The Circular Kitchen
Perspectives for Design and Implementation

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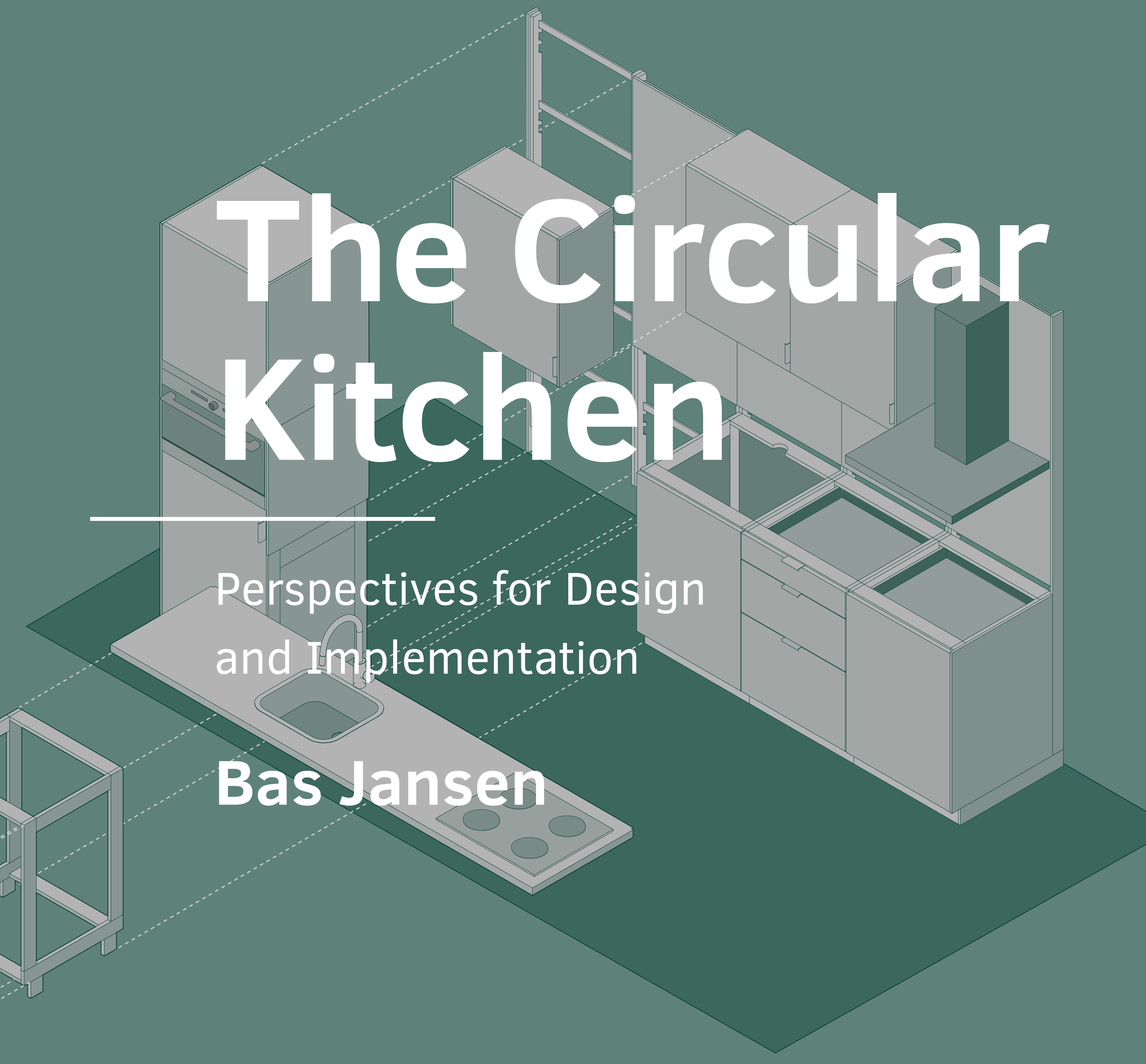

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The Circular Kitchen

Perspectives for Design and Implementation

Dissertation

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chair of the Board for Doctorates
to be defended publicly on
Monday 30 September 2024 at 12:30 o'clock

by

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This dissertation has been approved by the promotors.

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Preface

A journey I did not expect

Returning to academia to pursue a PhD was something I never anticipated. Interestingly, my path toward this research wasn't entirely uncharted. Having previously designed a kitchen with sustainable materials, I was tipped about this PhD position for the Circular Kitchen project. My experience as an architectural designer had already provided me with a solid foundation in design, and I had moved beyond the academic world, believing that chapter was closed. However, my longstanding interest in sustainable building materials and the principles of the circular economy gradually rekindled a curiosity I couldn't ignore.

This PhD research project presented a unique opportunity to dive deeper into these subjects, blending my professional experience with a new intellectual challenge. The combination of hands-on application and theoretical exploration drew me back into the academic realm. I was also seeking a fresh challenge at that time, and this project aligned perfectly with my evolving interests. So, I applied for the position and, within two weeks, was accepted.

Suddenly, my world was turned somewhat upside down—I was about to commit to a four-year project and work toward becoming a doctor. It was an amazing opportunity, yet it didn’t come without its downsides. I found myself anxiously pondering late at night about how to avoid accidentally plagiarizing, realizing the immense responsibility that came with this new academic pursuit. Now, at the end of this journey, I can safely say that I did not accidentally plagiarize and seem to have made it through pretty all right.

If you want to go fast, go alone; if you want to go far, go together

Let's be honest, this isn't the kind of section title that would naturally come from me. As those closest to me can attest, my natural inclination has always been to move quickly, chart my path, and ideally have a group aligned with my direction. I've often believed that efficiency and progress were best achieved when everyone was on board with a clear, decisive plan—preferably mine.

My usual approach would not have worked for this project. From the outset, it was a collective effort, requiring alignment across a consortium of stakeholders and the entire supply chain. The project's success depended on collaboration, where everyone's expertise and enthusiasm were crucial. In Delft, I felt part of a close-knit four-person core team. I owe deep gratitude to Prof.dr.ir. Vincent Gruis, whose calm guidance was invaluable, and to dr.ing. Gerard van Bortel, whose warm, positive approach made this journey truly rewarding. I also want to thank Anne van Stijn, with whom I worked closely for years—I could always rely on her for in-depth discussions, moral support, and amazing Christmas music all year round. In the analogy of a PhD journey, Anne was the best travel companion I could imagine (and sometimes also a great travel guide).

Additionally, I want to recognize our invaluable research partners at Chalmers University of Technology, who joined us to develop circular kitchens. Thanks to them Göteborg felt like our second home. My deepest thanks to prof. dipl.-des. Ulrike Rahe, prof.dr.ir. Paula Femenías, and my fellow PhD researchers Anita Ollár, Giliam Dokter (now aptly titled dr. Dokter), and Sofie Hagejärd for the warm welcome, the rich discussions, and the many insights that shaped our work together.

