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The case of the circular kitchen

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Design guidelines for circular building components based on LCA and MFA: The case of the Circular Kitchen

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Introduction. The building sector consumes 40% of resources globally, produces 40% of global waste and 33% of all emissions. The transition towards a Circular Economy (CE) in the built environment is vital to achieve Sustainable Development Goals (SDGs) such as responsible consumption and production. The built environment can gradually be made circular by replacing the current 'linear' building components with circular ones during maintenance and renovation. However, there are many possible design alternatives for circular building components; knowledge on which variants perform best – from an environmental perspective – is lacking.
Methods. In this article, we develop environmental design guidelines for circular building components. First, we synthesize design variants for an exemplary circular building component: the Circular Kitchen (CIK). Second, we compare the environmental performance of these variants and a 'business-as-usual' variant by applying a Material Flow Analysis (MFA) and Life Cycle Assessment (LCA). Finally, from the results, we derive design guidelines.
Results. We synthesized four design variants: (1) a kitchen made from bio-based, biodegradable materials, (2) a kitchen made from re-used materials, (3) a kitchen which optimises lifespans and materials, and (4) a modular kitchen in which components (with varying lifespans) are re-used by the manufacturer. From the LCA and MFA, we derived 7 design guidelines, which include: consider building components as a composite of sub-components, parts and materials with different and multiple use-, and life-cycles; match the materialisation of each part with the expected life cycle (merely substituting for re-used or low-impact materials does not provide the most circular design); facilitate various loops (e.g., repair, re-use, recycling) simultaneously.
Conclusions. The presented design guidelines can support industry in developing circular building components and, through implementation of these components, support the creation of a circular built environment.
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1. Introduction

The linear economy of "take-make-use-dispose" contributes to increasing pressure on natural resources, environmental pollution, carbon emissions and waste generation. The Circular Economy (CE) proposes an alternative economic model which decouples economic growth from resource consumption. The model originates from several schools of thought and has been popularised by the contributions of the Ellen MacArthur Foundation (e.g., [1]). In this article we understand CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by narrowing, slowing and closing material and energy loops" (adapted from Geissdoerfer et al. [2 p. 759]). Narrowing loops is to reduce resource use or achieve resource efficiency, slowing loops is to lengthen the use of a building component, part or material, and closing loops is to (re)cycle materials from end-of-life back to production [3]. Value Retention Processes (VRPs) – also called R-imperatives – are decisive for operationalizing the CE [4]; VRPs are, for example, re-use, repair, refurbish, recycle and recover.

The building sector is said to consume 40% of resources globally, produces 40% of global waste and 33% of all emissions [5]. Therefore, the transition towards a Circular Economy (CE) in the built environment is vital to achieve the Sustainable Development Goals (SDGs) such as responsible consumption and production. The built environment can gradually be made circular by replacing current 'linear building components' with 'circular building components' during maintenance and renovation.

The transition towards a circular built environment will require integral changes in the design, supply chain and business model of building components [6]. However, there are many parameters that have to be taken into account when designing circular building components. For each parameter many options can be identified (see e.g., van Stijn & Gruis [6]). Consequently, designers can develop different design variants for circular building components. For example, a circular designer can propose a facade with a long-life design, or a modular facade which will be repaired and updated regularly, or a bio-based, biodegradable facade. All these façade variants are 'circular' in their own way. Yet, knowledge on which design will result in the least amount of resource use, environmental impacts and waste generation remains lacking. Industry can therefore benefit from environmental design guidelines to support the development of circular building components.

To assess what is the most environmentally-circular design variant, an assessment method is needed. Previous research on circular assessment methodology includes literature reviews on existing methods, development of assessment frameworks and assessment tools (e.g., [7–10]). Moreover, many circular assessment tools were introduced in practice (e.g., the Material Circularity Indicator [11] or CPG-Tool [12]). The existing methods and tools on circular assessment vary: there are quantitative and qualitative methods; there are methods assessing the environmental, economic or social performance, or a combination of those. Looking at the environmental performance assessment, two methods are often used: Life Cycle Assessment (LCA) is – currently – the best defined method to analyse environmental impacts, and capable of analysing circular designs [13]; Material Flow Analysis (MFA) can be used in parallel with LCA to analyse the resource consumption of a design variant [7].

