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The technical or biological loop? Economic and environmental performance of circular building components

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ABSTRACT

The construction sector can become more sustainable by applying the Circular Economy concept, which distinguishes two main pathways: substituting materials for biological materials, or optimizing the use or reuse of technical materials. Practitioners sometimes choose one pathway over the other, but knowledge of which of these pathways yields the best circular performance for the building industry is lacking. To determine which pathway is the most circular, the performance of biological, technical, and hybrid variants for a circular kitchen and renovation façade are developed and compared with one another and with the linear 'business-as-usual' (BAU) practice components. The novel methods of Circular Economy Life Cycle Assessment (CE-LCA) and Circular Economy Life Cycle Costing (CE-LCC), and traditional material flow analysis (MFA) are used. The results show that the biological kitchen and façade consistently perform best in the CE-LCA, but perform second best and worst in the MFA respectively, and consistently perform the worst in the CE-LCC. Technical solutions perform best in the MFA. However, while the technical kitchen performs second best in the CE-LCA and best in the CE-LCC, the technical façade performs worst in the CE-LCA and third best in the CE-LCC. A purposeful, reversible, hybrid application of biological and technical materials yields the most consistent circular performance overall, performing best in the CE-LCC (saving 17 % compared to BAU), second best in the MFA (saving 23 % compared to BAU), and third best in the CE-LCA (an increase of 21 % compared to the BAU). This study shows that neither a purely biological nor purely technical solution performs best overall, but that a purposeful hybrid solution can mitigate the disadvantages of both pathways. Further research is recommended to assess more building components and other hybrid variants.

1. Introduction

The current linear economic model contributes to increasing amounts of greenhouse gas emissions, waste, and resource use. The building sector is said to be responsible for 33 % of all greenhouse gas emissions, around 40 % of all material consumption, and 40 % of all waste (Ness and Xing, 2017). Therefore, making the building sector more sustainable is crucial to the welfare of our society. A Circular Economy (CE) could represent a step towards a more sustainable built environment. According to Geissdoerfer et al. (2017), CE is *"a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, narrowing, and closing material and energy loops"*, in which slowing loops is to lengthen the use of a product, narrowing loops is to reduce resource use or achieve resource efficiency and closing loops is to recycle materials from the end-of-life back to production (Bocken et al., 2016). Narrowing is often achieved by optimizing the loops through 'lean' or eco-efficiency principles, and therefore does not necessarily lead to major changes in the design, supply chain, or business models of buildings and components. However, buildings and components need to cycle at their highest utility and value to slow and close cycles, which often requires adapted designs, supply chains, and business models (Lewandowski, 2016; Nasr et al., 2018; The Ellen MacArthur Foundation, 2017a).

Slowing and closing loops can be achieved in different ways (van Stijn et al., 2022; van Stijn and Gruis, 2019). The different possible pathways in CE can be divided on the basis of two types of material flows: biological materials and technical materials. Fig. 1 shows the circular loops in an adapted version of the CE 'butterfly model' by the Ellen

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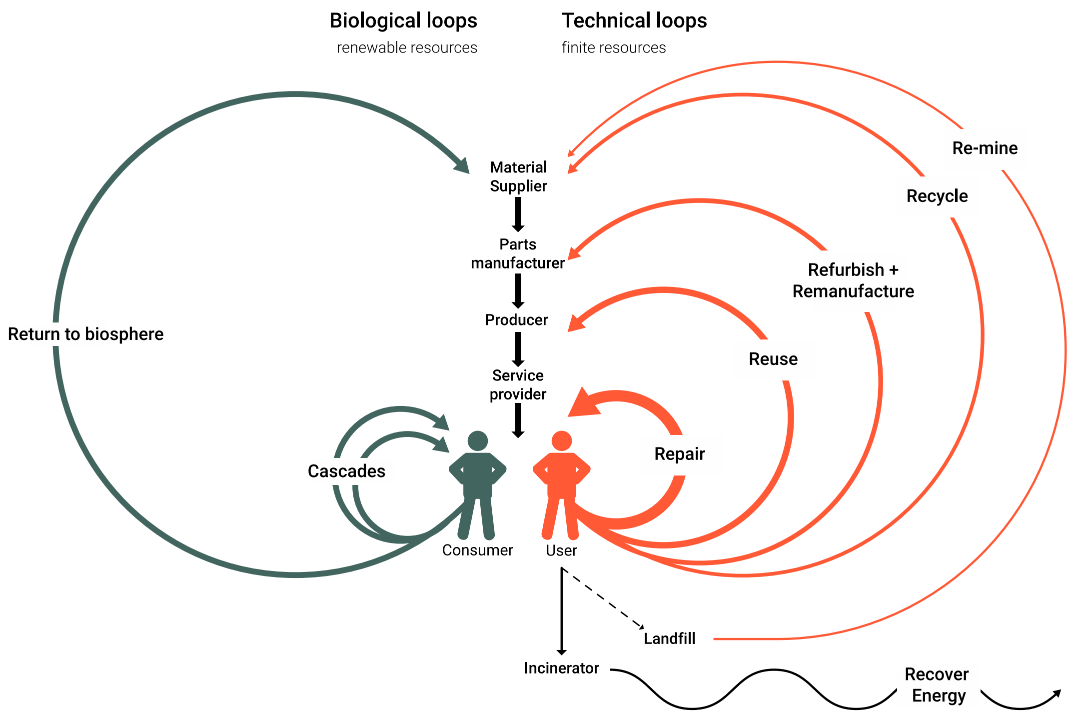

Fig. 1. CE system diagram, adapted by authors from the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2017b) and Reike et al. (Reike et al., 2018).

MacArthur Foundation (2017b), in which strategies for slowing and closing loops have been added according to the work by Reike et al. (2018).

Renewable resources are cascaded in the biological flows; loops are eventually closed by reintroducing materials into the biosphere in a restorative manner without harm or waste (Lewandowski, 2016). Reintroduction can occur 'naturally' (e.g., biodegrading), or 'industrially' (e.g., biochemical extraction, or industrial composting). Biological CE solutions tend to focus on substituting finite (technical) materials with renewables. However, circulating products at their highest utility and value remains a priority, and maintenance, repair, and reuse can take place as well. In the technical flows, finite material loops are slowed and closed through value retention processes (VRPs) (also called R-imperatives) such as repair, reuse, refurbishment, remanufacturing, repurposing, and recycling (Reike et al., 2018). In this article, the VRP definitions as proposed in Wouterszoon Jansen et al. (2020) are applied. Tighter, inner loops are preferred (e.g. repair, rather than recycling), preserving more embedded energy and other value, and preventing more waste than the outer loops do (The Ellen MacArthur Foundation, 2013). However, a key aspect of CE is to realize multiple, different VRPs, and not to aim for just one loop (Blomsma et al., 2018; van Stijn et al., 2022; van Stijn et al., 2020).

For a gradual transition to a circular built environment, current 'linear' building components can be replaced by circular building components during construction, maintenance, or renovation activities. Technical solutions will require integral changes in the building component's design, supply chain, and business model to accommodate VRPs (van Stijn et al., 2022), while biological solutions or adaptations potentially require less rigorous interventions in the supply chain and business model. Consequently, different design variants can be developed for circular components, and a decision to focus on one pathway over the other is often made in practice and policy. For example, a circular design team can develop a building component with a modular design to be reused and updated (a technical circular solution), or a bio-based design (a biological circular solution). Both these designs – one representing the biological flows, and one the technical flows – can be seen as circular. But, knowledge on which of these pathways results in the best circular performance of building components is lacking.

With an ever-increasing application of circular building components, designers, policy makers, and other decision-makers could benefit from this knowledge. Therefore, this study aims to identify which circular pathway yields the best performing building components, what conditions should be considered when applying these pathways, and possibilities for improving the circular performance of the building components.

2. Literature review

An assessment approach is needed for comparing the circular performance of design variants. Elia et al. (2017) aptly concluded that there is a lack of standardized methods in CE assessment, especially on the micro level. Some authors argue that CE products should be assessed integrally on their environmental, economic and social performance (Hunkeler et al., 2008; Sassanelli et al., 2019). Although social performance is regarded as a condition for the sustainability of a product in this study, our analysis follows a narrower definition of circular performance. On the one hand, the environmental performance needs to be assessed to evaluate whether resource use, environmental impacts and waste are – potentially – optimally reduced. On the other hand, the economic performance is evaluated: without feasible costs and sufficient benefits, circular components are not likely to be implemented and environmental reduction potential will not be realized. In this section we discuss existing studies that consider the environmental and economic performance of circular building components.

Corona et al. (2019), Sassanelli et al. (2019) Pomponi and Moncaster (2017), extensively discuss evaluative methods for circularity. Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) are often seen as suitable methods to evaluate the environmental performance of circular designs. Life Cycle Assessment (LCA) is the most mature method for analyzing environmental impacts and can be applied in a CE context. Material Flow Analysis (MFA) can analyze resource flows and consumption of building components in a CE;

Although these are well-defined methods, applying LCA and MFA to circular building components raises methodological questions: conventional building LCA, following the EN 15978 (2012), focuses on assessing the impacts of individual lifecycles of buildings and building components; only one subsequent reuse or recycling cycle is assessed (separately in module D). Subsequent cycles are not considered in the scope of this assessment, and how to extend the system boundary to include multiple and different uses and life cycles and how to share burdens and benefits between these cycles should be considered (Corona et al., 2019; Malabi Eberhardt et al., 2020; van Stijn et al., 2021). Moreover, LCA and MFA can assess large sets of impact categories and indicators. To support decision-making and determine which component performs 'best', LCA impact categories can be valued through different approaches (van Stijn et al., 2022; Vogtlander and Bijma, 2000). Van Stijn et al. (2021) and Eberhardt et al. (2020) developed a Circular Economy Life Cycle Assessment (CE-LCA) method and a Linear Degressive (LD) allocation approach suitable for the assessment of circular building components, respectively.

