resource use, amount of waste and emissions of all industries. The principles of the Circular Economy (CE) could offer an approach to create a more sustainable built environment. For a transition towards a circular built environment, a comprehensive assessment method is needed to support the development of circular building products. As a step towards such a method, we developed an economic assessment in the form of a Circular Economy Life Cycle Cost (CE-LCC) model. It is based on existing Life Cycle Cost techniques and adapted to meet the requirements of CE products. The model is developed to (1) consider products as a composite of components and parts with different and multiple use cycles, (2) include processes that take place after the end of use, (3) provide practical and usable information to all stakeholders, and (4) facilitate alignment of the functional unit and system boundaries with LCA. To test the model, it has been applied to the case of the Circular Kitchen (CIK). Three variants of the CIK were compared to each other and the 'business-as-usual' case to determine which variant is the most economically competitive on the long term. The model indicates that the most flexible variant of the CIK has the lowest LCC outcome, even when considering multiple interest, lifespan and remanufacturing and recycling scenarios. Although, the model could benefit from further research and application, it can support the transition towards a more sustainable (building) industry.

1. Introduction

The building industry is responsible for the highest amount of resource use, waste and emissions of all industries (Ness and Xing, 2017). Therefore, a more sustainable building industry is needed to ensure the stability of the global economy and natural ecosystems. Numerous definitions of sustainability exist. For the purpose of this paper we use the comprehensive definition as proposed by Geissdoerfer, Savaget, Bocken, & Hultink, (2017, p. 759): "the balanced and systemic integration of intra and intergenerational economic, social, and environmental performance." Research into sustainability in the building industry has mostly focused on reducing the operational energy use of buildings and their related emissions (Ness and Xing, 2017). However, reducing the consumption of material resources reduces CO₂ emissions as well (Kennedy, Cuddihy, & Engel-Yan, 2007; Wijkman & Skånberg, 2015).

The principles of a Circular Economy (CE) offer a step towards a sustainable built environment, by contributing to resource efficiency and effectiveness, reducing resource use and waste and therefore

lowering environmental impact. CE, according to Geissdoerfer et al. (2017, p. 759), is "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops", in which slowing loops is to lengthen the use of a product, closing loops is to recycle materials, and narrowing loops is to reduce resource use or achieve resource efficiency (Bocken, de Pauw, Bakker & van der Grinten, 2016).

The transition towards a circular built environment will require integral changes in the design, supply chain and business model of products¹ (van Stijn and Gruis, 2019). Therefore, tools and methods to support industry in this process are needed, which in general can be divided in two main types of methods: generative and evaluative (de Koeijer, Wever & Henseler, 2017). Generative tools support the development of design proposals, while evaluative tools are used to assess the developed designs. The focus in this article is on an evaluative method.

Many of the current assessment methods and tools remain fragmented (Sassanelli et al., 2019). They focus on a single, or a limited number of indicators. To assess circularity, a comprehensive,

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¹ In this paper, CE building components are assumed to be produced and sold by a manufacturer as a product, and will therefore be referred to as products from here on.

Nomenclature			
<i>PV</i>	Present Value	C_{wad}	Waste disposal costs
<i>FV</i>	Future Value	M	Manufacturer profit margin factor
<i>i</i>	Discount rate	C_{con}	Consumption costs
<i>t</i>	Time in years	C_{mai}	Maintenance costs
<i>TC</i>	Total (product) cost	V_r	Residual value
MAN	Manufacturer	C_{ref}	Refurbishment costs
CUS	Customer	C_{rep}	Repurposing costs
EUA	End of use actors	C_{enr}	Energy recovery costs
EOU	End of use	A_0	Average amount collected at EOU
EOL	End of life	A_2	Average amount reused
CC	(Total) component costs	A_4	Average amount refurbished
PC	(Total) part costs	A_5	Average amount remanufactured
C_{rma}	Material costs	A_6	Average amount repurposed
C_{mpr}	Material processing costs	A_7	Average amount recycled
C_{man}	Manufacturing costs	A_8	Average amount used for energy recovery
C_{tra}	Transport costs	A_{99}	Average amount of waste
C_{ins}	Installation costs	R_2	Expected percentage suitable for reuse
C_{rrr}	Reuse, recycling and remanufacturing costs	R_4	Expected percentage suitable for refurbishing
C_{din}	Deinstallation costs (or removal costs)	R_5	Expected percentage suitable for remanufacturing
C_{rnn}	Remanufacturing costs	R_6	Expected percentage suitable for repurposing
C_{rec}	Recycling costs	R_7	Expected percentage suitable for recycling
		R_8	Expected percentage suitable for energy recovery

quantitative assessment method is needed (Bradley et al., 2018; Buyle, Galle, Debacker & Audenaert, 2019; Sassanelli et al., 2019). Various authors have argued that circular assessment methods should integrally assess CE solutions, including the environmental, social and economic performance (Hunkeler, Lichtenvort & Rebitzer, 2008; Sassanelli et al., 2019). However, we apply a narrow approach of circularity that includes the environmental and economic perspective. Although we consider the social performance conditional for the sustainability of the developed solution, we do not include it as part of CE assessment. Furthermore, to justly compare CE-solutions, assessment of the value of a solution is needed (Schepens, Vogtländer & Brezet, 2016): solutions cannot be compared on their performance without comparing their value (i.e., the functional value and/or added value to the user or supply chain). Circular assessment will require finding the optimum between economic performance, environmental performance and functional value (i.e. multi criteria assessment (MCA)).

1.1. Towards Circular Life Cycle Costing

Although we recognize such a comprehensive method is needed, methods that can be used to assess the separate criteria (i.e. functional value, and environmental and economic performance) are not fully adapted to CE products and thus need to be developed first. In this article, we develop a Life Cycle Costing (LCC) method to assess the economic performance of CE products. LCC is a technique to calculate the total cost from cradle to grave, or over a selected period of time, that supports decision making processes during the development stage of products (Davis Langdon, 2007; Dhillon, 2009; Gundes, 2016; International Organization for Standardization [ISO], 2017).

To be able to assess products for a circular economy, a number of key properties have to be considered. First, in a CE, products will be designed for repair, reuse, upgradability, disassembly and recycling (Bocken et al., 2016). Components and parts of a product will most likely be exchanged at a different rate to increase the overall lifespan of the product. Therefore, products should be treated as composites of components and parts with different, and multiple use cycles. Second, value retention processes (VRPs) will take place to extend the lifespan of products that should be included in the assessment. Finally, in a transition to CE, multiple stakeholders will have to be involved in the development process to enable VRPs to take place. The assessment

should therefore be able to inform multiple stakeholders.