I also want to thank everyone outside of academia who contributed to this project. A special thanks to Robert Dalenoort of Syntrus Achmea; Joke Dufourmont and Virpi Heybroek of the AMS Institute; Jan van Os of ATAG; Nadia Silvestri, Natalia Alandete Lara, Sander Jahilo, and Zeno Winkels of the Climate KIC; Kevin Uitermark and Remco Sinnige of Dirkzwager Groep; Bart de Jong, Fred Springintveld, Goran Pogarcic, Ilse van Andel, and Peter Hildering of Eigen Haard; Albert Groothuizen, Jurn de Winter, and Tom Petiet of Portaal; Freek Hermsen, Raymond Heister, and Teun van Kuijk of Stichting Woonbedrijf SWS; Dick Lodder, Hans van Erven, Herman Brans, and Mark de Waard of Topline Maatwerkbladen BV; Joost van den Bergh, Monique Bezemer-Voll, and Wilfred Gerritse of Waterweg Wonen; Caroline Kroes, Hanneke van der Heijden, Gilles du Hen, and Carlijn Stoof of Woonstad Rotterdam; Karel de Koning and Ron Onverzaagt of Ymere.

I must especially thank Bas te Brake, Dave Lageschaar, Joop Boerekamps, Piet-Hein Kraakman, and Wim Diersen from Bribus Keukens. Bribus was our closest collaborator, and I spent countless hours with Joop and Dave, diving deep into prototype assembly and traveling to find the perfect connection manufacturer—working with you was truly a blessing. This research would not have been possible without your enthusiasm, knowledge, and critical reflection.

A heartfelt thank you also goes to my colleagues at Rochdale for their interest in my PhD and their patience and support throughout the last phases of this project.

To my friends and family—thank you for providing the much-needed distractions and unwavering support. A special thanks to my mom, dad, and sister, who may not have fully understood what I was up to over these last six years but have always been there with love and encouragement. To Daan, Ernst, and Joren, my climbing crew, thank you for the countless trips and for reigniting my passion for what we all know is more than just a hobby—it's a lifestyle. To Arthur, Benjamin, Mark, and Zeb, thank you for the laughter, the distractions, and the support when I needed it most. And finally, to Amanda, the love of my life—thank you for being the most understanding and loving person I know, for truly seeing me, and for your unwavering support.

As for what comes next, many people ask, "And now what?" The honest answer is, I’m not entirely sure. But I know I’ll have more time and mental space to figure that out, and that alone feels like a blessing.

Contents

List of Tables

List of Figures

Summary

Introduction

Recent reports emphasize the dire consequences of global warming exceeding 1.5°C, including ecosystem destruction and a fourfold increase in economic impacts by 2100. Despite housing being essential, the building sector's substantial greenhouse gas emissions and material consumption necessitate an urgent transition to more sustainable approaches in the built environment to mitigate environmental and economic risks.

The Circular Economy (CE) presents a viable approach for achieving a sustainable built environment by minimizing resource use, environmental impacts, and waste. Geissdoerfer et al. (2017, p. 759) state that the 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". Slowing loops means to extend the lifespan of a building, a building component (such as a façade or roof), subcomponent (such as a window frame including glazing) or part (such as glazing); narrowing loops is to reduce resource use or enhance resource efficiency; closing loops is to recycle materials from end-of-life back to production (Bocken et al., 2016).

The Netherlands aims for a 'fully circular' economy by 2050, with a 50% reduction in primary resource use by 2030 (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). Government-led initiatives and collaborations with industry stakeholders, such as the 2017 nationwide agreement to accelerate the transition to the circular economy (VNO-NCW et al., 2017) and subsequent transition agendas and roadmaps (Transitieteam Circulaire Bouweconomie, 2018, 2022), are driving the transition towards a circular built environment. This alignment between governmental policies and stakeholder interests creates an enabling environment for innovation and the advancement of circular practices.

Within that context, the housing sector could benefit the most from becoming more circular. Residential buildings, constituting over 87% of Dutch real estate (CBS, 2023a), face urgent renovation needs to reduce energy use, and an estimated one million homes need to be constructed to meet housing demand driving substantial embodied environmental impacts (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a, 2022b). Therefore, stricter regulations and circular economy principles are becoming central to new construction, renovation, and maintenance (Kamerbrief over Beleidsagenda Normeren En Stimuleren Circulair Bouwen, 2022). Housing associations manage a significant portion of Dutch homes, and are crucial in promoting circular practices (CBS, 2023b). Their substantial demand provides incentives for supply chain partners to develop circular alternatives, and their long investment perspective makes them well-suited for implementing CE principles.

Integrally developing circular building components

Authors such as Bocken et al. (2016), Mendoza et al. (2017), Pomponi and Moncaster (2017), Saidani et al. (Saidani et al., 2017), and van Stijn (2023) emphasize the importance of a comprehensive approach to circular design, urging consideration of the physical design, business model, and supply chain. Additionally, they argue that achieving circular design requires a systems approach, encompassing the entire design system from macro to micro levels.

However, achieving circularity at the city, or even building system level within a limited research timeframe is challenging. Hence, a building component approach is adopted. This approach, highlighted by researchers like van Stijn (2023) and Azcarate-Aguerre (2023), aims to narrow, slow, and close loops by substituting building components with circular alternatives during renovation, maintenance, or new construction. Specifically, this research focuses on developing a circular kitchen (the CIK) alongside other circular building components. While the environmental benefits of making a kitchen circular may be less significant than other components, the potential for widespread market adoption offers substantial overall environmental benefits due to kitchens' low complexity, standardized production, and continuous demand for production.

Research on circular building components such as a circular kitchen involves exploring numerous design strategies, materials, and models for narrowing, slowing, and closing loops. Van Stijn & Gruis (2019) identified a vast array of design options for technical, industrial, and business models, resulting in millions of potential unique designs. However, not all designs may be environmentally or economically desirable or feasible. Despite the rise in research on circular economy (CE), its application in the built environment remained nascent, with a limited understanding of which designs offer the best environmental and economic performance and which designs are feasible in a real-world context.

Dissertation Goals

To address the gaps identified in the previous section, this research has a design goal and research goals. The development of the circular building component aimed to address the absence of such components in practice. The research goals were designed to support the development of the CIK while also generating valuable methods and knowledge.

The design goal is **to develop a Circular Kitchen that is feasible in practice and performs better environmentally than non-circular kitchens**. The focus is on implementing the CIK within Dutch Housing Associations (HAs) due to the favorable context for circular component development in the Netherlands, but the potential applicability and knowledge gained could apply to broader sectors.

Four research goals were identified to support the design goal while simultaneously developing methods applicable to other circular building components. First, this research aims to create circular kitchens that are environmentally superior to non-circular ones while remaining feasible. Economic viability is crucial for feasibility, thus an life cycle costing (LCC) method is developed. Research goal 1 (RG1) is therefore to **develop an LCC method that determines the economic performance of circular building components**. Second, the identification of the best-performing circular building component variants, encompassing both environmental and economic aspects, is essential for decision-making in the CIKs design. Research goal 2 (RG2) is, therefore, to **identify which types of circular building component variants perform best environmentally and economically**. Third, many authors have studied barriers and enablers for a circular built environment. However, to effectively address these barriers, decision-makers require a deeper understanding of their relative importance, their occurrence in real-world cases, and their impact on component feasibility. Such knowledge can inform better design, policy-making, and decision-making processes. Therefore, the third research goal (RG3) is to **draw lessons from**

stakeholders' choices in the CIK development that can aid the future development of feasible circular building components. Finally, the CIK is developed within a research context, which may lead to different design outcomes compared to kitchens developed outside of a research context. Analyzing other circular kitchens can yield insights into their feasibility and validate choices made during the development of the CIK, aligning with the fourth research goal (RG4), which is to **identify which types of circular kitchens are feasible in practice, and examine their similarities and differences with each other and the CIK**.