Life Cycle Costing (LCC) is an appropriate method for assessing economic performance that can be applied to calculate the costs of a design variant over time (Langdon, 2007; Dhillon, 2009; Hunkeler et al., 2008). As with LCA, there are particular issues when applying LCC to circular products: products need to be considered as a composite of components and parts with different and multiple use cycles, VRPs need to be included, and the information provided should be useful to all stakeholders. Existing LCC models include Environmental-LCC (which facilitates including multiple stakeholders, but does not include multiple cycles or consider products as a composite) and the Total Life Cycle Cost model (TLCCM) by Bradley et al. (2018) (which meets all the criteria, except for considering products as a composite of components and parts with different and multiple lifecycles). Wouterszoon Jansen et al. (2020) developed a Circular Economy Life Cycle Costing (CE-LCC) method for building components that meets these criteria by adapting existing LCC models.

To determine which of the circular pathways – the biological or the technical – yields the best circular performance for building components, environmental and economic assessment methods that consider products as a composite of components and parts with different and multiple use cycles and include VRPs should be applied. Furthermore, which pathway performs best may depend on the type of building component. Therefore, multiple components should be assessed to increase the representativeness of the study.

Table 1 summarizes precedent studies that compared the environmental or economic performance of circular building components through LCA, MFA or LCC. Most authors compared the environmental performance of one type of circular building component: De Wolf (2017) and Malabi Eberhardt et al. (2021) focus on a building structure, Cruz Rios et al. (2019) and Quintana-Gallardo et al. (2021) focus on an external wall, Geldermans et al. (2019) focus on an interior partitioning wall and van Stijn et al. (2020) focus on a kitchen. Vandenbroucke et al. (2015) considered the environmental performance of multiple components, namely a ground-level floor, roof, external wall and an internal partitioning wall, as do van Stijn et al. (2022), who consider a kitchen and a renovation façade.

Wouterszoon Jansen et al. (2020) only considered the economic performance of one circular component: a kitchen. Two studies have considered both the environmental and economic performance of circular building components: Buyle et al. (2019) applied a combination of conventional LCC and LCA methods to assess, and Rajagopalan et al. (2021) applied a combination of qualitative assessment based on reversibility, finishing and acoustical comfort with Circular Building Life Cycle Assessment (CBLCA) and conventional LCC, and both studies assessed a circular interior partitioning wall.

However, Buyle et al. (2019) and Rajagopalan et al. (2021) did not apply methods that consider products as a composite of components and parts with different and multiple use cycles for both the environmental and economic assessment, and only assessed one type of component. Furthermore, none of the studies conclude as to whether the biological or technological pathway – specifically – leads to the best circular performance, and do not elaborate on what conditions should be considered when applying these pathways.

3. Method

The research underpinning this article was conducted in four steps. First, design variants for exemplary building components – the Circular Kitchen (CIK) and the circular renovation façade (Circular Skin) – that are suitable for the biological or the technological loop or a combination of these were selected. Second, the economic performance of these variants in comparison to a business-as-usual (BAU) variant – representing the current practice – was assessed using the CE-LCC model; these results were then combined with the results of the environmental performance assessment of van Stijn et al. (2022). Third, the outcomes were analyzed and which circular pathway yields the most circular building components was evaluated. Finally, possible improvements for the development of biological, technical, and hybrid circular building components were identified by reflecting on the outcomes. The remainder of this paper is structured according to these steps.

This study has several constraints. First, the methods for CE economic and environmental assessment are limited. Therefore, methods are applied that do not apply the same system boundaries. The CE-LCA model used by van Stijn et al. (2022) applies an allocation approach to divide burdens and benefits between cycles whilst the CE-LCC model more closely resembles a 'system expansion' approach. Therefore, the outcomes of both assessments are considered separately. Second, the cost data used for the CE-LCC was provided by stakeholders involved in the CIK and Circular Skin projects and are not sourced from an established database. However, the stakeholders involved based the data on extensive experience. Finally, the CIK and Circular Skin components were developed for the Dutch social housing sector. Although this might limit the application somewhat, 28 % of all dwellings in the Netherlands are social housing, making it the largest housing sector (den Ridder et al., 2020). The impact of these constraints and other limitations of the research are reflected upon in the discussion section.

4. Results

In the following subsections, this research's results are presented and reflected upon. Subsection 4.1 describes the CIK and Circular Skin design variants. Subsection 4.2 elaborates on the goal, scope, and lifecycle inventory of the CE-LCA, MFA, and CE-LCC. Subsections 4.3 and 4.4 show the results of the environmental and economic assessment of the variants respectively. To provide further support to these results, subsection 4.5 elaborates on the outcomes of the sensitivity analysis. The results are interpreted in subsection 4.6 and the design variants are ranked according to their performance. This subsection also reflects on the advantages and disadvantages of the biological and technical pathways, the conditions under which they apply, and how the circular performance of design variants could be improved.

4.1. Circular kitchen and circular skin design variants

Which pathway performs best may depend on the type of building component, therefore two exemplary circular building components are included: the CIK and Circular Skin. Both were developed in co-creation with TU Delft, AMS-institute, industry partners and customers. The components were also both initially developed for the social housing sector in the Netherlands, since this encompasses a substantial share of the Dutch housing sector and could provide the mass application needed for significant impact. However, the selected components some have significant differences. The kitchen, on the one hand, has a relatively high replacement rate (Ollár et al., 2020), consequently continuously contributing to the life cycle environmental impact of a building. The renovation façade, on the other hand, is replaced less frequently but is a relevant intervention as it is often applied to reduce the

Table 1
Precedent studies comparing environmental or economic performance of circular design options in building components.

Author	Building component	Circular design options compared	Assessment method		Design option(s) with the best performance	
			Environmental	Economic	Environmental	Economic
Buyle et al. (2019)	Interior partitioning wall	4 BAU designs and 3demountable and reusable designs	Consequential LCA	LCC	• Demountable and reusable designs with higher initial impact but low lifecycle impact; • Design with no possibilities for direct reuse but low initial impact.	• Demountable and reusable designs with higher initial costs but low lifecycle costs;
Cruz Rios et al., 2019)	External framed wall	1 single-use wood-framed wall and 1 reusable steel framed wall	Hybrid and process-based LCA	–	•If reused 2 times, a reuse rate of (>70 %), and short transport distance then reusable steel-framed wall; •If wood-framed wall is reused, then wood-framed wall has highest environmental benefits.	–
De Wolf (2017)	Building structure	BAU design and material efficient design with low carbon materials	LCA (embodied carbon only)	–	• Choosing low carbon materials and optimizing the structural efficiency to reduce the material quantity in the building structure.	–
Malabi Eberhardt et al. (2021)	Building structure	1 BAU design, 1 material efficient design; 1 bio-based design, 1 demountable and reusable design and 1 onsite adaptable design	CE-LCA (includes all cycles); MFA	–	• Combining resource efficiency, long use on-site through adaptability, low-impact renewable materials and (only then) facilitating future use cycles (off-site) for parts and materials.	–
Geldermans et al. (2019)	Interior partitioning wall	Adaptable design (modular; demountable); bio-based and non-virgin materials.	Circ-flex design guidelines and Activity-based Spatial MFA	–	• Combining design for adaptation with bio-based and reversible fiber composite materials.	–
Quintana-Gallardo et al. (2021)	External wall	rice straw panel and conventional double brick wall	LCA	–	• The biological rice straw panel external wall	–
Rajagopalan et al. (2021)	Interior wall systems	1 BAU design, and 1 reversible design with a wooden frame gypsum boards, 1 reversible design with solid wood, and 1 reversible design with a steel frame and wooden panels. Designs are tested according to three scenarios	Qualitative assessment based on reversibility, finishing and acoustical comfort, and quantitative assessment based on CBLCA	LCC	• The reversible design with steel frame performs best in all scenarios due to lower maintenance, replacement and refurbishment impacts	• Reversible design with steel frame performs better in shorter use cycles, and worst in longer use cycles. • Solid wood design performs well in short and long use cycles and is not tested in medium cycles
van Stijn et al. (2020)	Kitchen	1 BAU design, 1 bio based design, 1 design with reclaimed materials, 1 optimized design and 1 adaptable design	CE-LCA (includes all cycles); MFA	–	• Modular design which facilitates partial replacements of parts to prolong use of the entire kitchen and introduces more use-cycles in parts and materials.	–
van Stijn et al. (2022)	Kitchen and renovation façade	For each component: 1 BAU design, 1 bio-based design, 1 design with reclaimed materials. For the kitchen also: 1 optimized design and 1 adaptable design. For the façade also: 1 direct re-use variant and 1 plug-and-play variant	CE-LCA (includes all cycles); MFA		• For the kitchen, facilitating partial replacements to increase the overall lifespan of the component and materials and applying bio-based or non-virgin materials results in the best performance. The 'best' performing façade combines non-virgin materials with long lifespans and/or multiple reuse cycles on site. • If future cycles are unlikely, low impact, non-virgin, and/or bio-based materials which are biodegradable or recyclable in an open-loop supply chain perform better.	
Vandenbroucke et al. (2015)	Ground level floor; Flat roof; External wall; Internal Partitioning wall	Per component: 1 BAU design for new built; 1 BAU design for renovation; 1 demountable and adaptable design for renovation	LCA following building standard	–	• Demountable designs for all building components are only useful if the adjustments are done frequently; • Tipping point depends on how much extra material is needed to achieve demountability.	–
Wouterszoon Jansen et al. (2020)	Kitchen	1 BAU design, 1 demountable design with a separate frame, infill and finishing, 1 demountable design with a separate panel construction, infill and finishing, and 1 demountable design with a separate construction and infill	–	CE-LCC		• The demountable design with a separate frame, infill and finishing has the lowest LCC outcome in all scenario's

Table 2
Overview of the developed circular building components, their material composition, design strategy, supply chain and business model.