1.2. Limitations of current approaches to Life Cycle Costing

There are three main approaches to LCC: Conventional LCC (C-LCC), Environmental LCC (E-LCC) and Societal LCC (S-LCC). C-LCC was introduced in the 1930s by the US Department of Defense to include operating and maintenance cost in public procurement (De Menna, Dietershagen, Loubiere & Vittuari, 2018; Dhillon, 2009; Heralova, 2017). It has a single stakeholder perspective (producer or consumer) and does not always consider the complete life cycle; end of life (EOL) scenarios are not included (see Section 2). Multiple stakeholders can be included in E-LCC, which aims to complement the environmental life cycle assessment (LCA) with cost calculation. S-LCC can enlarge the boundaries of analysis further by including direct and indirect costs covered by society (De Menna et al., 2018; Hunkeler et al., 2008).

As stated, VRPs in the Circular Economy are carried out by a number of stakeholders (i.e., product manufacturer, customer, end of life actors (see Section 2) or other involved stakeholders).

Since E-LCC facilitates use in an MCA (in conjunction with LCA), and incorporates all the stakeholders involved, it can provide a viable basis for a Circular Economy LCC (CE-LCC). Considering costs that take place after the use period, such as dismantling and disposal costs, and the use of residual value has been explored in Fregonara, Giordano, Ferrando & Pattono (2017). However, these methods do not fully account for multiple, closed loop use- or life cycles, made possible through VRPs, which are a core concept of CE. A step towards such a model has been made by Bradley et al. (2018), incorporating multiple use cycles into a total life cycle costing model (TLCCM) based on generations of use.

Nevertheless, the TLCCM is based on the LCC calculation of a product as a singular unit and cannot (simultaneously) be applied to multiple scale levels. For example, it can easily be applied to a coffee cup that is used multiple cycles. But a new model is needed to calculate the cost for a more complex, circular composite product, such as a circular building façade in which components and parts will be exchanged at a different rate.

None of the existing LCC methods meet all of the requirements to assess CE products. Therefore, to support the development of circular

products, we adapt existing LCC techniques to (1) consider products as a composite of components and parts with different and multiple use cycles, (2) include processes that take place after the end of use, (3) provide practical and usable information to all stakeholders, and (4) facilitate alignment of the functional unit and system boundaries with LCA. In this paper, we develop an LCC method for the Circular Economy (CE-LCC) based on existing LCCs and apply it to a case of a circular building product.

2. Method

2.1. Linear versus circular processes

To make an LCC, processes that result in costs need to be defined. What these processes are and where they take place is determined by the design, industrial and business model for the product. A transition to CE affects all three, since material loops are narrowed, slowed and closed. While narrowing material loops does not affect the type of processes that take place or their location, slowing and closing loops have considerable consequences. To slow material loops, products are designed for product-life extension, in which the use period of goods is extended through the introduction of service processes such as reuse, maintenance, repair and upgrading. To close material loops, products are designed to be disassembled and recycled in a technological and biological cycle (see Table 1).

Processes that distinguish CE from linear economies follow from the strategies mentioned above. These processes are defined as value retention processes (VRPs) (also called R-imperatives) and are decisive for operationalizing CE (Blomsma and Brennan, 2017; Nasr, Russell, Bringezu, Hellweg, Hilton & Kreiss, 2018; Reike, Vermeulen & Witjes, 2018). Thus, to adapt LCC for application to circular products, VRPs are to be added to the model. To include VRPs in LCC, they need to be clearly defined. Numerous frameworks have been proposed including 3 up to 10 VRPs, not only varying in number of R-imperatives, but also in their meaning. In a critical literature review, Reike et al. (2018) established an overview of the most common perspectives on VRPs, including the key activities.

VRPs in the Circular Economy are carried out by a number of stakeholders (i.e., product manufacturer, customer, end of life actors or other involved stakeholders). We have adapted this overview in four ways (as seen in Table 2). First, to create space for additional information, we have removed three columns, containing object, owner and function. Although these columns were removed, the information they provided has been included in this article. Second, we have added two columns to the overview, containing possible stakeholders and the selected stakeholder for the VRP in the CE-LCC model, which will be further explained in Section 2.5. Third, to enable most of the VRPs in the overview, product collection at the end of life or end of use is needed. This is represented through adding ‘collect’ in the key market stakeholder activities where relevant. Finally, Nasr et al., (2018) illustrated the difference between a number VRPs in a clear way. We have adapted these illustrations and have expanded them to illustrate all the VRPs defined in this paper in the last column of Table 2. The adapted overview is applied in this paper and forms the starting point for the allocation of processes to stakeholders.

2.2. Time value

Time is a crucial element that must be considered in any cost model or economic framework. If the time-value relationship is ignored, cost reduction, no matter at what point in time, would seem favorable to higher cost alternatives (Bradley et al., 2018). It is therefore especially important to stress the importance of time value and discounting for models that consider multiple use cycles throughout longer return on investment (ROI) periods.

Therefore, all costs in the CE-LCC model should be considered at

present value (PV). Since stakeholders apply different discount rates (International Organization for Standardization [ISO], 2017), discount rates are defined per stakeholder. All costs in the model are discounted as described in Eq. 1:

$$PV_{SH\ x} = \frac{FV_{SH\ x}}{(1 + i_{SH\ x})^t} \tag{1}$$

in which the PV is calculated using the Future Value (FV), the discount rate (i) and the time in years (t). The subscript SH x is used to indicate Stakeholder x, which can be any of the stakeholders involved.

2.3. Model development

To make current LCC techniques applicable to CE products, a number of adaptations are made, forming the new CE-LCC model. First, it considers products as a composite of components and parts with different and multiple use cycles. Second, it includes processes that take place after the end of use. Third, it provides practical and usable information to all stakeholders, and finally, it allows for the alignment of the functional unit and system boundaries with LCA. In the following sections, the new model is further elaborated.

2.4. Use cycles

The new CE-LCC model accounts for multiple use cycles. To understand how, a single use cycle should be understood first. In this model, the first use cycle of a product starts with the processing of raw materials and ends at the end of use (EOU) by the customer. The length of a use cycle is determined by the expected functional lifespan, defined as the timespan in which the object meets the functional demands of the user. According to Wamelink, Geraedts, Hobma, Lousberg & De Jong (2010, p. 300), two factors influence the functional lifespan: regulations and the changing needs of the user, including the appearance of the product.

This indicates that a use cycle of a part, component or product can end before the end of its technical lifespan or end of life (EOL), defined as “the maximum period during which it can physically function” (Cooper, 1994, p. 5). Through VRPs, a new use cycle can take place beyond the EOU.

Since multiple use cycles take place on the component and part level within a use cycle of the product, the functional and technical lifespan of the components and parts can differ in the CE-LCC model. Since this affects the calculation of total cost (TC) for a product as well, we have applied a hierarchy: the TC of a product is calculated as seen in Eq. 2:

$$TC = \sum_{k=m}^n CC_m + CC_{m+1} + CC_{m+2} + \dots + CC_{n-2} + CC_{n-1} + CC_n \tag{2}$$

in which it is the sum of the total costs per component (CC), which is the sum of the total costs per part (PC), as can be seen in Eq. 3:

$$CC = \sum_{k=m}^n PC_m + PC_{m+1} + PC_{m+2} + \dots + PC_{n-2} + PC_{n-1} + PC_n \tag{3}$$

Table 1
Design strategies for the Circular Economy as proposed by Bocken et al. (2016).