In this article, we develop environmental design guidelines for circular building components based on LCA and MFA. Applying a research-through-design method, we develop these in three steps. In step 1, we synthesize design variants for an exemplary circular building component: the Circular Kitchen (CIK). The kitchen is a logical initial case as it has a relatively high replacement frequency and, therefore, can contribute significantly to the environmental impact in a building. In step 2, we compare the environmental performance of the design variants, and a business-as-usual variant, by conducting an MFA and LCA. In step 3, we derive design guidelines from the assessment results. Finally, we reflect upon the resulting guidelines and identify opportunities for further development. The remainder of this article is structured following these steps.

2. Design variants for the Circular Kitchen

In the first step, we synthesized the design variants for the CIK. These were developed in co-creation with TU Delft, AMS-institute, housing associations (as professional customers), and industry partners. The variants were developed by applying the circular design tool as presented by van Stijn and Gruis

[6]. The designs consist of a technical, industrial and business model. The researchers synthesized several variants for the CIK through systematically ‘mixing and matching’ circular design options for each design parameter (e.g., material, circular design strategy, lifespan, financial arrangement). These designs were further refined in various co-creation workshops with the housing associations and industry partners.

The CIK is initially targeted at Dutch housing associations. They are a logical primary target group, being professional landlords, owning 30% of the Dutch housing stock and having a substantial interest in implementing principles of the CE. The kitchens are relatively sober and, usually, no appliances are provided in social housing kitchens. Hence, the design variants of the CIK focussed on the cabinetry: circular layout variants of the kitchen, design aspects to stimulate circular behaviour, or redesigns of appliances were outside of the scope of the design.

Figure 1 contains visualisations of the technical models of each CIK variant. The business-as usual (BAU) kitchen (variant 0) represents the current practice; it consists of cabinets made of melamine-coated chipboard. Static joints are glued and connectors are used for movable joints (i.e., hinges and drawer sliders). On average, the entire kitchen is replaced every 20 years. The manufacturer sells the BAU kitchen to housing associations. Due to the low initial cost price of the kitchen, kitchens are rarely repaired, refurbished, or re-used. At the end-of-life (EOL), a contractor demolishes the kitchen and separates waste streams. The chipboard is usually incinerated for energy recovery at a municipal incineration plant.

The ‘Bio kitchen’ (variant 1) follows the biological loop of the circular economy model [1]: its cabinets are made, entirely, with panels from renewable and biodegradable materials. Examples of such materials are boards from agaric waste or hemp, mycelium boards, or (untreated) wood. We applied laminated timber boards bound with a biological resin (e.g., lignin). Panels are joint with connectors made from bio-based, biodegradable plastics. The manufacturer sells the Bio-kitchen to housing associations. As bio-materials are left untreated (i.e., uncoated), we assume a shorter lifespan of 10 years; at EOL, the kitchens are entirely composted at a local industrial compost facility.

The ‘Reclaim! Kitchen’ (variant 2) is based on substituting virgin materials with non-virgin alternatives. These are materials with recycled content (e.g., recycled cellulose boards, recycled plastics) or materials which are directly re-used. For this variant, we assumed a similar technical, industrial and business model as the BAU kitchen, only applying directly re-used material for all melamine-coated chipboards. As the material is directly re-used, we assume the kitchens have a lifespan of 10 years.

The Life+ kitchen (variant 3) optimizes the BAU kitchen without radically changing the technical, industrial and business model. A combination of circular design strategies is applied to optimize the design. The technical lifespan of cabinet parts is based on their functional lifespan. The construction of the kitchen cabinet could be used longer than the current 20 years. Hence, it is designed for long-life by substituting the chipboard in the constructive panels with plywood. The finishing parts (e.g., fronts), on the other hand, are designed for a short functional lifespan, by applying biological materials. The industrial model and business model remain similar to the BAU variant. The reduction of sales of the construction of the kitchen – due to the longer lifespan – is offset by offering maintenance packages and update services.

The Plug-and-Play (P&P) kitchen (variant 4) applies a combination of circular design strategies focusing on slowing and closing resource loops. The P&P kitchen is a modular design, separating parts based on their functional and technical lifespan. The P&P kitchen consists of a docking station to which kitchen modules can be (de-)attached facilitating future changes in lay-out. The construction of the modules is a long-life frame. Infill (e.g., drawers, shelves) with a medium lifespan and the finishing (e.g., fronts) with a short use-cycle are attached to the frame with click-on connections. Through this design, the function and appearance of the cabinet can be adapted. The kitchen is constructed with (durable) plywood, to allow for the longer technical lifespan and multiple use-cycles of parts. The kitchen manufacturer sells the docking station and base modules directly to the housing associations with a take-back guarantee, maintenance subscription and circular KPI’s. Extra modules and finishing-updates are offered to users through financial arrangements such as lease and sale-with-deposit, which motivate returning the product at the end of their use cycle. This business model also offers a clear incentive for the manufacturer to realise a kitchen which is easy to repair, update and to give a second life, or more. Collected products are sorted in a local 'Return-Street', to be traded, resold, lightly refurbished or sent back to the kitchen manufacturer. Products that are sent back to the manufacturer are sorted in their national 'Return-Factory' to be refurbished (i.e., infill and finishing parts are re-coated and re-used) and cascaded or recycled (e.g., the plywood is used for particle-board production).