		Material	Mass [kg]	Relative mass	Material characterization	Design strategy	Supply chain	Business model
Circular Kitchen	Business-as-usual	Particle board	24.92	76 %	Technical	Linear	Open loop recycling and energy recovery by third parties.	Sale
		High-pressure laminate (HPL)	5.17	16 %	Technical			
		Pine	0.52	2 %	Technical			
		Polyethylene (PE)	0.40	1 %	Technical			
		Stainless steel	1.83	6 %	Technical			
		polyvinyl acetate (PVAc)	0.10	0 %	Technical			
		Total	32.95	100 % technical				
	Biological	Bio board	24.92	95 %	biological	Similar design to the business-as-usual, but materials substituted by bio-degradable materials	Industrial composting	Sale
		Pine	0.52	2 %	biological			
		Bio polymer	0.85	3 %	biological			
		Total	26.29	100 % biological				
	Technical	Plywood	7.86	20 %	Technical	Plug and Play, modular, durable materials, multiple value retention processes	Maintenance, updates and reuse by manufacturer. Remanufacturing, recycling and energy recovery in collaboration with third parties	Lease or sale with buy/take-back, with maintenance and update services
		Stainless steel	0.15	0 %	Technical			
		(Birch) Triplex	0.97	2 %	Technical			
		High-pressure laminate (HPL) Coating	5.10	13 %	Technical			
		Birch Multiplex	21.78	56 %	Technical			
		Triplex	1.27	3 %	Technical			
		Nickel steel	0.24	1 %	Technical			
		Polyethylene (PE)	0.06	0 %	Technical			
		Galvanized steel	1.57	4 %	Technical			
		Total	39.02	100 % technical				
Circular Skin	Business-as-usual	Polyurethane (PU) Glue	2.20	1 %	Technical	Linear	Open loop recycling and energy recovery by third parties	Sale
		Expanded polystyrene (EPS)	43.66	16 %	Technical			
		Non-Cementitious, organic reinforcement grout	89.96	34 %	Technical			
		Glass fiber	1.46	1 %	Technical			
		Non-Cementitious, organic glue	39.69	15 %	Technical			
		Mineral stone-strip	89.96	34 %	Technical			
		Total	266.93	100 % technical				
	Biological	Bio polymer	22.90	5 %	Biological	Mix of using conventional bio-degradable materials and innovative bio materials	Industrial composting by third parties	Sale
		Spruce	179.61	38 %	Biological			
		Hempflax	136.65	29 %	Biological			
		Clay plaster base coat	98.78	21 %	Biological			
		Glass fiber mesh	1.46	0 %	Biological			
		Clay plaster finish	28.22	6 %	Biological			
		Total	467.63	100 % biological				
	Hybrid	Stainless steel	25.88	3 %	Technical	Plug and Play, modular, adjustable, easy to disassemble and reassemble, durable materials, standardized parts multiple value retention processes	Maintenance, updates and reuse by provider. Recycling and energy recovery in collaboration with third parties	Lease or sale with buy/take-back, with maintenance and update services
		Spruce wood	204.51	22 %	Biological			
		Plywood	82.62	9 %	Technical			
		Recycled cotton	211.85	23 %	Technical			
		Recycled wood fiber board	107.33	12 %	Technical			
		Recycled polyethylene (PE)	1.58	0 %	Technical			
		Aluminum	9.22	1 %	Technical			
		Rockwool	11.85	1 %	Technical			
		Cement	45.56	5 %	Technical			
		Brick	220.22	24 %	Technical			
		Total	920.62	22 % biological, 78 % technical				
	Technical	Polyurethane	2.95	1 %	technical	Easy to disassemble and reassemble, durable materials, standardized parts, reuse of parts	Reuse by provider or client. Recycling and energy recovery by third parties	Lease, sale with buy/take-back, or sale and resale
		Aluminum	43.66	13 %	technical			
		Stainless steel	5.85	2 %	technical			
		Expanded polystyrene (EPS)	43.66	13 %	technical			
		Ceramic tiles	232.84	71 %	technical			
		Total	328.95	100 % technical				

building's operational energy use. The building component variants were developed to the level of proof of concept by applying the design tool for circular building components presented by van Stijn and Gruis (2019) and consist of a technical, industrial and business model.

Table 2 provides an overview of the BAU variant and the biological (BIO), technical (TECH), and hybrid (HYBRID) design variants for the kitchen and renovation façade. The relative volume and mass of biological or technical materials they contain are specified to define how 'purely' biological or technical the variants are. The classification of a type of material as biological or technical is determined by its ability to be reintroduced into the biosphere in a restorative manner without harm or waste (Lewandowski, 2016). Therefore, materials that can be seen as bio-based, such as plywood, are classified as technological materials. The impact of classifying a component as either TECH, BIO or HYBRID is reflected on in the discussion.

4.1.1. The circular kitchen variants

Kitchens are usually supplied in a basic setup without appliances in the social housing sector in the Netherlands. Furthermore, uniform countertop options were used for all variants. Therefore, the CIK design focused on the cabinetry and appliances and the countertop remained beyond the scope of this study. Fig. 2 shows an overview of the variants.

The BAU design can be described as the industry standard: the cabinets are made with melamine-coated chipboard, joints are glued, and connectors are used for movable joints (i.e., hinges and drawer sliders). The kitchen is entirely replaced every 20 years on average and (almost) no VRPs take place. A contractor demolishes the kitchen at the end of life (EOL) and separates the waste flows. The chipboard is (usually) incinerated for energy recovery at an incineration plant.

The BIO-variant closely resembles the BAU and employs a design in which panels are glued together with bio-based glue and no circular loops are directly facilitated by the design. However, materials are substituted with bio-based ones and biodegradables. Similar to the BAU, this variant is sold to customers and is replaced every 20 years. The kitchen is fully composted at the EOL.

The TECH kitchen is developed by applying multiple CE design strategies to enable repair, re-use, remanufacturing, recycling and recovery cycles. The product design, business model, and supply chain model are redesigned in an integrated fashion. It has a modular, 'plug and play' design, in which parts are separated based on their functional and technical lifespan, and connected by click-connectors. Functional lifespan is defined as the period in which the object meets the functional demands of the user (Wamelink et al., 2010) and the technical lifespan as *"the maximum period during which it can physically function"* (Cooper, 1994). The TECH kitchen is sold with a take-back guarantee, and at the end of use (EOU) parts are collected by the kitchen manufacturer to either be reused, remanufactured or recycled. The kitchen is made from plywood, to allow for a longer technical lifespan and multiple use cycles of parts. The plywood is coated with a removable high-pressure laminate (HPL) where necessary.

4.1.2. The circular skin variants

The Circular Skin is an exterior insulation solution that is typically applied in (near) Zero Energy housing renovations and simultaneously provides an aesthetic upgrade. Such renovation façades are typically placed for an exploitation period of around 30 years (assumed EOU for all variants). Fig. 3 visualizes the technical models of the Circular Skin variants. In-situ application or off-site prefabrication is possible for each of the variants.