Slowing Material Loops	Closing Material Loops
Design for attachment and trust	Design for a technological cycle
Design for reliability and durability	Design for a biological cycle
Design for ease of maintenance and repair	Design for dis- and reassembly
Design for upgradability and adaptability	
Design for standardization and compatibility	
Design for dis- and reassembly	

Table 2
Value Retention Processes adapted from (Reike et al., 2018) by adding possible and selected stakeholders, illustrated as proposed for R2, R4, R5 in Nasr et al., (2018)

	R#	CE concept	Key customer Activity	Key market stakeholder activity	Possible Stakeholder (for allocation of costs)	Selected stakeholder for cost allocation in CE-LCC model	Process illustration
Product Downcycling	R9	Re-mine	Buy and use secondary materials	Grubbing, cannibalizing, selling (non-industrialized)/ high-tech extracting, reprocessing (industrialized).	Third Parties	-	
	R8	Recover energy	Buy and use energy (and/or distilled water)	Collect, Energy production as by-product of waste treatment	Third Parties	Third Parties (EOU Actors)	
	R7	Recycle	Dispose separately; buy and use secondary materials	Collect, check, separate, shred, distribute, sell	Manufacturer, Third Parties	Manufacturer	
	R6	Repurpose (Rethink)	Buy new product with new function	Collect, Design, develop, reproduce, sell	Third Parties	Third Parties (EOU Actors)	
Product upgrade	R5	Remanufacture	Return for service under contract or dispose	Collect, replacement of key modules or components if necessary, decompose, recompose	Manufacturer, Third Parties	Manufacturer	
	R4	Refurbish	Return for service under contract or dispose	Collect, replacement of key modules or components if necessary	Manufacturer, Third Parties	Third Parties (EOU Actors)	
	R3	Repair	Making the product work again by repairing or replacing deteriorated parts	Making the product work again by repairing or replacing deteriorated parts	Customer, Third Parties	-	
Client/user choices	R2	Resell/ Reuse	Buy 2nd hand, or find buyer for your non-used produced/possibly some cleaning, minor repairs	Buy, collect, inspect, clean, sell	Customer, Manufacturer, Third Parties	Manufacturer	
	R1	Reduce	Use less, use longer; recently: share the use of products	See 2nd life cycle Redesign	-	-	
	R0	Refuse	Refrain from buying	See 2nd life cycle Redesign	-	-	

2.5. Stakeholder Domains

The overall structure of the use cycles is separated into three domains in which the costs occur: the domain of the manufacturer, the domain of the customer and a domain for the EOU actors (Schmidt, 2003). In the latter, VRPs take place in which the manufacturer is assumed not to engage. As these VRPs all take part at the EOU or even EOL stage, this domain is referred to as that of EOU actors (e.g., refurbishing shops and waste management companies). Distinguishing domains (or areas) has two advantages according to Bradley et al. (2018): (1) it illustrates the relationship of the manufacturer and customer well: although the manufacturer and customer are independent actors, their decisions affect each other significantly, and (2) designers can see the costs for the stakeholders separately. According to Schmidt (2003), integrating domains beyond that of the client of the LCC offers other incentives as well; it can improve the competitiveness

of a product by including customer costs (for example, high investment costs can be countered with low maintenance costs) or by including future liabilities.

The stakeholder domains in which VRPs take place is case specific and depends on the business and industrial model. However, VRPs have been allocated to set domains to make the CE-LCC model operational. If the VRP domains of a case do not match the set domains of the CE-LCC model, the costs for that VRP can be moved to the correct domain without having a significant impact on the model structure. Table 2 shows the stakeholder domains in which the VRPs can take place, and where they are allocated in the CE-LCC model. The allocation is based on how suitable the product, component or part is after the VRP for its original function and its lifespan. If the same function and lifespan can be achieved, the VRP is allocated to the manufacturer, as it could benefit the manufacturer financially without having to divert from their core business. In the model, R0 and R1 (refuse and reduce) are not

allocated since they describe the reduction or absence of a financial transaction rather than a transaction and therefore cannot be included in an LCC (Hunkeler et al., 2008). R2 (reuse/resell) is assumed to occur when EOU is not EOL, given that collection takes place. Although R2 can take place in all domains, it is assumed that the manufacturer will engage in contracts that ensure recovery through collection after EOU. Therefore, R2 takes place in the domain of the manufacturer. R3 (repair) is defined as the replacement of deteriorated parts, which is included by considering products as composites of components and parts in the CE-LCC model and therefore does not need allocation to a domain. According to Nasr et al. (2018), the difference between refurbishment and remanufacturing lies in the standardization of the process, the setting in which the process takes place, and the expected state after the process. While refurbishment (R4) is seen as taking place in a non-factory or non-industrial setting, being non-standardized and offering life extension, remanufacturing (R5) is seen as a standardized, factory process offering a new full service-life afterwards. Therefore, R4 in the CE-LCC model takes place in the domain of EOU actors and R5 takes place in the domain of the manufacturer. R6 (repurpose) takes place in the domain of EOU actors, since it implies a (irreversible) change in function. R7 (recycle) is used in the definition of recycling materials that can then be applied as secondary materials. Following Bradley et al., (2018), it is allocated in the domain of the manufacturer, as it can imply a saving compared to the acquiring of virgin materials for the manufacturer. R8, as R6 implies a permanent change in function to fuel for energy production and therefore takes part in the domain of EOU actors. As R9 concerns urban mining or landfill mining, it is a VRP that extends beyond the level of a product, its component or parts. Therefore, it cannot be included in the CE-LCC model. Figure 1 shows the structure for calculating costs per part that forms the basis of our CE-LCC model, applying multiple use cycles and various domains of stakeholders that are involved in the life cycle of a circular product.

The CE-LCC model calculates the total cost that arises from a product. Therefore, the outcome of the CE-LCC model is the total costs made for a product by all stakeholders involved throughout period of time: the sum of the costs for the whole product from each of the domains, as can be seen in Eq. 4:

$$TC = TC_{MAN} + TC_{CUS} + TC_{EUA} \quad (4)$$

Bradley et al. (2018a, p. 144) have stated that such a total outcome may seem unimportant for a single stakeholder involved. However, it does show the total cost footprint of a product, which is useful for stakeholders' sustainable value creation.