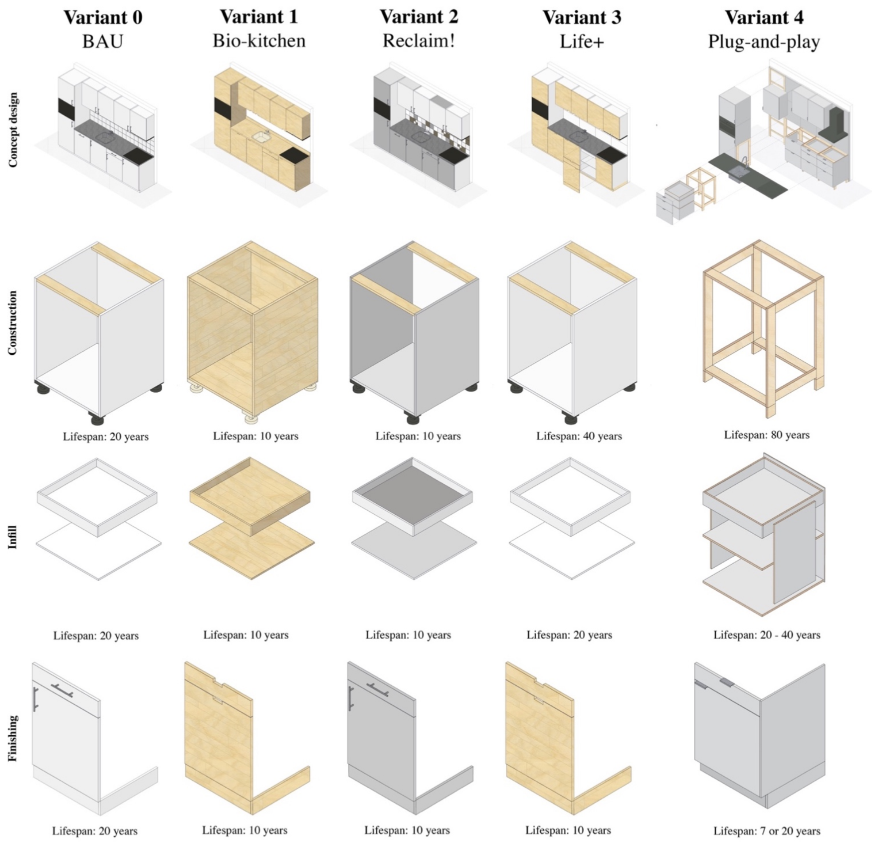

Figure 1. Technical model of the design variants showing materialisation and lifespan.

3. Material Flow Analysis and Life Cycle Assessment of the CIK design variants

In the second step, we conducted an MFA and LCA to compare the environmental performance of the design variants.

3.1. Methods for Material Flow Analysis and Life Cycle Assessment

For the LCA, we followed the EN15978 standard [14]. The LCA procedure consists of four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation of results. We deviated from the standard in how we deal with secondary functions within the LCA. One of the main challenges in a circular LCA is dividing burdens between systems. For example, parts of a circular kitchen are re-used in several kitchens and materials are cascaded multiple times. To deal with such secondary functions, the standard suggests 'system expansion' and a 'cut-off approach' [14]. However, the crediting in these approaches is difficult to standardize, impairing comparability. Furthermore, in circular LCAs, secondary functions are a core part of the system and should not be simplified. Therefore, in this circular LCA we extend the system boundary, including all secondary functions: for all components, parts and materials, the use-, and lifecyles in-, and outside of the assessed system are included. For example, in the Reclaim! kitchen, the production and use of virgin material in a previous use-cycle is included. In the P&P kitchen, multiple re-use cycles of the kitchen fronts (in other kitchens) are included, as is the downcycling of the front materials, and incineration for energy recovery. We apply a linear degressive allocation method (as proposed by Allacker et al. [15]) to divide burdens between different cycles.