The 'BAU façade' represents a solution commonly applied in practice. The BAU is a 'lean' solution, which is integrated and lightweight. It consists of EPS foam which is glued to the façade with a polyurethane (PU) adhesive; a glue and grout mortar and glass-fiber mesh is applied on top of the expanded polystyrene (EPS), followed by thin mineral brick strips. The BAU façade is sold to the housing association. A relatively short lifespan of the glue (±30 years) was assumed; the integrated system is tailored to the specific project, so it has limited potential for repair, future adjustments in layout and finishing, or reuse on other façades. Therefore, it was assumed that EOU will equal EOL, and set the lifespan of the façade at 30 years. The materials of the façade are

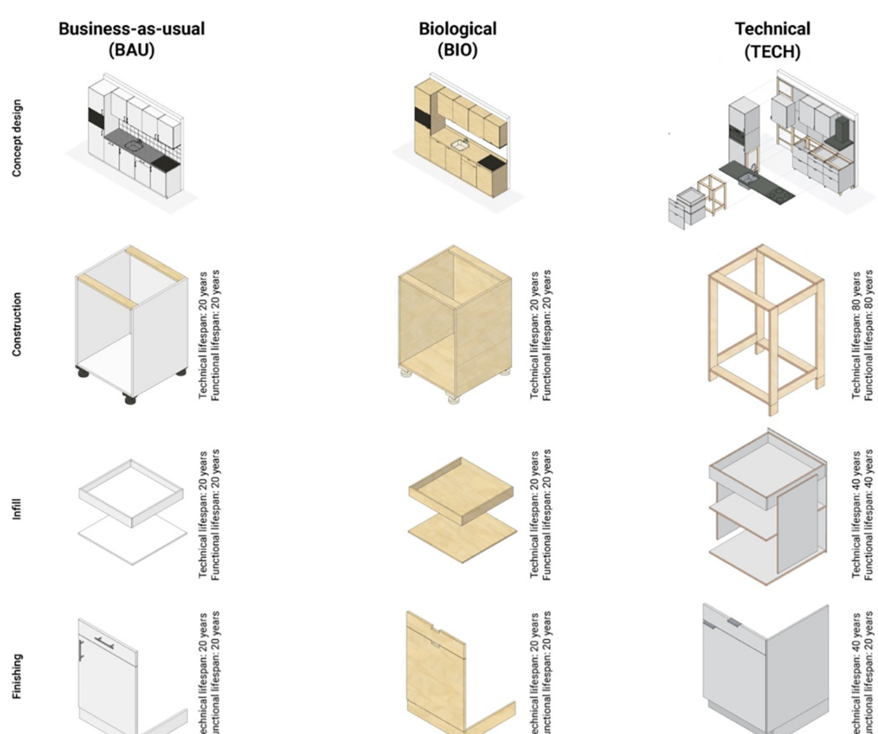

Fig. 2. The Circular Kitchen design variants, divided according to functional layers.

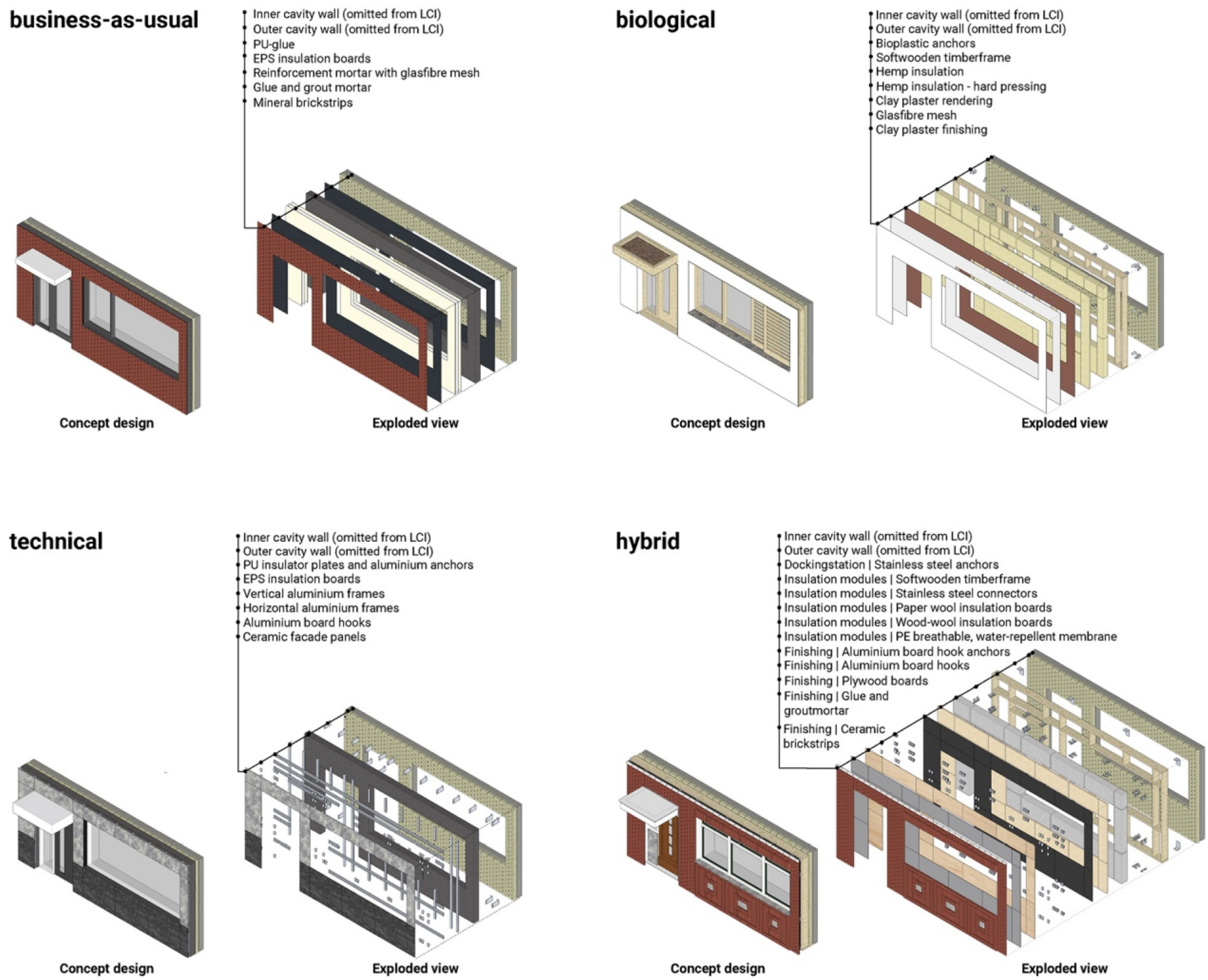

Fig. 3. The Circular Skin design variants, including an exploded view.

separated – as much as possible – into separate waste flows and incinerated or landfilled at EOL.

The BIO façade uses bio-based and biodegradable materials. It is constructed of a timber frame, filled with hemp insulation, and finished with a hemp-insulation board covered with clay plaster. This frame is attached to the existing façade with anchors. All connectors are made from bio-based and biodegradable plastics. A new layer of clay plaster is applied every 15 years, and the EOL of the façade is assumed to equal the EOU (at 30 years). All materials are composted at EOL.

The TECH façade consists of building products with a long technical lifespan (> 90 years), with the application of standardized sizes and connectors allowing easy disassembly, and reassembly. Hence, the design enables direct reuse of these products. It consists of EPS boards, clamped behind an aluminum framework, to which ceramic façade panels are clicked. The façade is sold to the building owner and at the EOU the façade is dissembled, resold, and reassembled on another building.

The HYBRID façade applies a combination of strategies to slow and close the loops. The HYBRID façade is characterized as a modular, 'plug and play' façade, in which parts are separated according to their functional and technical lifespan. An insulation module – consisting of an adjustable timber frame filled with recycled cellulose – is attached to the existing façade with wall anchors. The adjustable timber frame facilitates future changes in layout as well as reuse on another façade. The exterior of this timber frame is covered by a recycled, wood-wool board and it can be finished by attaching a variety of standard-sized panels through aluminum anchors. In this case, a high-quality ceramic brickstrip panel was attached. This façade is either leased or sold with a buy- or take-back guarantee. At EOU, the insulation modules can be reused twice, while the façade panels have four reuse cycles. The subcomponents are disassembled and their materials are either recycled, downcycled, or incinerated at EOL.

4.2. Circular Economy Life Cycle Assessment, Material Flow Analysis, and Circular Economy Life Cycle Costing comparison of circular kitchen and circular skin variants

The CE-LCA and MFA conducted by van Stijn et al. (2022) and CE-LCC conducted in this paper followed four stages: (1) goal and scope definition, (2) CE Life Cycle Inventory (CE-LCI), (3) CE Life Cycle Impact Assessment (CE-LCIA), material flow analysis, and life cycle cost calculation and (4) interpretation of results. The CE-LCC was aligned with the CE-LCA and MFA throughout these steps where possible. The results of the CE-LCC will be presented below following these stages; key information required to understand the CE-LCA and MFA results by van Stijn et al. (2022) is summarized per step.

4.2.1. Goal and scope of the Circular Economy Life Cycle Assessment, Material Flow Analysis, and Circular Economy Life Cycle Costing

The goal of the CE-LCA, MFA, and CE-LCC was to compare the environmental impacts, material flows, and life cycle costs of the BAU and circular design variants of the kitchen and façade. As the kitchen configurations in social housing are quite homogeneous, a lower cabinet was considered representative of the whole kitchen. A section of façade for a reference terraced dwelling was considered representative of the façades.

The Functional Unit (FU) was aligned with van Stijn et al. (2022): the FU for the kitchen was the use of a 'specific' lower kitchen cabinet in a circular system for a period of 80 years. For the façade, the FU is the use of a 'specific' renovation façade for the reference façade, with an insulating value of approximately R_c 5.0 m^2K/W, in a circular system over a period of 90 years. The assessment periods were selected as they were the longest lifespan in the kitchen and façade variants.