2.6. Manufacturers Domain

Cost calculation for parts is done differently per stakeholder and is therefore specified per stakeholder domain. Since the costs for the customer are influenced by the costs made by the manufacturer, the costs for the manufacturer need to be determined first. These costs are determined as described in Eq. 5:

$$PC_{MAN} = PC_{MAN 0} + \sum_{t=1}^{t=P+1} \frac{PC_{MAN t}}{(1 + i_{MAN})^t}$$

$$= \sum_{t=0}^{t=P+1} \frac{PC_{MAN t}}{(1 + i_{MAN})^t} \quad (5)$$

where, the PC for the manufactures is calculated as the sum of the costs for the part per year. The model is aimed at the initial implementation of CE products and therefore excludes the cost benefit of the VRPs in the first use cycle, taking place at $t = 0$. The initial manufacturer's costs can be split up into costs for (raw) materials, material processing, manufacturing, transport and installation. Eq. 6 shows the calculation of PC_{MAN} at $t = 0$:

$$PC_{MAN t} = C_{rma} + C_{mpr} + C_{man} + C_{tra} + C_{ins}, \quad (6)$$

For every use cycle after the first ($t > 0$), the costs for raw material, material processing, manufacturing, transport and installation are

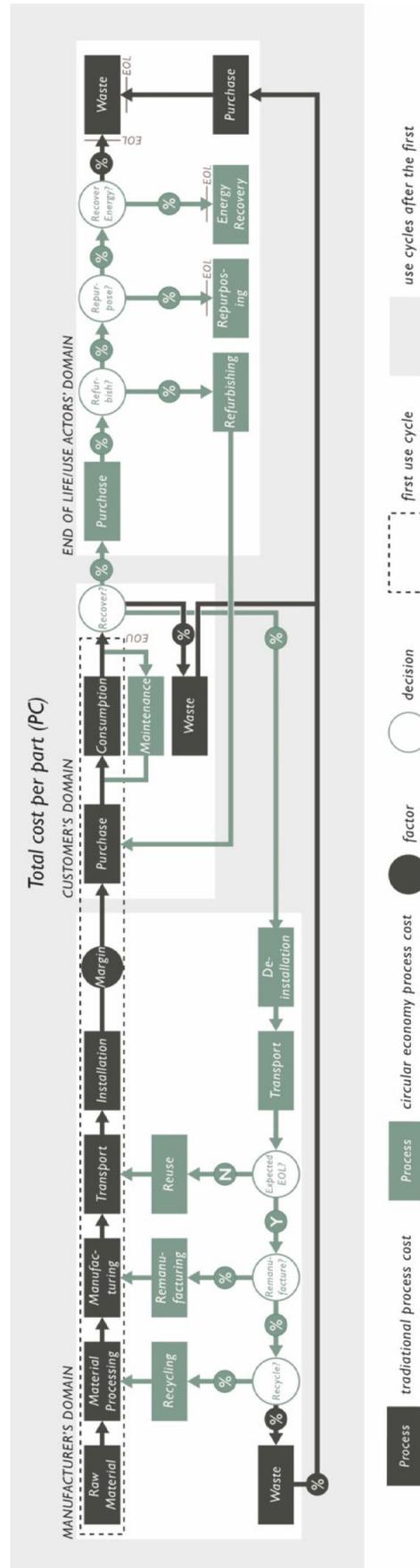


Figure 1. The overall structure of use cycles of a part in the CE-LCC model.

reduced by the savings made through VRPs as described in Eq. 7:

$$PC_{MAN\ t} = C_{rma}(1 - A_7 - A_5 - A_2) + C_{mpr}(1 - A_5 - A_2) + C_{man}(1 - A_2) + C_{tra} + C_{ins} + C_{rrr}. \quad (7)$$

in which the A values relate to the VRPs. VRPs in the model require extra costs to be made, such as de-installation and transport, but reduce the costs for raw materials, production and/or manufacturing, determined by the type of VRP. These costs are defined as seen in Eq. 8:

$$C_{rrr} = A_{0\ MAN}(A_1(C_{din} + C_{tra}) + A_2(C_{din} + C_{tra} + C_{rnn}) + A_3(C_{din} + C_{tra} + C_{rec}) + A_{99\ MAN}(C_{wad})) \quad (8)$$

To determine the savings or costs of VRPs, an average percentage of parts that is expected per VRP needs to be determined. At the end of a use cycle, a percentage of the parts is recovered by the manufacturer, a percentage is recovered by EOU actors and a percentage is not recovered. Then it is determined which VRP can be applied to the part in a number of steps. First, it is determined if the end of the technical life of the part is reached (EOL). If not, the part can be reused directly and the value of R_2 is 1:

$$\text{If } EOU = EOL, \quad R_2 = 0 \quad (9)$$

$$\text{If } EOU \neq EOL, \quad R_2 = 1 \quad (10)$$

in which the R_x is the expected average percentage of parts suitable for the VRP indicated as R0-R9 in Table 2.

When the technical life ends and R_2 is 0, in a second step, it is determined which percentage of the parts can be remanufactured. In a third step, it is determined which percentage of the parts that remain can be recycled. Then, for the remaining amount of parts that cannot be reused, remanufactured or recycled by the manufacturer, costs occur for waste disposal by the manufacturer.

R_x is the expected average percentage of parts suitable for VRP x . However, since the VRP determination sequence is interdependent, R_x is not the actual average amount of the part that will undergo VRP x . This average amount is formulated as A_x (a value between 0 and 1). The mathematical relations of the A_x values can be seen as follows:

$$A_{0\ MAN} = 1 - A_{0\ EOU} - A_{99\ CUS} \quad (11)$$

$$A_{0\ MAN} = R_{0\ MAN} \quad (12)$$

$$A_2 = (A_{0\ MAN})R_2 \quad (13)$$

$$A_5 = (A_{0\ MAN} - A_2)R_5 \quad (14)$$

$$A_7 = (A_{0\ MAN} - A_2 - A_5)R_7 \quad (15)$$

$$A_{99\ MAN} = A_{0\ MAN} - A_2 - A_5 - A_7 \quad (16)$$

where the amount collected by the manufacturer ($A_{0\ MAN}$) is determined directly by $R_{0\ MAN}$ (Eq. 12), which also determines the amount the EOU actors collect ($A_{0\ EOU}$) and the amount of waste the customer has ($A_{99\ CUS}$) (Eq. 11). R_2 determines the amount of reuse (Eq. 13). The amount that is not reused can be remanufactured, depending on R_5 (Eq. 14), and the amount that cannot be remanufactured can be recycled, depending on R_7 (Eq. 15). The amount of parts wasted by the manufacturer is then determined by the amount recovered, reused, remanufactured and recycled (Eq. 16) All R_x values are entered into model, apart from R_2 , which is determined as described above in Eqs. 9 and 10.

2.7. Customers Domain

As stated in the previous section, the costs for the customer depend on the costs for the manufacturer. The costs for the customer are defined as described in Eq. 17:

$$PC_{CUS} = PC_{MAN} \cdot M + \sum_{t=0}^{t=P+1} \frac{C_{con} + C_{mai} + A_{99\ CUS} \cdot C_{wad}}{(1 + i_{CUS})^t} \quad (17)$$

in which, to translate the manufacturers costs to the purchase costs for the customer, they are multiplied by M , the margin the manufacturer applies to account for profit and overhead that is not included in the other costs. The savings made through VRPs by the manufacturer are calculated into the price of purchase after the first use cycle, thus giving the customer an incentive for returning the parts at the EOU. Apart from the purchase costs, consumption (C_{con}) and maintenance costs (C_{mai}) are included in the calculation for the customer. Furthermore, the parts that are not recovered by the manufacturer or EOU actors at EOU cause waste disposal costs (C_{wad}) in the customers domain. As stated in Section 2.2, stakeholders can use varying discount rates. Therefore, in the calculation of the costs for the customer, a customer's discount rate (i_{CUS}) is used.