We applied openLCA version 1.9 software and characterization factors from the Centre for Environmental Studies (CML) baseline 2001 [16]. The Life Cycle Inventory (LCI) of the background system was based on the Ecoinvent 3.4 APOS database [17], using system processes to get aggregated results. Biogenic carbon (e.g., in wood) was excluded. The development of the foreground system was described in section 2.

In the MFA we aligned the goal and scope with those applied in the LCA. The material flows were analysed using the LCI developed for the LCA. In the MFA we calculated the (direct) material import and export of the foreground system in [kg]. For the material import, we distinguished virgin and non-virgin input. For the export, we distinguish re-useable and recyclable materials. By subtracting these from the import, we calculated the material consumption of the system. As MFA is based on the law of matter conservation within the system boundary, no secondary functions were allocated to the assessed system.

3.2. Results of the Material Flow Analysis and Life Cycle Assessment
In this section, we elaborate on the results of the MFA and LCA.

3.2.1. Goal and scope. The goal of the LCA and MFA was to compare the environmental performance of the developed circular kitchen design variants and the BAU kitchen. As the kitchen configurations are quite homogeneous in composition, a lower cabinet was considered representative for the whole kitchen. Hence, the functional unit of the MFA and LCA was *the use of a lower kitchen cabinet for the period of 80 years*. The 80 years period was selected as it was the longest lifespan in the kitchen variants. The system boundary was a comprehensive cradle-to-cradle analysis, including stages A-C for the materials, parts and components. We included the production, use, VRPs (re-use, repair, refurbishment, remanufacturing, repurposing, recycling, energy recovery) in-, and outside the assessed kitchen system, and (any) disposal by landfilling at EOL. In the foreground system, we excluded capital goods.

3.2.2. The Life Cycle Inventory. We developed the design variants' LCIs in several flowcharts; these were highly modular LCIs in which building components, parts and materials were separated based on material, lifespan and lifecycle(s). Assumptions were made for any unknown parameters. As suppliers and VRP-partners were still unknown, estimations were made on transport distances and (re)production processes. We also estimated the number of use- and lifecycles, and (in some cases) the functional and technical lifespan of components, parts and materials. The P&P kitchen, in particular, facilitates users to adjust the finishing parts of their kitchen which could decrease their functional lifespan. Therefore, for the P&P kitchen we distinguished between two scenarios. In the first scenario, the finishing parts were changed every 20 years (comparable to the BAU kitchen); in the second scenario, they were changed in a higher frequency, namely every 7 years (average period of tenancy in social housing).

3.2.3. The Life Cycle Impact Assessment and Material Flow Analysis. The results of the LCA and MFA are summarised in Table 1. The variants 'Bio' and 'Reclaim!' have a lower environmental impact on more than half of the 11 environmental-impact indicators than the BAU. Only variants 'Life+' and 'P&P' (in both scenario's) realise an impact reduction in all indicators in comparison to the BAU case. Notably, the global warming potential of the P&P 20 and the P&P 7 variants are 49% and 40% lower, respectively, than the BAU. Looking at the MFA results, both the variants 'Bio' and 'Reclaim!' result in a higher material import and consumption than the BAU kitchen. The variant 'Life+' has a slightly lower material import (13%) and material consumption (13%) than the BAU. The 'P&P 20' variant reduces the material import by almost a quarter. On the other hand, the 'P&P 7' variant increases the material import with more than 160%. Yet, both the 'P&P' variants reduce material consumption significantly, 93% and 90% respectively.

Table 1. Results of the LCA and MFA.