Approach and Methods

The research approach combines Research-through-Design (RtD) and Action Research (AR), involving cycles of designing and assessing circular kitchen designs. This Action Research-through-Design (ARtD) approach engages stakeholders in developing and testing the CIK, aiming to address real-world challenges while contributing to knowledge acquisition and implementation of the CE in the built environment.

The research commenced with a design process that raised numerous questions. Some of these questions found answers within existing literature, while others lacked relevant theories. Four research questions emerged from these inquiries, and these questions formed the basis of the research goals. Given the diversity of these research goals, the research methods employed varied per goal. Nevertheless, the overarching approach remained consistent.

A systematic design approach structured the development and testing of circular building components. It involved phases such as 'proof-of-concept,' 'prototype,' 'demonstrator,' and 'market implementation,' each encompassing analysis, synthesis, simulation (or test), and evaluation activities. Although deviations from the planned process necessitated multiple iterations and adjustments, this approach enhanced understanding and facilitated progress.

Results

Results research goal 1

In this study, three existing LCC approaches were identified: Conventional LCC (C-LCC), Environmental LCC (E-LCC), and Societal LCC (S-LCC). While C-LCC typically has a single stakeholder perspective and may overlook end-of-life scenarios, E-LCC broadens the perspective to include multiple stakeholders, and S-LCC considers both direct and indirect costs to society. However, existing methods do not fully incorporate the complex, multiple use cycles inherent in circular products and components.

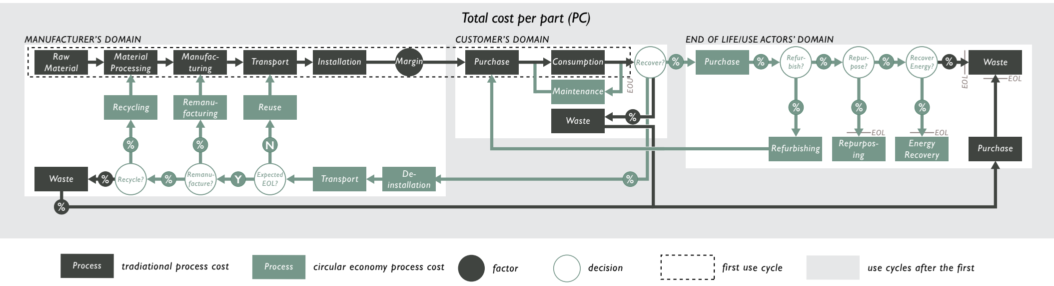


FIG. SUM.1 The overall structure of use cycles of a part in the CE-LCC model.

To support the development of circular products, existing LCC techniques were adapted to (1) consider products as composite entities with varying use cycles, (2) include post-use processes, (3) offer practical information to stakeholders, and align functional units and system boundaries with life cycle analysis (LCA). The developed CE-LCC method (see Figure Sum.1) was applied to compare CIK variants, with the most adaptable variant showing the most favorable long-term LCC outcome. This model aids decision-makers in assessing the economic viability of circular products and thus supports the transition towards sustainability in the building industry.

Results research goal 2

This study aimed to assess the circular performance of building components, comparing biological (BIO) and technical (TECH) circular pathways in terms of environmental and economic performance. Circular economy life cycle assessment (CE-LCA)(expressed in shadow costs), material flow analysis (MFA), and CE-LCC (expressed in total costs (TC)) were used to compare CIK and circular façade design variants. Rankings were provided based on the outcomes for business-as-usual (BAU), BIO, TECH, and hybrid (HYBRID) design variants (see Table Sum.1). Results revealed that BIO solutions performed best in terms of shadow costs but ranked lower in MFA and TC, while some TECH solutions showed the opposite trend. HYBRID variants demonstrated potential for improved performance by combining BIO and TECH materials.

Importantly, BAU components consistently ranked lower than circular variants, suggesting the potential for enhancing environmental and economic performance through circular pathways. The study emphasized the need to apply materials and circular design principles effectively, aiming to mitigate environmental impacts, extend lifespan, and introduce multiple future cycles for components, parts, and materials. This reinforces the importance of transitioning to circular building components for a more sustainable built environment.

TABLE SUM.1 Ranking of business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants. 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

Results research goal 3

This study focused on identifying choices that stakeholders made toward a feasible circular design and the impact of those choices, aiming to support designers, policymakers, and decision-makers in other circular design processes. A longitudinal case study of a circular building component, the CIK, was conducted. The researchers actively co-created the CIK's design, which is shown in Figure Sum.2, its supply chain model, and its business model throughout five phases, documenting all decisions made by stakeholders. Five lessons were derived by analyzing these stakeholders' decisions and reflecting on the development process.

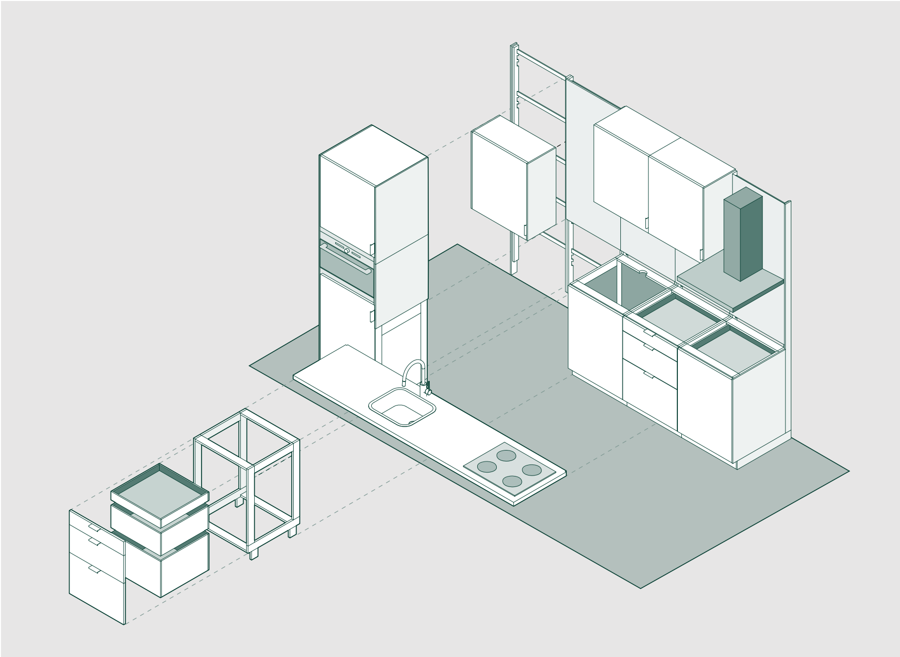


FIG. SUM.2 The CIK's physical design

Lesson one emphasized the importance of prioritizing feasible circular design options over more ideal circular options, as the immediate implementation of circular solutions is more beneficial to a more sustainable built environment than postponing the implementation to create a 'more circular' design. The second lesson underscored the significance of component aesthetics for broad acceptance among clients and end-users, highlighting the need for satisfying various preferences. The third lesson stressed the substantial impact of decisions made at the detail scale on a component's feasibility and circularity, recommending simultaneous design at different scales. The fourth lesson emphasized the importance of participation of stakeholders that are representative of the whole supply chain in aligning the value proposition and ensuring effective project focus. It suggested involving individuals with optimal influence, technical knowledge, and project dedication. The fifth lesson revealed the need for sufficient time and resources when considering integral redevelopment of the physical design, supply chain model, and business model.