The scope definition in CE-LCA deviates from the EN 15978 (2012) standard; in the system boundary all cycles in building(component), its (sub)components, parts, and materials are included; these include cycles occurring inside and outside of the building component system (van Stijn et al., 2021). For example, in the TECH kitchen, multiple reuse cycles of the kitchen fronts (in other kitchens) were included, as was the downcycling of the front materials, and incineration for energy recovery. The system boundary for the CE-LCC was aligned as much as possible with the CE-LCA; it considers the total costs for a product system over a set time and includes costs that take place during manufacturing, during use, at the EOU and EOL (i.e. costs for realizing VRPs, as well as potential waste costs), and all costs during subsequent cycles. However, it excludes cycles outside of the building component system (i.e., VRPs which occur in open loops by partners outside of the components value chain). The MFA scope was limited to the building component's use cycle, measuring the direct import and export of that use cycle. In the CE-LCA, MFA, and CE-LCC, capital goods (e.g., production and VRP facilities, machinery) were excluded.

4.2.2. Circular Economy Life Cycle Inventory of the kitchen and façade variants

As the design variants were concept designs, assumptions were made for any unknown parameters. Estimations were made on transport distances, production and VRPs, number of use cycles and lifecycles, and (in some cases) the functional and technical lifespan of components, parts, and materials. Assumptions were also made for the volume of materials needed (e.g., insulation thickness, amount and profile thickness of the connectors). Furthermore, assumptions were made for costs for some parts and materials and the interest rates used per stakeholder. Assumptions were aligned between variants.

4.3. Environmental performance

4.3.1. Circular Economy Life Cycle Assessment method

Van Stijn et al. (2022) modeled the CE-LCIs in openLCA (version 1.9) software; the background system was modeled with the Ecoinvent 3.4 APOS database (Wernet et al., 2016), using system processes to get aggregated results. The CE-LCIA was calculated using characterization factors from the Institute of Environmental Sciences (CML)-IA baseline (Guinée et al., 2001). As all cycles were considered, it was assumed that carbon uptake equals carbon emission over the lifecycle of the material. Therefore, the '0/0 approach' was applied to biogenic carbon, and biogenic carbon (e.g., in wood) was excluded. To divide burdens and benefits between the cycles, the CE 'Linearly Degressive' (LD) approach – presented in Eberhardt et al. (2020) – was followed.

Eleven impact categories were calculated (i.e., mid-points); to support decision making, the impacts were also translated to the prevention-based costs, single indicator 'shadow costs' (see Stichting Bouwkwaliteit (2019)), which is commonly applied in LCAs in Dutch building practice.

4.3.2. Circular Economy Life Cycle Assessment results

The results of the CE-LCIA of van Stijn et al. (2022) are shown in Table 3. The BIO variant for the Circular Skin has reduced impacts on 8 out of 11 impact categories compared to the BAU Skin. The savings are visible in the shadow costs which are reduced by 57 % in total compared to the BAU. The TECH and HYBRID both reduce and increase impacts compared to the BAU variant: they significantly reduce abiotic depletion for fossil fuels, acidification, global warming potential (GWP), and photochemical oxidation. Yet, they cause large increases in abiotic depletion and all toxicity impact categories. These shifts in burdens result in an increase of 143 % and 21 % in shadow costs of the TECH and HYBRID skins compared to the BAU, respectively. Notably, all variants reduce the GWP significantly compared to the BAU variant by 68 % (BIO), 45 % (TECH), and 61 % (HYBRID).

The BIO and TECH kitchen realizes an impact reduction in all indicators in comparison with the BAU. Subsequently, the shadow costs of the BIO and TECH kitchens are 55 % and 52 % lower, respectively. Notably, the GWP of the BIO and TECH is 60 % and 57 % lower than the BAU, respectively.

Table 3
Environmental impacts and shadow costs for Circular Skin and Circular Kitchen business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants.

	Impact category	Unit	Circular Skin				Circular Kitchen		
			BAU	BIO	TECH	HYBRID	BAU	BIO	TECH
	Global warming potential	kg CO2 eq	9.78×10^{2}	3.17×10^{2}	5.33×10^{2}	3.78×10^{2}	1.48×10^{2}	5.98×10^{1}	6.40×10^{1}
	Ozone layer depletion potential	kg CFC-11 eq	3.25×10^{-5}	2.81×10^{-5}	3.38×10^{-5}	4.74×10^{-5}	1.32×10^{-5}	9.16×10^{-6}	6.92×10^{-6}
	Photochemical ozone creation potential	kg C2H4 eq	1.95×10^{-1}	1.65×10^{-1}	1.38×10^{-1}	1.39×10^{-1}	5.10×10^{-2}	2.03×10^{-2}	2.54×10^{-2}
	Acidification potential	kg SO2 eq	2.81×10^{0}	2.20×10^{0}	2.31×10^{0}	1.64×10^{0}	5.99×10^{-1}	3.51×10^{-1}	2.99×10^{-1}
	Eutrophication potential	kg PO_4^{3-} eq.	5.96×10^{-1}	3.23×10^{0}	7.35×10^{-1}	7.43×10^{-1}	2.22×10^{-1}	1.23×10^{-1}	1.05×10^{-1}
LCA	Abiotic depletion potential for elements	kg Sb eq	1.15×10^{-3}	8.02×10^{-3}	2.86×10^{-2}	5.93×10^{-3}	1.55×10^{-3}	8.55×10^{-4}	9.77×10^{-4}
	Abiotic depletion potential for fossil fuels	MJ	1.36×10^{4}	2.87×10^{3}	6.27×10^{3}	4.11×10^{3}	1.81×10^{3}	8.65×10^{2}	7.88×10^{2}
	Fresh water aquatic ecotoxicity potential	kg 1.4-dB eq.	2.95×10^{2}	1.16×10^{2}	6.49×10^{3}	1.83×10^{3}	8.30×10^{1}	1.80×10^{1}	3.73×10^{1}
	Human toxicity potential	kg 1.4-dB eq.	2.85×10^{2}	1.25×10^{2}	4.88×10^{2}	5.79×10^{2}	1.82×10^{2}	2.71×10^{1}	9.11×10^{1}
	Marine aquatic ecotoxicity potential	kg 1.4-dB eq.	1.27×10^{6}	3.01×10^{5}	2.74×10^{6}	1.37×10^{6}	1.70×10^{5}	5.26×10^{4}	7.62×10^{4}
	Terrestrial ecotoxicity potential	kg 1.4-dB eq.	5.87×10^{-1}	1.39×10^{0}	1.35×10^{0}	1.79×10^{0}	4.93×10^{-1}	3.32×10^{-1}	2.81×10^{-1}
		€ / impact unit							
	Global warming potential	0.05	€ 48.88	€ 15.87	€ 26.65	€ 18.92	€ 7.41	€ 3.00	€ 3.75
	Ozone layer depletion potential	30	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	Photochemical ozone creation potential	2	€ 0.39	€ 0.33	€ 0.28	€ 0.28	€ 0.10	€ 0.04	€ 0.06
	Acidification potential	4	€ 11.26	€ 8.82	€ 9.25	€ 6.55	€ 2.39	€ 1.40	€ 1.34
	Eutrophication potential	9	€ 5.36	€ 29.05	€ 6.62	€ 6.69	€ 2.00	€ 1.10	€ 1.08
	Abiotic depletion potential for elements	0.15	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 271.41	€ 129.72	€ 129.25
	Abiotic depletion potential for fossil fuels	0.00007696	€ 1.05	€ 0.22	€ 0.48	€ 0.32	€ 0.00	€ 0.00	€ 0.00
	Fresh water aquatic ecotoxicity potential	0.03	€ 8.85	€ 3.48	€ 194.85	€ 54.82	€ 2.49	€ 0.54	€ 1.21
	Human toxicity potential	0.09	€ 25.69	€ 11.23	€ 43.92	€ 52.10	€ 16.38	€ 2.43	€ 8.56
	Marine aquatic ecotoxicity potential	0.0001	€ 127.29	€ 30.11	€ 274.17	€ 137.17	€ 17.01	€ 5.26	€ 8.37
	Terrestrial ecotoxicity potential	0.06	€ 0.04	€ 0.08	€ 0.08	€ 0.11	€ 0.03	€ 0.02	€ 0.02
Shadow costs	Total		€ 228.81	€ 99.19	€ 556.30	€ 276.95	€ 319.22	€ 143.52	€ 153.63
	Rank based on shadow costs		2	1	4	3	3	1	2

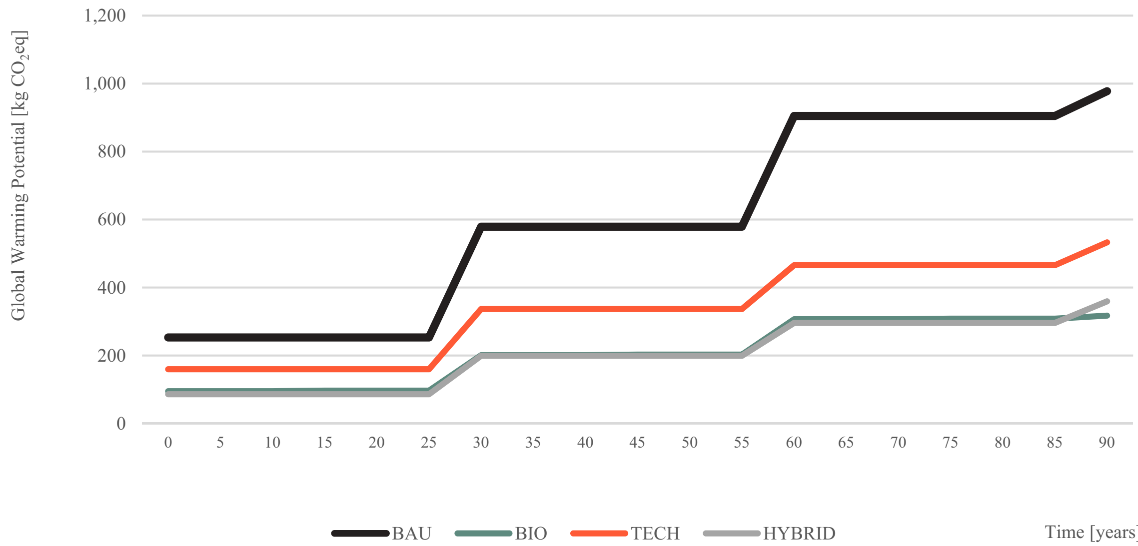

Fig. 4. Global warming potential allocated to Circular Skin business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants in time.