Indicator	Unit	Design variants					
		BAU	**Bio**	**Reclaim!**	**Life+**	**P&P 20**	**P&P 7**
Abiotic depletion (fossil fuels)	MJ	$1,81 \times 10^{3}$	$1,73 \times 10^{3}$	$1,49 \times 10^{3}$	$1,26 \times 10^{3}$	$8,62 \times 10^{2}$	$1,05 \times 10^{3}$
Abiotic depletion	kg Sb eq	$1,55 \times 10^{-3}$	$1,71 \times 10^{-3}$	$1,23 \times 10^{-3}$	$7,08 \times 10^{-4}$	$9,89 \times 10^{-4}$	$1,35 \times 10^{-3}$
Acidification	kg SO_2 eq	$5,99 \times 10^{-1}$	$7,02 \times 10^{-1}$	$5,20 \times 10^{-1}$	$4,63 \times 10^{-1}$	$3,35 \times 10^{-1}$	$4,04 \times 10^{-1}$
Eutrophication	kg PO_4^{3-} eq	$2,22 \times 10^{-1}$	$2,45 \times 10^{-1}$	$1,96 \times 10^{-1}$	$1,78 \times 10^{-1}$	$1,20 \times 10^{-1}$	$1,45 \times 10^{-1}$
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	$8,30 \times 10^{1}$	$3,59 \times 10^{1}$	$9,37 \times 10^{1}$	$5,83 \times 10^{1}$	$4,03 \times 10^{1}$	$4,87 \times 10^{1}$
Global warming potential	kg CO_2 eq	$1,48 \times 10^{2}$	$1,20 \times 10^{2}$	$1,45 \times 10^{2}$	$1,07 \times 10^{2}$	$7,50 \times 10^{1}$	$8,95 \times 10^{1}$
Human toxicity	kg 1,4-DB eq	$1,82 \times 10^{2}$	$5,41 \times 10^{1}$	$2,36 \times 10^{2}$	$1,51 \times 10^{2}$	$9,51 \times 10^{1}$	$1,06 \times 10^{2}$
Marine aquatic ecotoxicity	kg 1,4-DB eq	$1,70 \times 10^{5}$	$1,05 \times 10^{5}$	$1,70 \times 10^{5}$	$1,16 \times 10^{5}$	$8,37 \times 10^{4}$	$1,02 \times 10^{5}$
Ozone layer depletion	kg CFC-11 eq	$1,32 \times 10^{-5}$	$1,83 \times 10^{-5}$	$1,02 \times 10^{-5}$	$1,01 \times 10^{-5}$	$7,33 \times 10^{-6}$	$9,09 \times 10^{-6}$
Photochemical oxidation	kg C_2H_4 eq	$5,10 \times 10^{-2}$	$4,05 \times 10^{-2}$	$4,65 \times 10^{-2}$	$4,02 \times 10^{-2}$	$3,13 \times 10^{-2}$	$3,67 \times 10^{-2}$
Terrestrial ecotoxicity	kg 1,4-DB eq	$4,93 \times 10^{-1}$	$6,64 \times 10^{-1}$	$4,89 \times 10^{-1}$	$3,98 \times 10^{-1}$	$2,97 \times 10^{-1}$	$3,61 \times 10^{-1}$
Material import	[kg]	132	210	264	115	101	214
Virgin import	[kg]	85	210	0	81	57	85
Non-virgin import	[kg]	47	0	264	34	44	129
Re-usable material export	[kg]	0	0	0	0	38	123
Recyclable material export	[kg]	9	0	18	8	55	79
Material consumption	[kg]	123	210	246	107	8	12

Note: The colour shows a 5-level gradient between the worst (dark grey) and best (white) value. The best value is the lowest value in all indicators, except in the re-usable and recyclable material export.

3.2.4. Interpretation of the results of the Material Flow Analysis and Life Cycle Assessment. From the results of the MFA and LCA we conclude the following: first, applying a (low-impact) biological material, re-used or recycled material can reduce the environmental impact and material consumption. However, substitution of materials does not necessarily lead to the best environmental performance. Any gains in the initial lifespan of the building component can be offset if the lifespan of the component is reduced, resulting in a higher replacement rate. Second, optimising a BAU design can reduce material consumption and environmental impact. However, the potential of optimisation remains limited. Third, we find that most of the impact is related to the material production and material treatment processes. So, increased transport – to realise VRPs – has less impact than replacement with a new building component. Fourth, the P&P kitchen has the least environmental impact and material consumption. The reduction can be traced back to longer use and introducing more use-cycles of components, parts and materials. Crucial herein is the integral redesign of the technical, industrial and business model. Without (re)designing an accompanying industrial and business model in co-creation with stakeholders, the circularity facilitated in the technical design cannot be guaranteed. This negatively influences the assumptions made in the LCA and MFA. Furthermore, we find that fractional replacement is vital to reduce the impact and material consumption: this requires a modular design in which the building component is considered as a composite of components, parts and materials with different and multiple use-, and life cycles. Moreover, it is not the change in a single design parameter (e.g., selecting another material or other lifespan), but the interaction between design parameters which reduces the material consumption and environmental impact. In other words, it is about combining the right lifespan, the right material, and the right VRP (e.g., re-use, recycling, biodegrading) for each component and part. Finally, the environmental performance improves by facilitating multiple VRPs, instead of one.