While these lessons may not cover all contexts comprehensively, they offer insights into decision-making during circular component development, potentially aiding future component development.

Results research goal 4

In this study, seven circular kitchens, including the CIK, were identified and compared to identify which types of circular kitchens are feasible in practice. These kitchens can be seen in Figure Sum.3a-g. These kitchens were manufactured by both established companies and start-ups, revealing differences in the degree of innovation applied. The established manufacturers tended to align more closely with non-circular kitchen models, while start-ups implemented more radical innovations. Detailed information was primarily available concerning the technical model, while insights into industrial and business models were relatively scarce.

Notably, the kitchen designs displayed a bifurcation based on material choices for their structure, specifically between frame structures using technical materials (in this case steel) and panel-based structures using biological materials (different types ranging from plywood to cellulose panels). The CIK stood out with its bio-based frame structure, which was later adapted by the manufacturer, indicating its infeasibility. A distinction was also noted regarding the use of retaining walls, a feature present in both frame and panel-based kitchens.

All of the examined circular kitchens prioritized circular design options to facilitate closing future loops, thereby enhancing their long-term environmental performance. However, it is crucial to acknowledge that the feasibility of circular kitchen types may change over time, and the absence of certain types in current practice does not necessarily signify their infeasibility. Additionally, since these kitchens were recently developed and none have reached their end-of-life stage, the extent to future resource loops will be closed and the actual benefits they will yield remains uncertain.

This study, while specific to the Dutch housing sector, provides valuable insights into feasible circular kitchen technical models. Such knowledge can ease the implementation of future circular kitchens, potentially streamlining industry-wide standardization and enhancing the circular transition. The study also highlights the disparity between ideal and feasible circular designs in a research context, and circular kitchens in practice, emphasizing the importance of considering market implementation in such projects.

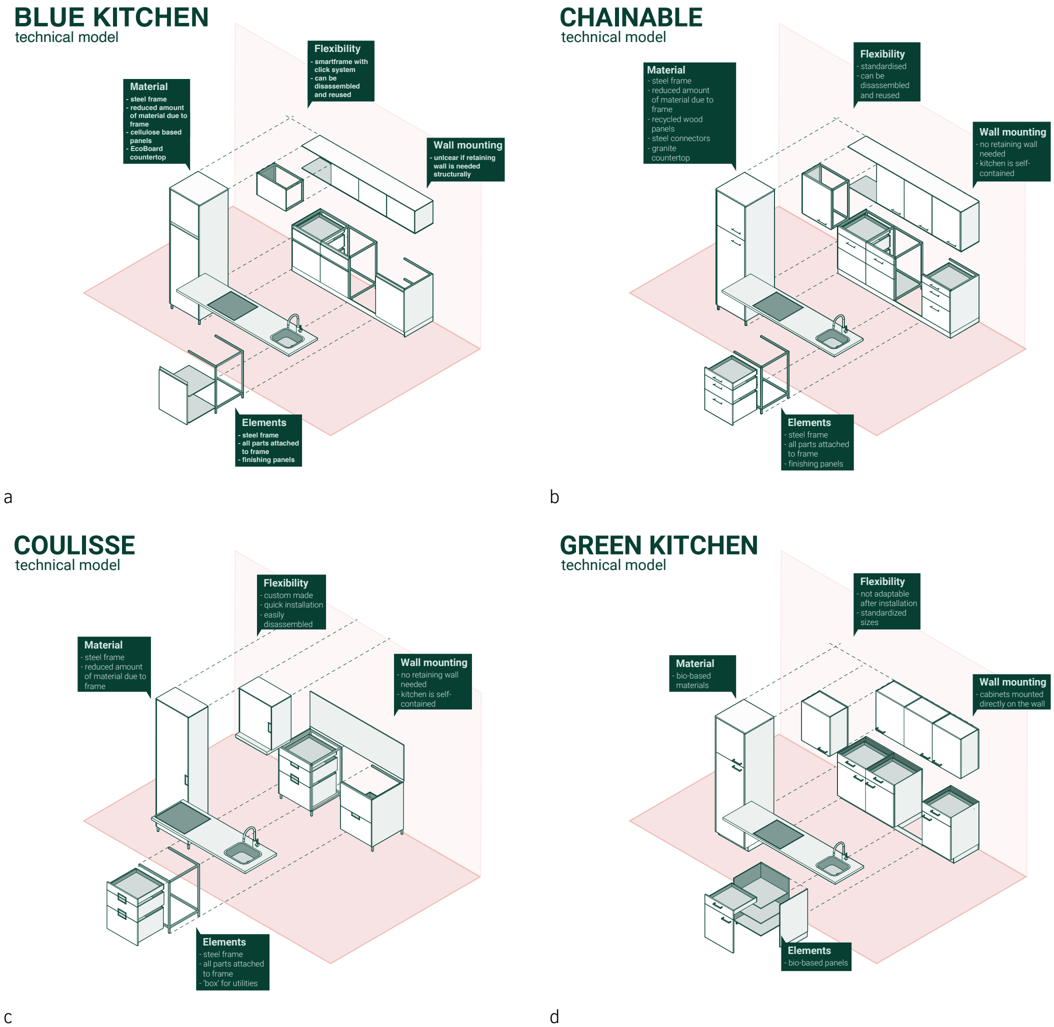
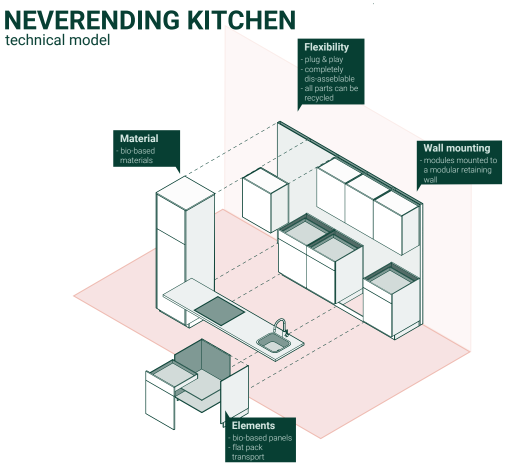


FIG. SUM.3 Technical models of the (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, and (g) CIK.