2.8. EOU actors Domain

The EOU actors carry out the VRPs that are not executed by the manufacturer: refurbishment, repurposing and energy recovery. These VRPs are very likely to be executed by separate EOU actors. However, to make the model operational, the complexity has been limited and these actors are combined in a single domain. At the end of use, the assumption is made the EOU actors will acquire the parts at the costs of the residual value (V_r). The EOU actors' costs are calculated as seen in Eq. 18 and 19:

$$PC_{EUA} = \sum_{t=0}^{t=P+1} \frac{PC_{EUA\ t}}{(1 + i_{EUA})^t} \quad (18)$$

$$PC_{EUA\ t} = A_{0\ EUA} \cdot V_r + A_4 \cdot C_{ref} + A_6 \cdot C_{rep} + A_8 \cdot C_{enr} + A_{99\ EUA} \cdot C_{wad} \quad (19)$$

in which they have costs for refurbishment, repurposing, energy recovery and at the end, for waste disposal. Just as in the determination of VRP related costs for the manufacturer, the A values of the EOU actors' VRPs are calculated as seen in Eq. 20, 21, 22, 23 and 24:

$$A_{0\ EUA} = R_{0\ EUA} \quad (20)$$

$$A_4 = (A_{0\ EUA})R_4 \quad (21)$$

$$A_6 = (A_{0\ MAN} - A_4)R_6 \quad (22)$$

$$A_8 = (A_{0\ MAN} - A_4 - A_6)R_8 \quad (23)$$

$$A_{99\ EUA} = A_{0\ MAN} - A_4 - A_5 - A_8 \quad (24)$$

in which the interdependency of the amount of parts that undergo a VRP is similar to Eqs. 11-16, starting with the amount of parts recovered by the EOU actors, determined either by $R_{0\ EUA}$, or by $A_{0\ MAN}$ and $A_{99\ CUS}$, as seen in Eq. 11.

3. Test-case: the Circular Kitchen

We have developed the CE-LCC to aid the building industry to make decisions in the development stages of circular products. To test it, we applied it to an example of a circular building component: the Circular Kitchen (CIK).

The CIK is currently being developed for the Dutch social housing sector by TU Delft and industry partners and is funded by EIT Climate-KIC and AMS institute. The aims of the CIK are to develop a market-ready circular kitchen that reduces the environmental impact of kitchens through slowing and closing loops, while remaining affordable and functional. Slowing and closing the loops is done through a separation in parts based on function (and related functional and technical lifespan). The CIK consists of a docking station to which kitchen modules can be attached. The modules consist of a construction (with a

long lifespan) to which infill (with a medium lifespan) and finishing (with a short lifespan) can be attached. As opposed to current kitchens, no glue is used to connect the parts to each other. Instead, click-on connections are used that allow for tool-free assembly and disassembly. Therefore, parts of the kitchen can be easily remanufactured and recycled separately while offering more flexibility throughout the use period, thus prolonging the overall lifespan of the kitchen.

The CIK is capable of illustrating the effect of having a component with parts that differ in lifespan and type of lifecycle, as for example a façade would. Furthermore, the CIK offers a building component that is already designed for standardization and is mass-produced by a manufacturer, a key principle of CE (see Table 1). Moreover, the kitchen manufacturer's 80 years of experience with mass-production allows for more accurate data to be used than currently possible for most other CE building components.

3.1. Comparisons: Variants

As part of the development process of the CIK, three variants (see Fig. 3), consisting of 4 lower cabinets, 4 wall cabinets, and a high cabinet, were proposed to the stakeholders involved. Variant 1 consists of a frame construction made of modified timber, while variants 2 and 3 consist of a more traditional panel construction of durable plywood. Furthermore, in variants 1 and 2, the construction and finishing parts are separated into two layers, while variant 3 has panels that function both as construction and finishing. Figure 2 shows these CIK variants and the business as usual (BAU) kitchen.

All the input data was gathered from the stakeholders involved in

the CIK project. Where no data was available, estimations were made by the stakeholders. To test the sensitivity of a number of parameters in the model, the CIK variants and the business-as-usual case were compared over a period of 75 years in three types of scenarios: (1) different interest rates, (2) different expected lifespans of parts, and (3) different percentages of remanufacturing (R5) and recycling (R7). Table 3 shows these scenarios and the altered parameters.

3.2. Comparison 1: Interest Scenarios (I1, I2 & I3)

Throughout the 75-year period, variables that determine the discount-value, such as the interest rate and inflation, might change. While the Social Housing Guarantee Fund (WSW) is expecting the interest on Dutch 10 year bonds to rise to 4.5% within 20 years (Autoriteit Woningcorporaties, 2018), the recent rise in negative yield bonds (Ainger, 2019) has led others to believe that low, or even negative yields, might stay (Harding, 2019). Since interest rates have a profound influence on the investments companies make, three scenarios for comparison were compared: (I1) 4.5%, (I2) 2% and (I3) -0.5% (based on Dutch 10 year state bonds in September 2019 (IEX, 2020)) nominal interest, all with an inflation of 2% (based on data from CBS (2020)). The discount rate for the scenarios was calculated as seen in Eq. 25:

$$i = \frac{1 + \text{nominal interest}}{1 + \text{inflation}} - 1 \tag{25}$$

The associated total costs for each scenario can be plotted using the model as seen in Figures 3a, 3b, and 3c (International Organization for