The GWP allocated to the Circular Skin and CIK has been plotted in Figs. 4 and 5, respectively, over time. These figures show that the circular variants have less allocated GWP impact than the BAU initially for both components; the relative reduction increases through time. For the façade, the figures show that the HYBRID and BIO variants' allocated GWP resemble each other through time. The same is true for the kitchen's TECH and BIO variants. Only the case of the façade shows a variant that causes more GWP than the other circular variants: the TECH façade.

4.3.3. Material Flow Analysis method

In the MFA of van Stijn et al. (2022), the (direct) material import and export of the building component over its service life was calculated in kg. Virgin or non-virgin flows, and renewable or non-renewable flows were distinguished for the material import. Reused, remanufactured, recycled, biodegraded, or recovered, and discarded flows were distinguished for the export. By subtracting the former three flows from the total import, the material consumption of the design variant was calculated.

4.3.4. Material Flow Analysis results

The results of the MFA of van Stijn et al. (2022) can be seen in Table 4. All variants increase the material import compared to the BAU for the Circular Skin. Yet, the TECH and HYBRID variants both significantly reduce the material consumption, by 100 % and 76 %, respectively. The BIO and TECH variants result in lower material import and consumption than the BAU for the kitchen. Notably, the TECH kitchen reduces material consumption significantly, namely by 93 %.

4.4. Economic performance

4.4.1. Circular Economy Life Cycle Costing method

The CE-LCC outcome, expressed in total costs (TC), is calculated as the sum of all the costs that occur for the components and subcomponents, and parts. Furthermore, the costs that occur during the lifetime are separated into two domains for this study: the manufacturers' domain and the customers' domain. The total CE-LCC outcome is the sum of the costs from both domains. Finally, as costs are calculated over a time period in LCC, total outcomes are considered at net present value (NPV), considering the time value of money.

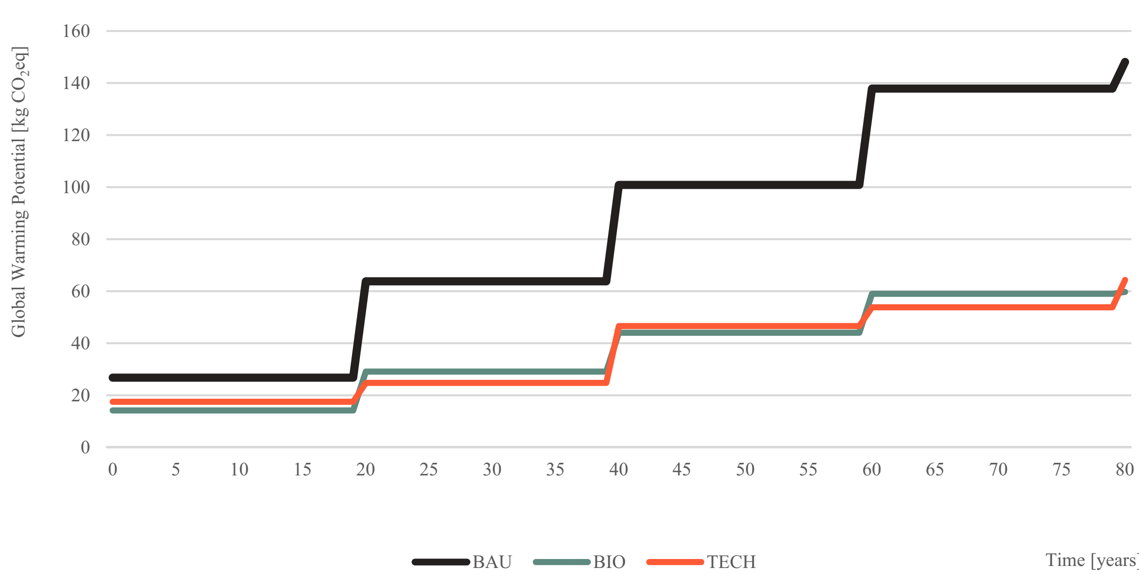

Fig. 5. Global warming potential allocated to Circular Kitchen business-as-usual (BAU), biological (BIO), and technical (TECH) variants in time.

Table 4
Material flows for Circular Skin and Circular Kitchen business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants.

	Impact category	Unit	Circular Skin				Circular Kitchen		
			BAU	BIO	TECH	HYBRID	BAU	BIO	TECH
MFA	Import | Total	kg	801	1488	987	1731	132	105	101
	Import | Virgin	kg	801	1488	329	518	92	105	63
	Import | Non-virgin	kg	0	0	658	1213	40	0	38
	Import | Renewable	kg	0	1483	0	1035	92	105	76
	Import | Non-renewable	kg	801	4	987	696	40	0	25
	Export | Reused	kg	0	0	899	1416	0	0	28
	Export | Remanufactured	kg	0	0	0	0	0	0	34
	Export | Recycled	kg	350	0	87	206	9	0	30
	Export | Recovered/biodegraded	kg	138	1488	0	109	123	105	8
	Export | Discarded	kg	313	0	0	0	0	0	0
	Material consumption	kg	451	1488	0	109	123	105	8

4.4.2. Circular Economy Life Cycle Costing results

The results of the CE-LCC are shown in Table 5. The BAU does not have the lowest TC for the Circular Skin, although it is developed to be low cost. The purchase price is the lowest, but the installation costs are relatively high (the BIO skin's installation costs are 4 % lower, the TECH's 36 %, and the HYBRID's 49 %). The BIO façade shows an increase in all cost categories relative to the BAU and has a 33 % increase in TC. Although the TECH façade shows a significant increase compared to the BAU in TC as well (24 %), it does not show similar increases to the BIO façade in all categories; the majority of the increase in TC originates from increased material costs. The TECH façade's material costs increase by 65 % compared to the BAU. The HYBRID façade is the only variant that shows a decreased TC: 17 % lower than the BAU, despite the higher purchase price and material costs.

The BAU kitchen - a product developed with a focus on low manufacturing costs - does not show the lowest TC either, even though it does have the lowest initial purchase price. The BIO kitchen, however, has the highest outcomes in all LCC categories and shows a 34 % increase in total costs compared to the BAU. Its purchase price is lower than that of the TECH kitchen, which is 82 % higher than that of the BAU kitchen, and 31 % higher than that of the BIO kitchen. However, the TECH kitchen shows a reduction of 7 % on TC, as all LCC cost categories are reduced except for deinstallation costs (since it is the only variant in which deinstallation is done).

Figs. 6 and 7 show the TC of all façade and kitchen variants respectively, plotted over time as described in ISO 15686-5 (International Organization for Standardization [ISO], 2017). The figures show that the BAU variants have the lowest TC up to the end of the first use cycle (30 years for the façade and 20 years for the kitchen). The HYBRID façade has the lowest TC after the first use cycle. The TECH façade performs worst in the initial cycle, but has smaller subsequent increases of net present costs, narrowing the gap in economic performance towards the BAU and HYBRID Skin variants over time. The TECH kitchen has the highest TC in the first 20 years, but after that period its TC closely resembles that of the BAU kitchen. The TECH kitchen has the lowest TC after the third use cycle. The BIO kitchen and façade consistently perform second best in the first use cycle, but also consistently perform worst after this point. The results through time for both the HYBRID façade and TECH kitchen and façade show the effect of gradual replacements of subcomponents and parts, instead of the whole façade or kitchen: after the initial purchase, only small increments in TC can be seen compared to the other variants.

4.5. Sensitivity analysis

Sensitivity analysis has been conducted as well to provide further support to the conclusions on the results presented above. As argued by van Stijn et al. (2021), if CE assessment includes all cycles, the uncertain assumptions in these cycles should be tested. The sensitivity analysis conducted on the CE-LCA and MFA of the Circular Kitchen and Skin can be found in van Stijn et al. (2022). Their research tested the influence of assumptions on the number of cycles and the lifespan of parts and found that adding 1 or 2 reuse cycles results in a decrease in impacts for all kitchen and façade variants. Savings were the highest for variants that do not have future cycles and apply virgin materials (BAU & BIO). Furthermore, when varying the technical and functional lifespans, their research found that varying the technical and functional lifespans in parallel results in the highest sensitivity.

Table 5
Economic performance of Circular Skin and Circular Kitchen business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants.