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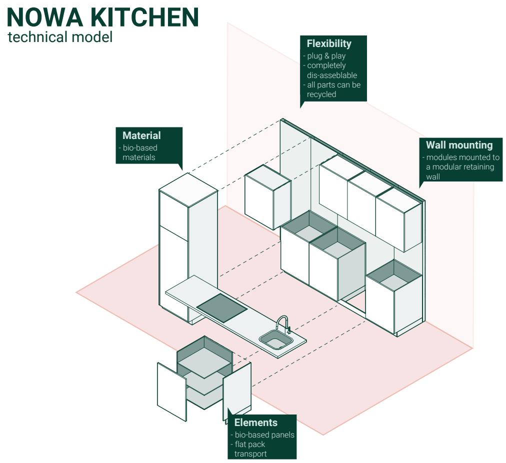

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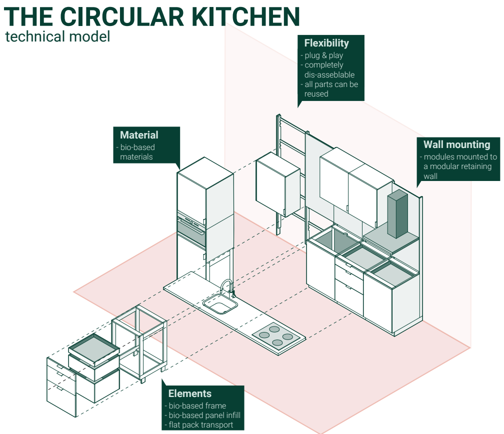

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FIG. SUM.3 Technical models of the (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, and (g) CIK.

TOC

Conclusions

The building industry plays a critical role in advancing sustainability, with a shift to a Circular Economy (CE) offering the potential for reducing resource consumption and waste. Circular kitchens stand out as promising options due to their simplicity in manufacturing, existing standardization, streamlined supply chains, and controlled indoor usage, minimizing implementation risks. Various strategies can be employed to develop circular building components like kitchens, aiming to narrow, slow, or close resource loops.

This research aimed to a feasible Circular Kitchen (CIK) that reduces environmental impacts compared to current, non-circular kitchens, targeting housing associations as primary clients due to their significant market presence and long-term investment strategies. To achieve this, four research goals (RGs) were defined: developing an LCC method for economic evaluation of circular components (RG1), assessing the environmental and economic performance of circular building components (RG2), deriving lessons from stakeholders' choices in CIK development (RG3), and investigating the feasibility of circular kitchens beyond the CIK project (RG4).

So, was the goal of developing such a circular kitchen reached? Was the CIK feasible in practice, and did it perform better environmentally than current, non-circular kitchens? And if not, which strategies would be advisable to develop a better circular kitchen?

Conclusions on the design goal

All evaluated CIK designs outperformed standard non-circular kitchens economically and environmentally. The last design variant of the CIK, the TECH kitchen in Study 2, achieved the highest MFA performance and second-highest in CE-LCA. Conversely, the BIO kitchen excelled in CE-LCA and ranked second in MFA. While BIO designs share similarities with non-circular kitchens, implementing TECH designs requires substantial supply chain and business model changes. Insecurity regarding these changes potentially impacts environmental outcomes negatively. Biological solutions offer greater assurance regarding their environmental performance due to their impact reduction taking place early in the lifecycle, independent of future adoption of value retention processes (VRPs), such as reuse, remanufacturing, and recycling. Economic feasibility is paramount, with stakeholders emphasizing cost minimization and price parity with non-circular kitchens. Despite higher initial costs, the most adaptable CIK variant proved cost-effective over extended periods, confirmed by the second study comparing TECH and BIO kitchens. However, real-world feasibility was limited, as observed in studies three and four. Housing associations still prioritize total costs sparingly, and mass-producing CIKs necessitates significant investments in new production facilities. Additionally, the decision to make these investments coincided with unforeseen negative feedback received after placing demonstrator kitchens in several homes. Consequently, the CIK failed to transition beyond the research phase. In conclusion, the design goal was not reached, and the CIK did not reach application in the real world. Nevertheless, knowledge gained from the complete CIK research project were utilized to further develop a different, less ambitious circular kitchen design that is aimed to be implemented soon.

Reflections

This research comprehensively investigated circular kitchens across four studies, offering insights that extend beyond individual findings. This concluding section, therefore, presents three insights: improving the feasibility of circular kitchens, designing for a circular built environment, and improving the CE's role in achieving sustainability. These reflections offer implications for practice, as well as directions for further research.

Reflections on better, more feasible circular kitchens

As can be concluded from the Section "Conclusions on the design goal", the CIK design was not feasible in the context that it was envisioned in. But how could a circular kitchen be feasible in this context? And how could that feasible circular kitchen still yield better environmental performance than the current standard kitchen?

Study four shows the diverse approaches taken by start-ups and established manufacturers in developing circular kitchens. While start-ups favor radical innovation, established manufacturers, like the CIK's producer, opt for incremental improvements (outside of a research context). This suggests that when aiming for large-scale implementation that can only be reached with large-scale production, the feasibility of the design should be prioritized, while still improving environmental performance compared to current, non-circular kitchens. Feasibility is achieved by reducing initial costs and aligning production methods and supply chains with current industry standards. Enhancing environmental performance involves applying low-impact or longer-lifespan materials, slowing potential loops through standardization, modular design, and demountable joints, and facilitating repairs and replacements where possible for minimal additional costs.