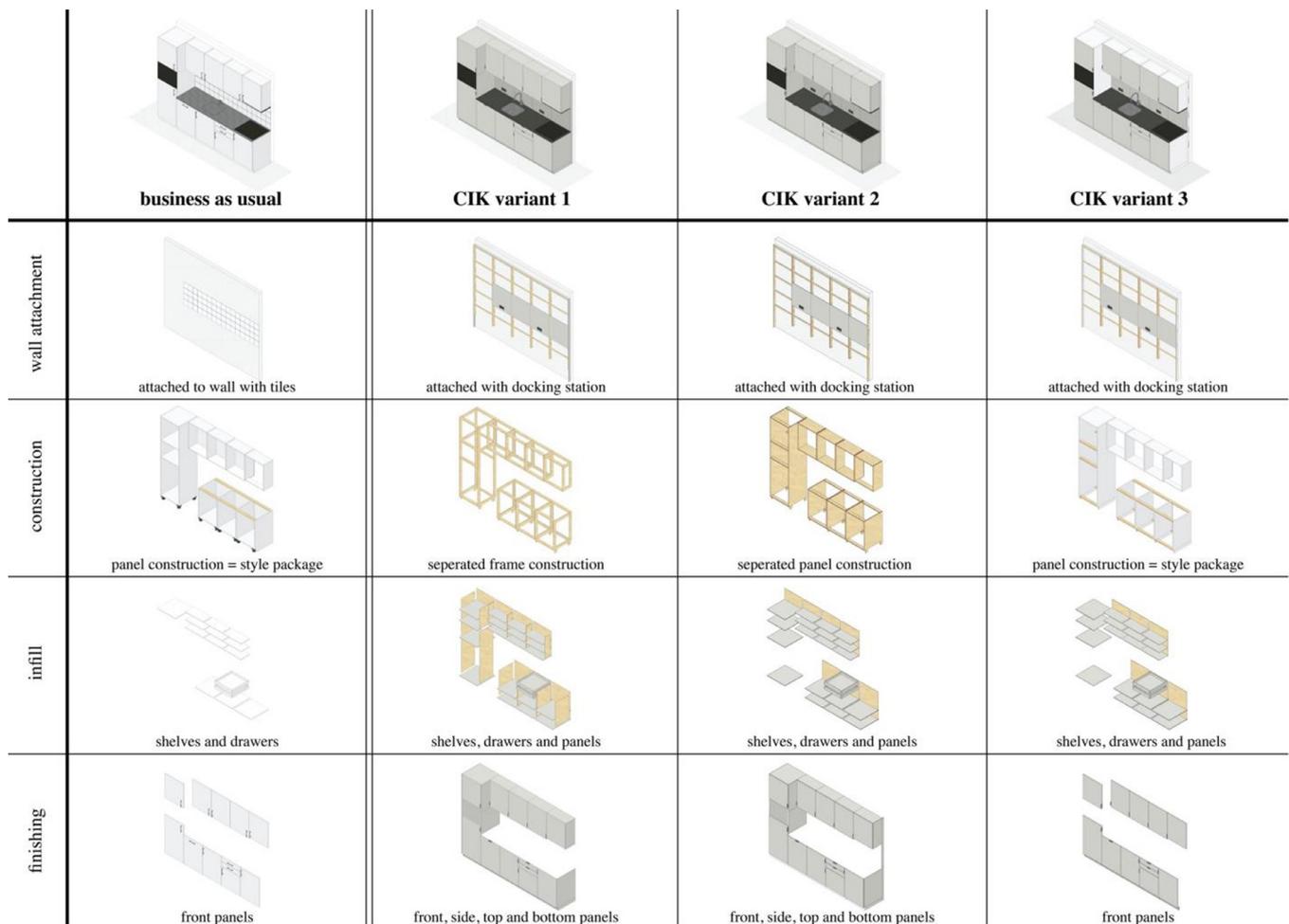


Figure 2. Overview of the variants compared, shown in both the assembled setup (top row) and the functional layers displayed separately (bottom 4 rows).

Table 3
Overview of values used in the three comparisons of the CIK variants and the BAU kitchen.

	variant	comparison 1: interest rates			comparison 2: technical lifespan in years					comparison 3: VRPs in percentages					
		I1:	I2:	I3:	L1: BAU & CIK 75%	L2: BAU & CIK 100%	L3: BAU & CIK 125%	L4: BAU 100%, CIK 75	L5: BAU 100%, CIK 125%	V1: 75% R5 R7	V2: 100% R5 R7	V3: 125% R5 R7			
customer interest rate	All	4,5%	2%	-0,50%	4,5%	4,5%	4,5%	4,5%	4,5%	4,5%	4,5%	4,5%	4,5%	4,5%	
manufacturer interest rate	All	3%	2%	-0,50%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	
all	0				15	20	25	20	20	0%	0%	0%	0%	0%	
construction	1				60	80	100	60	100	0%	75%	0%	100%	0%	
construction	2				48	64	80	48	80	0%	8%	0%	10%	0%	
construction & style package	3				30	40	50	30	50	45%	8%	60%	10%	75%	
connectors	1,2,3				26	35	44	26	44	0%	0%	0%	0%	0%	
infill	1,2,3				30	40	50	30	50	23%	8%	30%	10%	38%	
infill	1,2,3				15	20	25	15	25	0%	60%	0%	80%	0%	
style package	1,2,3				30	40	50	30	50	23%	8%	30%	10%	38%	

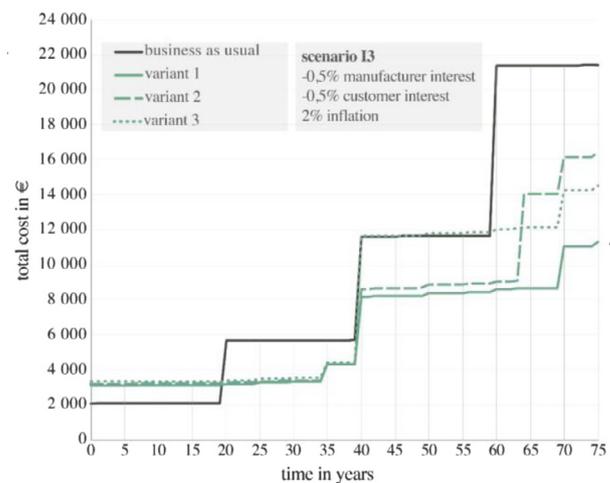
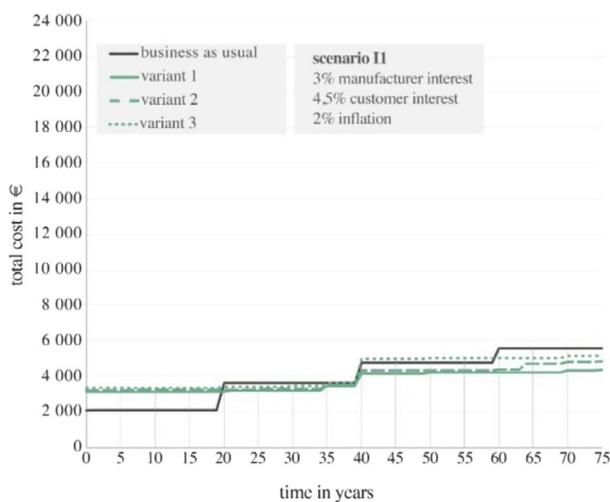


Figure 3. (continued)

Figure 3. (a) Comparison scenario I1 of total costs for three CIK variants and the business as usual case. (b) Comparison scenario I2 of total costs for three CIK variants and the business as usual case. (c) Comparison scenario I3 of total costs for three CIK variants and the business as usual case.