	Cost category	Unit	Circular Skin				Circular Kitchen		
			BAU	BIO	TECH	HYBRID	BAU	BIO	TECH
Manufacturer	Total material costs	€ at NPV	€ 1624	€ 1993	€ 2672	€ 1658	€ 141	€ 216	€ 155
	Total installation costs	€ at NPV	€ 1504	€ 1445	€ 957	€ 773	€ 57	€ 57	€ 21
	Total deinstallation costs	€ at NPV	€ 141	€ 643	€ 215	€ 146	€ -	€ -	€ 10
	Total transport costs	€ at NPV	€ 216	€ 216	€ 362	€ 216	€ 20	€ 20	€ 3
	Life cycle costs manufacturer	€ at NPV	€ 3486	€ 4296	€ 4208	€ 2793	€ 218	€ 292	€ 189
Customer	Purchase price	€	€ 1587	€ 1762	€ 3275	€ 2168	€ 110	€ 153	€ 201
	Total material costs	€ at NPV	€ 1473	€ 1815	€ 2726	€ 1616	€ 180	€ 276	€ 230
	Total Installation costs	€ at NPV	€ 1374	€ 1319	€ 874	€ 761	€ 73	€ 73	€ 29
	Total deinstallation costs	€ at NPV	€ 115	€ 521	€ 175	€ 118	€ -	€ -	€ 9
	Total transport costs	€ at NPV	€ 190	€ 190	€ 208	€ 190	€ 23	€ 23	€ 2
	Total maintenance costs	€ at NPV	€ -	€ 664	€ 44	€ -	€ -	€ -	€ -
	Total consumption costs	€ at NPV	€ -	€ -	€ -	€ -	€ -	€ -	€ -
	Life cycle costs customer	€ at NPV	€ 3152	€ 4510	€ 4027	€ 2685	€ 276	€ 372	€ 270
	Total costs	€ at NPV	€ 6638	€ 8806	€ 8235	€ 5477	€ 494	€ 665	€ 459
	Rank		2	4	3	1	2	3	1

Note: The purchase price is not an LCC type total cost, but the price paid at first purchase for the component.
Note: Material costs include all costs directly related to material use, such as material processing, manufacturing, reuse, remanufacturing, recycling and waste costs.

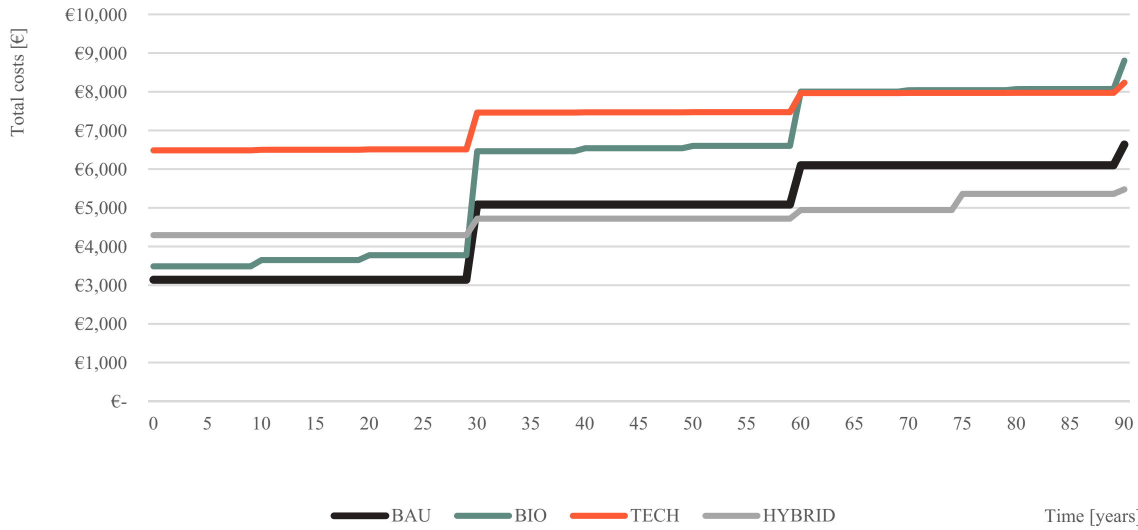

Fig. 6. Total costs for the Circular Skin business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants plotted over time.

The influence of assumptions on two parameters was found most relevant to test for the CE-LCC: the lifespan and the interest rate. The CE-LCC sensitivity analysis can be found in the online supplementary material in section S1. The results of the CE-LCA, MFA, and CE-LCC, and sensitivity analysis are interpreted in the following section to identify which circular pathway yields the most circular building components, what conditions should be considered when applying these pathways, and if there are possibilities for improvement.

4.6. Interpretation of the result: the technical or biological loop?

To give an overview of the 'best performing' variants, they have been ranked on the total outcomes of the CE-LCA (based on the shadow costs), MFA (average savings, based on material import, virgin import, non-renewable import, discarded/biodegraded export, and material consumption, see Table 6), and LCC study over 80 years for the kitchen and 90 years for the façade. In this comparison good environmental performance is defined as 'low shadow costs' and 'low average on material import, virgin import, non-renewable import, discarded/biodegraded export and material consumption', and good economic performance is defined as 'low total costs'. The best performing variant is ranked 1 and the worst either 3 – in the case of the kitchen – or 4 – in the case of the façade. Notes have been added to characterize the performance per component.

The results show that although the average outcome on MFA categories can be high for the BIO variants (an increase of 173 % compared to the BAU for the BIO skin), these variants consistently perform best in shadow costs (a reduction of 57 % compared to the BAU for the skin, and 55 % for the kitchen). Note that this is true if the biological materials do not significantly reduce the lifespan of the component or if not (much) more material is required to fulfill the same function compared to the BAU. Furthermore, the results show that substituting technical for biological materials can cause shifts in environmental burdens. Economically, the BIO components consistently perform best of the circular components in the first use cycle, but the total costs for the BIO components are high (33 % increase in TC compared to the BAU for the skin, and 34 % for the kitchen).

Initial material import might increase compared to the BAU components to realize modularity for the TECH components. However, they significantly reduce the average outcomes of the MFA categories (52 % savings for the skin, and 63 % for the kitchen compared to the BAU). The TECH components do not consistently improve the shadow costs compared to the BAU: the kitchen reduces shadow costs by 55 % compared to the BAU, and the skin increases the shadow costs by 143 %.

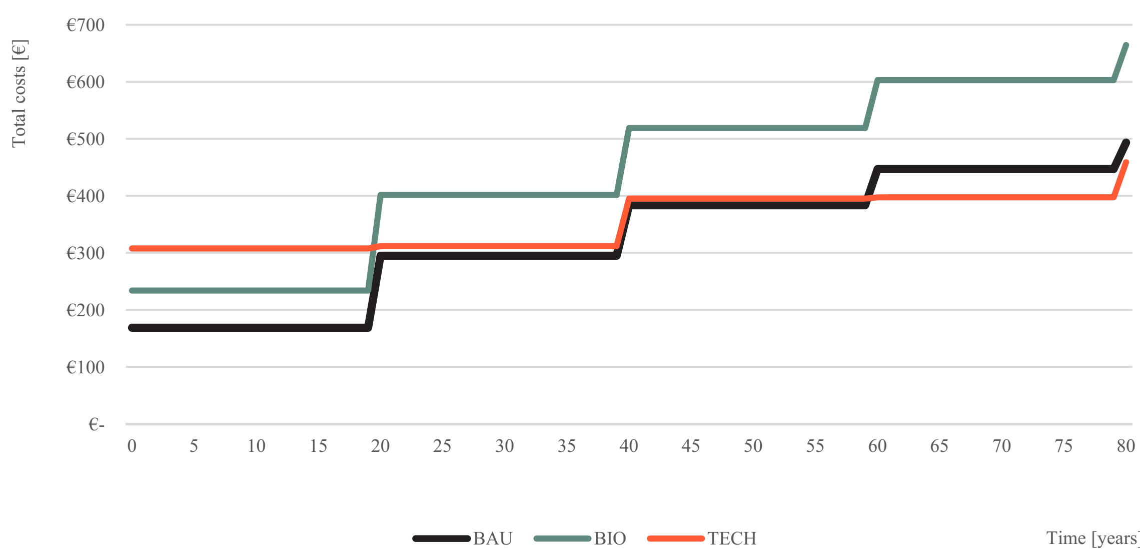

Fig. 7. Total costs for the Circular Kitchen business-as-usual (BAU), biological (BIO), and technical (TECH) variants plotted over time.

Table 6
MFA savings of the circular biological (BIO), technical (TECH), and hybrid (HYBRID) variants compared to the business-as-usual (BAU) variant.

	Impact category	Unit	Circular Skin				Circular Kitchen		
			BAU	BIO	TECH	HYBRID	BAU	BIO	TECH
MFA savings	Import | Total	% saved	0 %	−86 %	−23 %	−116 %	0 %	20 %	24 %
	Import | Virgin	% saved	0 %	−86 %	59 %	35 %	0 %	−14 %	32 %
	Import | Non-renewable	% saved	0 %	99 %	−23 %	13 %	0 %	100 %	38 %
	Export | Recovered/biodegraded	% saved	0 %	−981 %	100 %	21 %	0 %	14 %	93 %
	Export | Discarded	% saved	0 %	100 %	100 %	100 %	0 %	0 %	100 %
	Material consumption	% saved	0 %	−86 %	100 %	86 %	0 %	14 %	93 %
	Average		0 %	−173 %	52 %	23 %	0 %	22 %	63 %
	Rank		3	4	1	2	3	2	1

Furthermore, the TECH kitchen and TECH façade do not show similar CE-LCC outcomes (a decrease of 7 % on TC for the kitchen, and an increase of 24 % on TC for the skin). The explanation lies in the difference between the TECH designs and the BAU. The TECH kitchen does not vary too much in the type of material used from the BAU kitchen (both consist mostly of wood products). Whereas the change in materials (i.e., the aluminum frames & ceramic façade finishing) in the façade significantly increases the initial environmental impacts (in some categories) and material costs compared to the BAU, and this could not be compensated with the benefits of realizing future cycles over time. However, they both show that gradually replacing parts instead of entire components and introducing multiple cycles can have a positive effect both on environmental and economic performance. Nevertheless, extensive, long-term changes in the supply chain and business model are needed due to this dependence on VRPs to reduce environmental impact and life cycle costs. Therefore, this strategy should be used cautiously, and the possible long 'payback period' should be considered.