4. Environmental design guidelines for circular building components

In the third step, we have derived environmental design guidelines from the LCA and MFA results discussed in section 3.2.4. These guidelines are summarised in Table 2.

Table 2. Environmental design guidelines for circular building components.

1. (Re)design the technical, industrial and business model integrally and in co-creation with involved stakeholders.
2. Consider all circular design parameters (e.g., material, circular design strategy, financial arrangement) in interrelation with each other.
3. Consider not only the initial building component placed, but also consider (re)placements in the future.
4. Facilitate fractional replacement in the building component by considering building components as a composite of sub-components, parts and materials with different and multiple use-, and life cycles. Note that a modular design – which initially requires more material – can be more circular in the long-term than a leaner building component.
5. Consider the expected lifespan, lifecycle(s), and VRPs in the materialisation (of each part) of the building component. Merely substituting linear materials with circular materials (e.g., biological, low-impact, re-used or recycled) does not necessarily result in a more circular building component.
6. Combine circular design options to facilitate multiple VRPs as opposed to focussing on a single VRP. Increased transport – to realise VRP processes – outweighs placement of a new building component.
7. Prefer complete re-design of a building component above optimising the current linear variant.

5. Discussion

Through an LCA and MFA, we have quantified the environmental performance of 4 design variants for an exemplary circular building component. From these results, we derived guidelines which can support industry in developing circular building components. These guidelines could significantly change the circular approach in practice. The current focus is often on material substitutions combined with (some) design-for-disassembly measures. This is logical when designs are one-off-projects, in which only the initial lifecycle can be considered. Yet, our findings suggest that this approach does not lead to the best environmental performance. Instead, we propose that co-creation, with a project-transcending approach, is necessary to realise a circular built environment.

In this article we have adapted existing LCA and MFA methods to assess the environmental performance of a circular building component. However, existing standards and tools were not developed for (ex-ante) circular assessment. Further research is needed, for example, in how we deal with multifunctionality of components, parts and materials, how to set - or expand - system boundaries, how to model a circular LCI, and how to allocate burdens between multiple use- and lifecycles. Additionally, in performing circular LCA's we found that additional background datasets on circular materials and VRPs are needed.

The design guidelines could benefit from further validation. The design guidelines were based on the LCA and MFA results of 4 design variants for a circular kitchen. Future research needs to determine if the design guidelines are also valid for other design variants and building components, such as the structure (long lifespan) or the façade (middle-long lifespan). Also, the outcomes of the LCA and MFA depend on the underlying assumptions in the LCI. What happens to the results if the lifespan of the bio-kitchen is doubled, or if tenants trade-in the finishing of their P&P kitchen every year, or if transport distances for VRPs increase? Some assumption on cycles lie far into the future, making them uncertain. A sensitivity analysis is recommended to identify 'tipping points' in the circularity of design variants. Moreover, we focused on the environmental performance; to fully assess the circularity of a building component, a circular assessment method needs to be applied. This should be a multi-criteria assessment (MCA), which considers the environmental performance in relation to the economic performance (Life Cyle Costing) and functional value (i.e., (perceived) quality). Finally, the variant with the best environmental performance might not be the most viable variant in industry. To support industry in developing circular components which are implementable and accepted by all stakeholders, research on the acceptance and feasibility of circular building components is needed.

6. Conclusion

The built environment can gradually be made circular by replacing current 'linear building components' with 'circular building components' during maintenance and renovation. There are many possible design alternatives for circular building components. To support industry in developing circular building components, knowledge on what are the most circular designs – from an environmental performance perspective – is needed. Therefore, in this article, we developed environmental design guidelines for circular building components. We developed these in three steps. First, we synthesized 4 design variants for an exemplary circular building component: the Circular Kitchen (CIK). These included (1) a kitchen made from bio-based, biodegradable materials, (2) a kitchen made from re-used materials, (3) a kitchen which optimises lifespan and materials, and (4) a modular kitchen in which components (with varying lifespans) are re-used by the manufacturer. Second, we compared the environmental performance of these variants – and a business-as-usual variant – applying MFA and LCA. We found that variant 4 (modular) leads to the highest reduction in both material consumption and environmental impact. From the assessment results, we derived 7 environmental design guidelines for circular building components.

Future research could focus on further developing CE-LCA and CE-MFA application methods, validation of the design guidelines, circular assessment methods balancing the functional value, environmental and economic performance, and the feasibility and acceptance of circular building components. Yet, the derived guidelines make an important step in supporting industry in developing circular building components and advocate for changes in the current circular approach in practice.

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