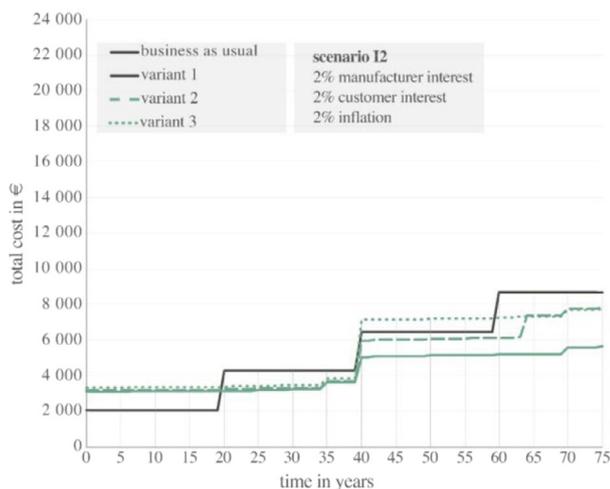


Figure 3. (continued)

Standardization [ISO], 2017). The BAU kitchen has the lowest TC up to year 20 due to the lower investment costs. However, BAU kitchens are expected to be fully replaced every 20 years. Therefore, from year 20

onwards, the circular variants have a lower TC in all scenarios, with the exception of variant 3 from year 40-60, which shows a steep rise in TC at year 40. This is due to the replacement of the layer that is both the construction and the finishing that is expected to happen around this time. The TC of variant 2 closely resembles that of variant 1, up to the moment where the construction is expected to be replaced. Variant 2 uses a panel construction that consumes more, and a different type of material than frame construction of variant 1. In the 2% and -0.5% interest scenarios, the TC of variant 2 even rises above that of variant 3. Even though the interest rates have significant influence on the results, variant 1 has the lowest TC at all timepoints after 20 years in all interest scenarios.

3.3. Comparison 2: Lifespan Scenarios (L1, L2, L3, L4 & L5)

To test for the overall sensitivity of the model to the expected technical lifespan, which determines the EOL of the parts, five scenarios have been compared. To simulate a general overestimation, the technical lifespan of all parts is reduced to 75% of the original estimation in the first scenario (L1). The second scenario (L2) represents the original estimation of the technical lifespans. The third scenario (L3) simulates an underestimation of the lifespans, which are increased to 125%. To test over- or underestimation of the CIK parts, only the lifespans for the CIK variants are reduced to 75% in a fourth scenario (L4) and increased to 125% in fifth scenario (L5).

As with the first comparison, the associated total costs for each scenario can be plotted using the model as seen in Figures 4a, 4b, 4c,

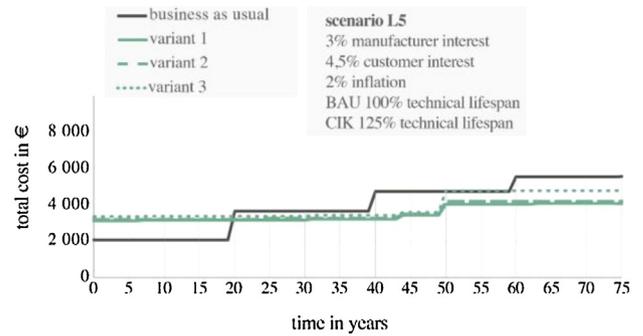
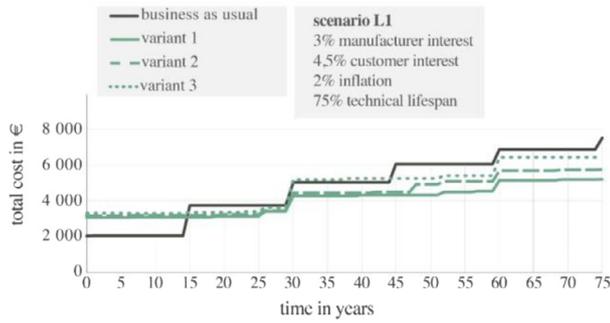


Figure 4. (a) Comparison scenario L1 of total costs for three CIK variants and the business as usual case. (b) Comparison scenario L2 of total costs for three CIK variants and the business as usual case. (c) Comparison scenario L3 of total costs for three CIK variants and the business as usual case. (d) Comparison scenario L4 of total costs for three CIK variants and the business as usual case. (e) Figure 4e. Comparison scenario L5 of total costs for three CIK variants and the business as usual case.

Figure 4. (continued)

4d, and 4e. Since the lifespans are altered, the point in time at which the CIK variants have lower TC changes. In scenario L1 (Fig. 4a.), where the BAU kitchen has a lifespan of 15 years (75% of the original estimate), the TC of the BAU kitchens exceeds that of the CIK variants after 15 years, except for variant 3 in between year 30 and 45. In scenario L3, where the lifespans have been set at 125% of the original estimates, the difference in TC between the CIK variants and the BAU decreases, and variant 3 has a higher TC than the BAU after 50 years, but ends up lower at 75 years again. Scenario L1, L2, and L3 show that the difference in TC decreases if the lifespan of all materials increases. Furthermore, if the materials for the CIK variants have a lifespan of 75% of the estimated values, as in scenario L4, then the BAU kitchen has a lower TC than variant 2 and 3 throughout most of the period. However, if the CIK variants last longer than estimated (scenario L5), they consistently have a lower TC than the BAU kitchen after 20 years, except for variant 3 between year 50 and 60. The comparison of these scenarios shows that the expected technical lifespan of the parts used has a significant impact on the TC outcomes for the variants. However, even though variant 1 does not consistently have a lower TC than the BAU throughout the period in scenario L4, it does have a lower TC after 75 years.

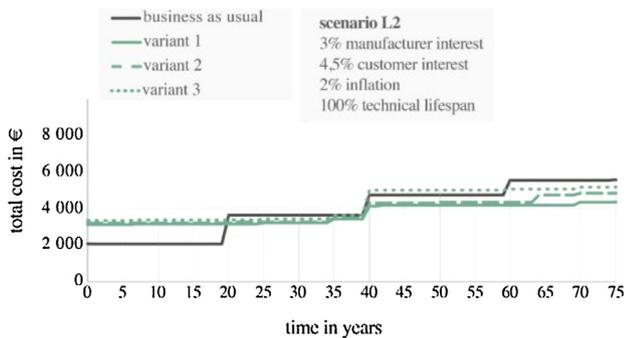


Figure 4. (continued)

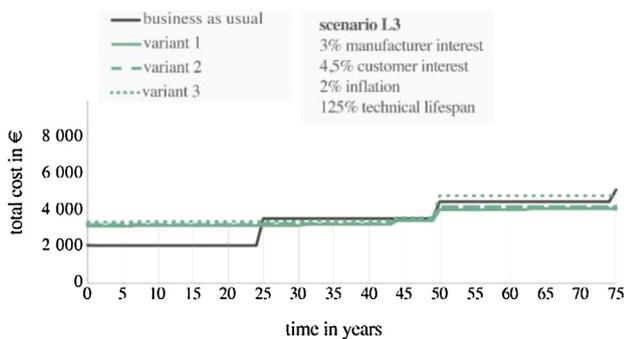


Figure 4. (continued)

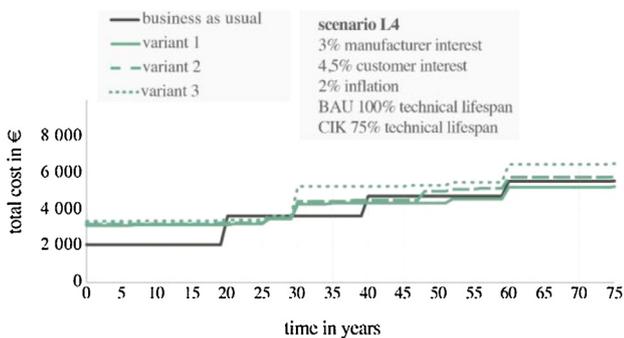


Figure 4. (continued)

3.4. Comparison 3: VRP Scenarios (V1, V2 & V3)

The third comparison tests for the sensitivity of the VRPs in the CIK case. The percentages of remanufacturing (R5) and recycling (R7) for the parts are reduced to 75% (scenario V1) of the original estimates (scenario V2) and increased to 125% (scenario V3). The R values for materials that are not expected to be recyclable or remanufacturable are kept at 0%. Furthermore, the construction material for variant 1 is expected to be 100% recyclable. Since the R value cannot exceed 100%, this value is kept at 100% for scenario V3.