The HYBRID variant solves some of the issues that arise with a pure BIO or TECH variant for the façade, performing best in the CE-LCC (saving 17 % compared to BAU), and second best in the MFA (saving 23 % compared to BAU). However, it only performs third best in the CE-LCA (an increase of 21 % compared to the BAU). In these HYBRID variants, materials should be used purposefully. Biological materials should be applied where the technical lifespan of the material matches the functional lifespan of the part/subcomponent (e.g., finishing of a kitchen cabinet, or a protected, untreated wooden façade construction), and technical materials should be used where needed to prolong the lifespan of the component as a whole (e.g., a removable laminate layer to protect wood products from moisture in the kitchen, or water and vapor barriers to protect the wooden construction in a façade). Metal connectors (e.g., frames, screws, and bolts) could be replaced by biodegradable alternatives where these are available and suitable.

It can therefore be concluded that in terms of environmental and economic performance, a consistent improvement in all categories compared to the BAU is possible, as seen in Table 7. However, it does not lie in the selection of one pure pathway, i.e., either biological or technical, but in an effective application of materials and circular design principles. The approach that is most sure to be effective is to reduce environmental impacts now, whilst not increasing material import and reducing lifespan (overly much), through using biological material where possible and technical materials where needed. Simultaneously, one can decrease impacts, costs, and material use over time by realizing partial replacements to extend the lifespan of the whole component and introduce multiple future cycles for components, parts, and materials.

5. Discussion

Although this study gives insights into different circular pathways and the effect they might have on environmental and economic performance, there are several points of discussion.

First, these outcomes might not apply to all building components, in all contexts; designs for a façade differ significantly from designs for a climate installation, and (requirements, and therefore) designs for a façade in the Netherlands differ significantly from designs for a façade in some other countries. Nevertheless, Cruz Rios et al. (2019), De Wolf (2017), Rajagopalan et al. (2021), Geldermans et al. (2019), and Malabi Eberhardt et al. (2021) – who also compared multiple circular design options – support our findings: their variants that perform best environmentally apply combinations of circular pathways purposefully. Furthermore, Rajagopalan et al. (2021) also show that reversible, hybrid application of both technical and biological materials can lead to good economic performance.

Second, the qualification of material as biological or technical might be up for debate in some cases. Even though the wood products (such as plywood) used in the TECH kitchen are bio-based, these products cannot be brought back into the biosphere directly without negative effects at all. Therefore, plywood is qualified as technical material. However, it contains both biological (wood) and technical (glue) resources, and it resembles biological materials more than it resembles most of the materials used in the TECH façade on many accounts. Therefore, it can be useful to not consider materials by an absolute qualification of being either technical or biological, and materials could also be seen as hybrid (preferably the resources could then be separated on the material level). The TECH kitchen could also be seen as a HYBRID kitchen in that case.

Third, the building components following the technical pathways require extensive changes in the supply chain and business model. If these changes are not realized and fewer VRPs take place, or different financial

Table 7
Ranking of business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants and pathways. In this ranking, 1 is the best performing variant, and 3 (kitchen) or 4 (façade) the worst.

Pathway	Component	Shadow costs	MFA	TC	Notes
BAU	Façade	2	3	2	Medium environmental impact, low investment costs
	Kitchen	3	3	2	High environmental impact, low investment costs
BIO	Façade	1	4	4	Low shadow costs, high material consumption, low investment costs, high total costs
	Kitchen	1	2	3	Low shadow costs, high material consumption, low investment costs, high total costs
TECH	Façade	4	1	3	No material consumption, high investment costs, high shadow costs, partial replacements lead to small increments in all impacts, high total costs
	Kitchen	2	1	1	Low material consumption, high investment costs, partial replacements lead to small increments in all impacts, low total costs
HYBRID	Façade	3	2	1	Medium environmental impact, low total costs

agreements are made (for example, agreements that lack incentives for VRPs), different design variants might become preferable from an environmental and economic performance perspective. From the environmental performance perspective, the design should then rather be an efficient, lightweight solution that is kept in use as long as possible; materials should be low-impact, non-virgin and/or bio-based, and biodegradable or recyclable in open loops (van Stijn et al., 2022). Cruz Rios et al. (2019) show similar outcomes for an external wall: the technical variant can have good environmental performance, but only if it is reused two times. While the wooden frame variant they tested has the highest environmental benefits if it is reused only once. However, if no VRPs are realized, from an economic performance perspective the design should focus on low initial costs, which often conflicts with the need for low-impact, bio-based materials. To optimally organize and incentivize future cycles in the supply chain and business model, components would need to be developed as 'reproducible products' (i.e., standardized and/or mass-produced). However, designing all cycles falls outside the scope of a 'normal' building project, and realizing the VRPs would require long-term collaborations in the supply chain. Biological solutions offer greater reassurance of environmental performance in project-based work, since their impact is mostly created at the front end of the use cycle, and is not dependent on VRPs that take place in the (far) future.

Fourth, the sensitivity analysis showed that the assumptions on a number of parameters affect the outcomes of the CE-LCA, MFA, and CE-LCC and alter which components perform best. For example, varying the technical lifespans of both components has shown to significantly influence the outcomes of the analyses: the variant with the lowest TC, environmental impacts, and material consumption changes from scenario to scenario.

Fifth, future efforts are needed to improve the application of the methods in this study in CE assessment. The CE-LCA and CE-LCC do not apply the same system boundaries; the CE-LCA model applies an allocation approach to divide burdens and benefits between cycles whilst the CE-LCC model more closely resembles a 'system expansion' approach. Furthermore, CE-LCA and CE-LCC include multiple future cycles, making the results more uncertain, and so, creating the need for careful interpretation of results; these methods could benefit from further research. Furthermore, the MFA method used does not yet include multiple cycles in the system boundary. Using the Ecoinvent database, van Stijn et al. (2022) applied a process analysis LCI technique which is known to suffer from the so-called 'truncation error' (Crawford et al., 2018; Lenzen, 2000; Majeau-Bettez et al., 2011). Environmental impacts associated with inputs and outputs located outside of the system boundaries are not considered in these background datasets. Although this is true for all LCA studies applying a process analysis database, the truncation error might be more significant when all loops are included in the LCA's foreground system.

Finally, in (CE)-LCA, different approaches can be applied to support decision making, which in turn might lead to different designs performing better from an environmental impact perspective (see van Stijn et al. (2022)). Also, the results show that variants performing 'well' on environmental impacts do not always perform as well in the MFA or CE-LCC. Deciding on the basis of all the indicators and aspects remains challenging; decision-making could become a matter of 'cherry picking' without systematic approaches, which might lead to undesirable shifts in burdens.

6. Conclusion

When developing circular building components, designs can be made that follow the biological or technical pathway of the CE. However, which of these pathways yields the best 'circular performance' for building components was unclear. Circular performance is described as a combination of environmental performance and economic performance for this study. To identify which pathway yields the best circular performance, the results of circular environmental assessment – applying CE-LCA and MFA – were combined with circular economic performance assessment through CE-LCC.

The results show that the biological kitchen and façade consistently perform best on shadow costs, but perform second best and worst in the MFA respectively and consistently perform the worst economically. Technical solutions consistently perform best in the MFA and can reduce environmental impact by gradually replacing parts. However, while the technical kitchen performs second best in the CE-LCA and best in the CE-LCC, the technical façade performs worst in the CE-LCA and third best in the CE-LCC. The HYBRID variant of the façade shows that better alternatives can be achieved by combining (separable) biological and technical materials purposefully.

Since the BAU components are never the best performing variant on any of the indicators, this research concludes that applying circular pathways can improve the environmental and economic performance of building components. However, an improvement on all indicators cannot be made by following one pure pathway, i.e., either biological or technical, but in an effective application of materials and circular design principles. The approach that is recommended is to reduce environmental impacts now, whilst not increasing material import and reducing lifespan (overly much), through using biological materials where possible and technical materials where needed. Simultaneously, one can decrease impacts, costs, and material use over time by realizing partial replacements to extend the lifespan of the whole component and introduce multiple future cycles for components, parts, and materials.

Future studies could focus on the assessment of other building components, such as a building structure or climate installations to test the generalizability of this study, and should explore more hybrid design variants. Furthermore, professional practice could benefit from developing a (more) systemic assessment approach in order to better facilitate decision-making.

Nevertheless, this study shows that continuing with business-as-usual is never the best option, and a transition to a more sustainable built environment can be realized by applying circular building components.

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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Appendix A. Supplementary data

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