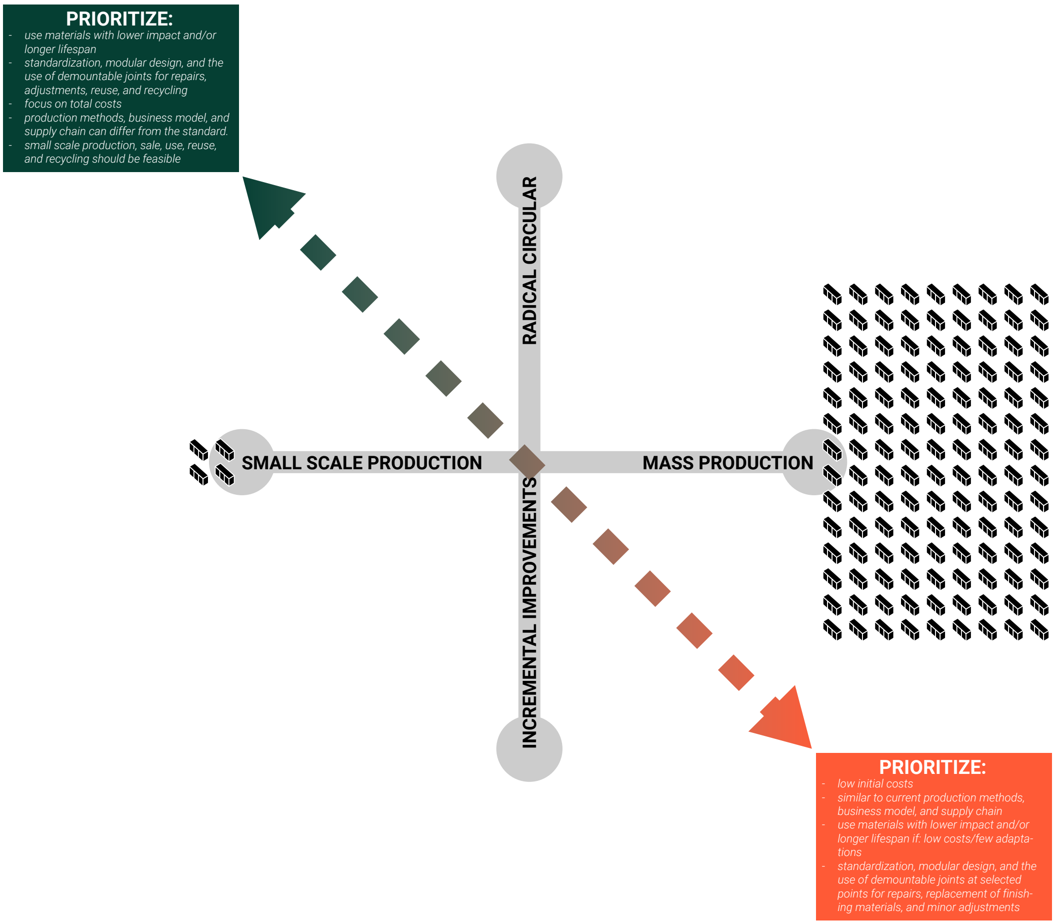

FIG. SUM.4 Circular design priorities based on the intended initial scale of production

For manufacturers focused on gradual growth rather than immediate large-scale market adoption, radical innovation towards optimal environmental performance becomes viable. This entails narrowing material loops upfront, slowing and closing future loops through various design strategies. Design decisions can be based on the feasibility of total costs, and designs can apply production methods, business models, and supply chains that differ from the current industry standard. However, sustaining production, sales, reuse, and recycling is crucial, with ongoing efforts directed at improving financial viability to expand market share, and with it the environmental benefits. These priorities are depicted in Figure Sum.4.

Reflections on designing for a circular built environment

The production of standardized modular building components as products necessitates significant reconsideration of design methodologies from both product and building design perspectives. Although scholars of design theory acknowledge that many design phases tend to overlap or occur concurrently in practice (Milton & Rodgers, 2011), product and architectural design theories typically propose a design process with multiple subsequent phases (Ginting, 2020; Roozenburg & Eekels, 1995; Ulrich & Eppinger, 2008). In the first phases, the design is abstract (or global) and it progressively acquires more detailed specifications in subsequent phases – converging from global to detailed.

However, the third study of this dissertation showed that the successful design of modular building components relies heavily on decisions regarding connections, production methods, and materials that are conventionally made in the later phases of the design process. Therefore, the conventional design methods might not suffice, and an alternative approach is needed. This approach applies to both designing at the building and the component level.

Designers should determine the desired level of modularity early on and adapt the focus within the design process accordingly. A fully standardized modular building or component requires a detailed design approach from the start, diverging toward a global scale. Some examples of this approach can already be seen in the Dutch social housing sector, for instance in the newly built modular homes of the Bouwstroom (Aedes & VTW, 2022). Conversely, a fully custom building can follow the traditional converging design approach. Designs that neither follow a standardized modular approach, nor a completely custom approach fully, might require both the global and the detailed level as a starting point of the design process. Figure Sum.5 shows this proposal for such selection of design method based on the degree of standardized modularity. As is the case for conventional design phases, design iterations can go back and forth between phases – a design process is rarely a linear one – and this figure merely indicates one or multiple starting points for the design process, and a priority and general direction.

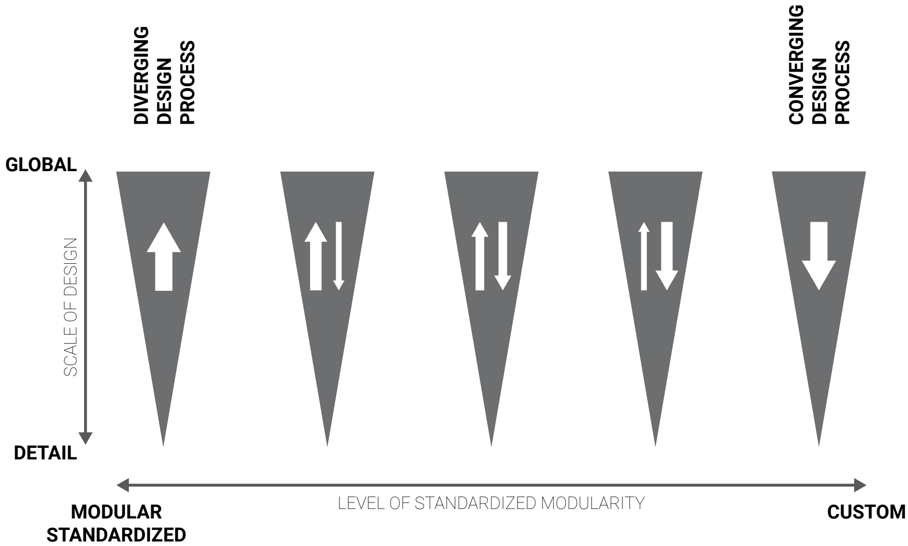

FIG. SUM.5 Implications of the degree to which standardized, modular design strategies are applied to the design process, in which white arrows imply the direction of the design process. The right side of the diagram represents the current traditional practice, and the left represents a process optimized for modularity.

Reflections on slowing and closing loops

The CE offers potential solutions to reducing resource use, environmental impacts, and waste in the built environment, but blindly pursuing circularity may exacerbate environmental challenges. This research highlights the need to differentiate between circular strategies in fostering sustainability within the built environment. Study 2 reveals that not all circular design options improve environmental performance, sometimes even increasing resource use and waste generation. Additionally, circular components often require higher upfront investments, while only offering potential long-term benefits. Study 3 identifies challenges in developing components for future VRPs, requiring changes in business models, supply chains, and design methodologies. While feasible changes exist, they are mainly observed

TOC

in small-scale production. Designing for future VRPs introduces uncertainty due to the long timespan in which they are beneficial environmentally, and their reliance on long-term stakeholder collaboration. Components relying on future VRPs may require multiple use cycles to achieve superior environmental performance, adding to the uncertainty of their benefits.

This research emphasizes the importance of prioritizing strategies with immediate environmental benefits due to the risks and challenges associated with achieving long-term benefits through building components designed for future Value Retention Processes (VRPs). Strategies such as Refuse, Rethink, and Reduce, along with substituting high-impact materials with low-impact, renewable ones and slowing and closing existing material loops, are crucial for consistently achieving a more sustainable built environment. In conclusion, not all circular approaches are beneficial to environmental goals in the short or long term, either due to their lack of environmental performance improvement or feasibility.