As in the previous comparisons, the associated total costs for each

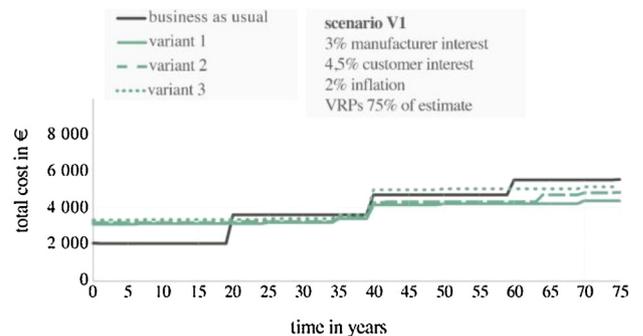


Figure 5. (a) Comparison scenario V1 of total costs for three CIK variants and the business as usual case. (b) Comparison scenario V2 of total costs for three CIK variants and the business as usual case. (c) Comparison scenario V3 of total costs for three CIK variants and the business as usual case.

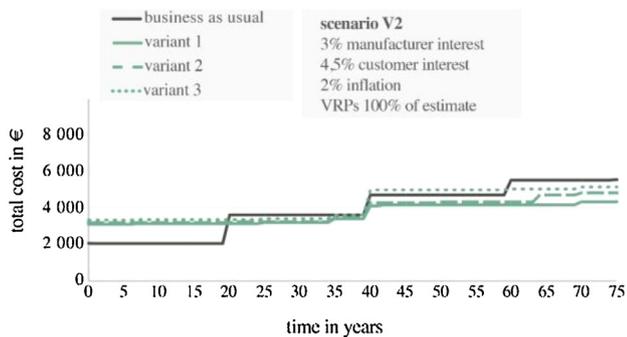


Figure 5. (continued)

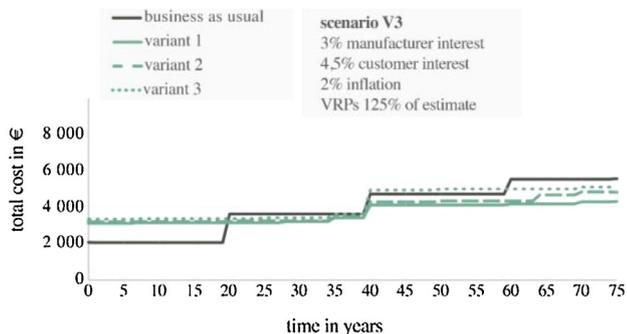


Figure 5. (continued)

scenario is plotted and can be seen in figure 5a, 5b, and 5c. These figures show that both reducing the VRPs to 75% and increasing them to 125% has only a minor impact on both the absolute and relative outcome. The TC of the kitchens compared only show very minor differences throughout time.

3.5. Summary of results

The interest rate and the expected lifespan of the parts have a significant impact on TC. Even though CIK variant 1 and 2 have a lower TC than the BAU kitchen after 20 years in all interest scenarios, the BAU kitchen has a lower TC than variant 2 when reducing the lifespans for the CIK variant to 75% of the original estimation. Nevertheless, variant 1 consistently has the lowest TC after 75 years in all scenarios, therefore showing that a circular kitchen with a high degree of separation between functional layers can be economically competitive in the Netherlands on the basis of LCC.

4. Discussion

Applying the CE-LCC model to the case of the CIK has shown that the model can be used to compare the economic performance of circular product designs in terms of life cycle costs. In doing so, it can inform both decisions in the development process and purchasing decisions of clients. However, to evaluate the model further and to generate insights for future CE products developments, the model should be tested in multiple other cases, both in the building industry and in other industries that produce durable goods, such as automobiles or consumer electronics.

Furthermore, data was gathered from multiple stakeholders and some data was estimated by industry experts when no other sources were available. To increase the accuracy of the outcomes of such a model, we need data sets that are consistent and are interpreted similarly by every sector, as many sectors now use custom terminology.

Moreover, as the model will generally be applied to long periods of time, changing costs over time (due to resource scarcity, increased waste-costs, etc.) will probably occur. To assess the degree of

uncertainty associated with the results, dynamic modeling or further sensitivity analysis should be conducted. This form of risk management should constitute an integral part of the process (Boussabaine and Kirkham, 2008).

Additionally, we noted that the system boundary of the model is of great importance. The CE-LCC model is limited to the impact on the stakeholders that are directly involved in the supply chain, while costs that fall outside of this scope could be included in the model. Although within LCA, environmental burdens would be allocated back to the system studied, we question if the uncertainty of the data and the added complexity to the model will give more useable and accurate results. Furthermore, externalities that can be internalized through taxes or subsidies could influence the outcomes of the CE-LCC. We recommend that future research focusses on whether to include the costs that now fall outside of the scope in the CE-LCC model and how to do so while preserving accuracy and avoiding double counting.

Finally, to justly compare CE-solutions, the economic and the environmental performance should be assessed together with the functional value and/or added value to the user or supply chain of a solution (Scheepens et al., 2016). Therefore, we argue that circular assessment will require finding the optimum between LCC, LCA and functional value in the form of a multi criteria assessment (MCA).

5. Conclusion

Through applying principles of a circular economy, the building industry can become more sustainable and reduce its resource use, produced amount of waste and emissions. To support the development of products for a circular built environment, the building industry needs assessment methods for the environmental and economic performance of circular solutions. This paper demonstrates such a method for the economic assessment: the CE-LCC model. The model was based on existing LCC techniques and developed to (1) consider products as a composite of components and parts with different and multiple use cycles, (2) include processes that take place after the end of use, (3) provide practical and usable information to all stakeholders, and (4) allow for alignment of the functional unit and system boundaries with LCA.

The model was applied to the case of the Circular Kitchen and was used to compare three CIK variants and the business-as-usual case. Of the four kitchens compared, the most flexible variant of the CIK has the lowest LCC outcome on the long term, even when multiple scenarios are considered regarding interest rates, expected technical lifespan of the parts, and the expected VRP percentages.

The CE-LCC model can provide decision makers with an economic assessment that is an essential part of a comprehensive circular assessment. In doing so, it can support the transition towards a more sustainable (building) industry.

Declaration of interests

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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