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Samenvatting

Introductie

Recente rapporten benadrukken de ernstige gevolgen van een opwarming van de aarde van meer dan 1,5°C, waaronder de vernietiging van ecosystemen en een verviervoudiging van de economische gevolgen tegen 2100. Ondanks dat huisvesting essentieel is, maken de aanzienlijke uitstoot van broeikasgassen en het materiaalverbruik van de bouwsector een dringende transitie naar duurzamere benaderingen in de gebouwde omgeving noodzakelijk om ecologische en economische risico's te beperken.

De Circulaire Economie (CE) presenteert een mogelijke aanpak voor het bereiken van een duurzame gebouwde omgeving door het gebruik van grondstoffen, milieu-impact en afval te minimaliseren. Geissdoerfer et al. (2017, p. 759) stellen dat de CE "een regeneratief systeem is waarin de input en verspilling, emissie en energielekkage van grondstoffen worden geminimaliseerd door het vertragen, vernauwen en sluiten van materiaal- en energiekringlopen". Kringlopen vertragen betekent het verlengen van de levensduur van een gebouw, een bouwcomponent (zoals een gevel of dak), een subocomponent (zoals een raamkozijn inclusief beglazing) of een onderdeel (zoals beglazing). Het vernauwen van de kringlopen betekent het gebruik van grondstoffen te verminderen of de grondstoffenefficiëntie te verbeteren. Het sluiten van kringlopen is het recyclen van materialen vanaf het einde van hun levensduur (Bocken et al., 2016).

Nederland streeft naar een 'volledig circulaire' economie in 2050, met een reductie van 50% in het gebruik van primaire hulpbronnen in 2030 (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). Door de overheid geleide initiatieven en samenwerkingen met belanghebbenden uit de sector, zoals de landelijke overeenkomst uit 2017 om de transitie naar de circulaire economie te versnellen (VNO-NCW et al., 2017) en daaropvolgende transitieagenda's en roadmaps (Transitieteam Circulaire Bouweconomie, 2018, 2022), zijn de drijvende kracht achter de transitie naar een circulaire gebouwde omgeving. Deze afstemming tussen overheidsbeleid en de belangen van belanghebbenden creëert een gunstig klimaat voor innovatie en de bevordering van circulaire praktijken.

Binnen die context zou de woningbouwsector het meeste kunnen bijdragen door een meer circulaire aanpak. Er is momenteel voor woongebouwen, die meer dan 87% van het Nederlandse vastgoed uitmaken (CBS, 2023a), een dringende renovatiebehoeften om het energieverbruik terug te dringen, en er moeten naar schatting een miljoen woningen worden gebouwd om aan de woningvraag te voldoen, wat substantiële gevolgen voor het milieu heeft (Ministerie van Binnenlandse Zaken). Daarom wordt strengere regelgeving ingevoerd, en circulair bouwen en onderhouden gestimuleerd (Kamerbrief over Beleidsagenda Normeren En Stimuleren Circulair Bouwen, 2022). Woningcorporaties beheren een aanzienlijk deel van de Nederlandse woningen en zijn cruciaal in het bevorderen van circulaire praktijken (CBS, 2023b). Hun substantiële vraag stimuleert partners in de toeleveringsketen om circulaire alternatieven te ontwikkelen, en hun lange investeringsperspectief maakt ze zeer geschikt voor het implementeren van circulaire principes.

Integraal circulaire bouwcomponenten ontwikkelen

Auteurs zoals Bocken et al. (2016), Mendoza et al. (2017), Pomponi en Moncaster (2017), Saidani et al. (Saidani et al., 2017) en van Stijn (2023) benadrukken het belang van een alomvattende benadering van circulair ontwerp, en dringen aan op aandacht voor het fysieke ontwerp (of technisch model), het bedrijfsmodel en de toeleveringsketen (of industrieel model). Bovendien stellen zij dat het bereiken van circulair ontwerp een systeembenadering vereist, die het hele ontwerpsysteem omvat, van het macroniveau van de stad tot microniveau van het bouwproduct.

Het realiseren van circulariteit op stad- of zelfs gebouwniveau binnen een beperkt onderzoek tijdsbestek is echter uitdgend. Er wordt daarom gekozen voor een bouwcomponentbenadering. Deze aanpak, die ook gebruikt wordt door onderzoekers als van Stijn (2023) en Azcarate-Aguerre (2023), heeft tot doel kringlopen te verkleinen, vertragen en sluiten door bouwcomponenten te vervangen door circulaire alternatieven tijdens renovatie, onderhoud of nieuwbouw. Concreet richt dit onderzoek zich, naast andere circulaire bouwcomponenten, met name op het ontwikkelen van een circulaire keuken (de CIK). Hoewel de milieuvoordelen van het circulair maken van een keuken misschien minder groot zijn dan die van andere componenten, biedt het potentieel voor wijdverbreide marktacceptatie substantiële milieuvoordelen vanwege de lage complexiteit van keukens, de gestandaardiseerde productie en de voortdurende vraag naar productie.

Onderzoek naar circulaire bouwcomponenten, zoals een circulaire keuken, omvat het onderzoeken van talloze ontwerpstrategieën, materialen en modellen voor het vernauwen, vertragen en sluiten van kringlopen. Van Stijn & Gruis (2019) identificeerden een breed scala aan ontwerpopties voor technische, industriële en bedrijfsmodellen, resulterend in miljoenen potentieel unieke ontwerpen. Het is echter mogelijk dat niet alle ontwerpen haalbaar of ecologisch of economisch wenselijk zijn. Ondanks de toename van het onderzoek naar de CE, bleef de toepassing ervan in de gebouwde omgeving beperkt, en dus was er beperkt inzicht in welke ontwerpen de beste ecologische en economische prestaties bieden en welke ontwerpen haalbaar zijn in een reële context.

Doelen van deze dissertatie

Omdat er zowel een gebrek aan toepassing van circulaire principes in de bouw, als aan kennis over die toepassing is, heeft dit onderzoek een ontwerpdoel en onderzoeksdoelen. De ontwikkeling van de circulaire bouwcomponent had tot doel de afwezigheid van dergelijke componenten in de praktijk aan te pakken. De onderzoeksdoelen waren bedoeld om de ontwikkeling van de CIK te ondersteunen en tegelijkertijd waardevolle methoden en kennis te genereren.

Het ontwerpdoel is **een circulaire keuken ontwikkelen die in de praktijk toepasbaar is en milieuvriendelijker presteert dan niet-circulaire keukens.** De focus ligt op de implementatie van het CIK binnen Nederlandse woningcorporaties (WOCO's) vanwege de gunstige context voor de ontwikkeling van circulaire componenten, maar de ontwikkelde keuken en de opgedane kennis zou van toepassing kunnen zijn op bredere sectoren.

Er werden vier onderzoeksdoelen geïdentificeerd om het ontwerpdoel te ondersteunen en tegelijkertijd methoden te ontwikkelen die toepasbaar zijn op andere circulaire bouwcomponenten. In de eerste plaats heeft dit onderzoek tot doel circulaire keukens te creëren die vanuit milieuoogpunt superieur zijn aan niet-circulaire keukens, terwijl ze toch toepasbaar blijven. Economische prestatie is cruciaal voor de toepasbaarheid, daarom is een life cycle costing (LCC) methode ontwikkeld. Onderzoeksdoel 1 (RG1) is daarom **het ontwikkelen van een LCC-methode die de economische prestaties van circulaire bouwelementen bepaalt.** Ten tweede is de identificatie van de best presterende varianten van circulaire bouwcomponenten op zowel milieu- als economische prestatie essentieel voor de besluitvorming bij het ontwerp van de CIK. Onderzoeksdoel 2 (RG2) is dan ook om **in kaart te brengen welke typen circulaire bouwcomponentvarianten ecologisch en economisch het beste presteren.** Ten derde hebben veel auteurs barrières en factoren voor een circulair gebouwde omgeving bestudeerd. Om deze barrières effectief aan te pakken, hebben besluitvormers echter een dieper inzicht nodig in het relatieve belang ervan, het voorkomen ervan in praktijkgevallen en hun impact op de haalbaarheid van componenten. Dergelijke kennis kan bijdragen aan betere ontwerp-, beleids- en besluitvormingsprocessen. Daarom is het derde onderzoeksdoel (RG3) **het trekken van lessen uit de keuzes van belanghebbenden in de CIK-ontwikkeling die kunnen helpen bij de toekomstige ontwikkeling van haalbare circulaire bouwcomponenten.** Ten slotte wordt de CIK ontwikkeld binnen een onderzoekscontext, wat tot andere ontwerpresultaten kan leiden dan wanneer er buiten deze context wordt ontwikkeld. Het analyseren van andere circulaire keukens kan inzichten opleveren over de toepasbaarheid van deze keukens en kan de ontwerpkeuzes die zijn gemaakt voor de CIK valideren. Het vierde onderzoeksdoel (RG4) is dus **identificeren welke typen circulaire keukens in de praktijk toepasbaar zijn, en de overeenkomsten en verschillen tussen deze keukens en de CIK onderzoeken.**

Aanpak en methoden

De onderzoeksaanpak combineert Research-through-Design (RtD) en Action Research (AR), waarbij cycli van het ontwerpen en beoordelen van circulaire keukenontwerpen plaatsvonden. In deze Acrtion Research-through-Design (ARtD)-aanpak werden belanghebbenden bij het ontwikkelen en testen van de CIK betrokken (in co-creatie), met als doel uitdagingen uit de echte wereld aan te pakken en tegelijkertijd bij te dragen aan kennisverwerving en implementatie van de CE in de gebouwde omgeving.

Het onderzoek begon met een ontwerpproces dat veel vragen opriep. Sommige van deze vragen vonden antwoorden in de bestaande literatuur, terwijl voor andere vragen geen relevante theorieën bestonden. Uit deze onderzoeken kwamen vier onderzoeksvragen naar voren, en deze vragen vormden de basis van de onderzoeksdoelen. Gezien de diversiteit van deze onderzoeksdoelen varieerden de gebruikte onderzoeksmethoden per doel. Niettemin bleef de overkoepelende aanpak consistent.

Een systematische ontwerpaanpak structureerde de ontwikkeling en het testen van circulaire bouwcomponenten. Het omvatte fasen als ‘proof-of-concept’, ‘prototype’, ‘demonstrator’ en ‘marktimplementatie’, die elk analyse-, synthese-, simulatie- (of test-) en evaluatieactiviteiten omvatten. Hoewel afwijkingen van het geplande proces meerdere iteraties en aanpassingen noodzakelijk maakten, verbeterde deze aanpak het begrip en vergemakkelijkte het de voortgang.

Resultaten

Resultaten onderzoeksdoel 1

In deze studie werden drie bestaande benaderingen voor LCC geïdentificeerd: Conventional LCC (C-LCC), Environmental LCC (E-LCC) en Societal LCC (S-LCC). Hoewel C-LCC doorgaans een één stakeholderperspectief heeft en scenario’s aan het einde van de levensduur over het hoofd kan zien, verbreedt E-LCC het perspectief om meerdere belanghebbenden te omvatten en houdt S-LCC rekening met zowel directe als indirecte kosten voor de samenleving. De bestaande methoden incorporeren echter niet volledig de complexe, meervoudige gebruikscycli die inherent zijn aan circulaire producten en componenten.

Om de ontwikkeling van circulaire producten te ondersteunen, zijn bestaande LCC-technieken aangepast om (1) producten te beschouwen als samengestelde entiteiten met verschillende gebruikscycli, (2) processen na gebruik op te nemen, (3) praktische informatie aan belanghebbenden te bieden en (4) functionele eenheden en systeemgrenzen op één lijn te brengen met levenscyclusanalyse (LCA). De ontwikkelde CE-LCC-methode (zie Figuur Sam.1) werd toegepast om CIK-varianten te vergelijken, waarbij de meest aanpasbare variant de gunstigste LCC-uitkomst op de lange termijn liet zien. Dit model helpt besluitvormers bij het beoordelen van de economische levensvatbaarheid van circulaire producten en ondersteunt zo de transitie naar duurzaamheid in de bouwsector.

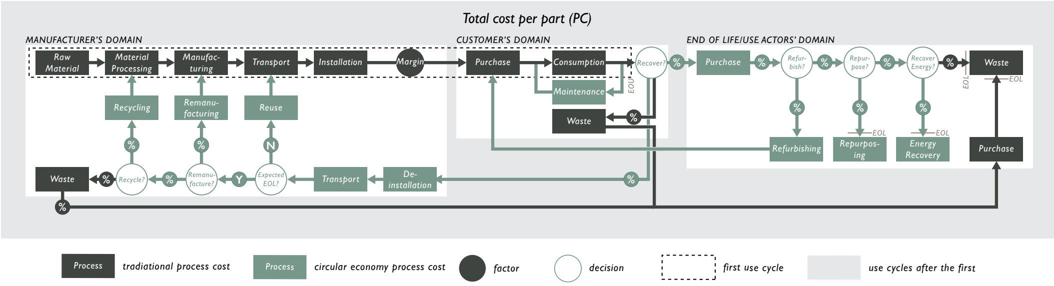


FIG. SAM.1 De algemene structuur van gebruikscycli van een onderdeel in het CE-LCC-model.

Resultaten onderzoeksdoel 2

Deze studie had tot doel de circulaire prestaties van bouwcomponenten te beoordelen, waarbij biologische (BIO) en technische (TECH) circulaire ontwerprichtingen werden vergeleken in termen van ecologische en economische prestaties. Er werd gebruik gemaakt van circulaire economie LCA (CE-LCA), waarvan de prestatie uitgedrukt werd in schaduwkosten, materiaalstroomanalyse (MFA) en CE-LCC, uitgedrukt in totale kosten (TC) om ontwerpvarianten van de CIK en een circulaire façade te vergelijken. Ranglijsten werden opgesteld op basis van de uitkomsten voor business-as-usual (BAU), BIO, TECH en hybride (HYBRID) ontwerpvarianten (zie Tabel Sam.1). Uit de resultaten bleek dat BIO-oplossingen het beste presteerden op het gebied van schaduwkosten, maar lager scoorden op het gebied van MFA en TC, terwijl sommige TECH-oplossingen de tegenovergestelde trend lieten zien. HYBRID-varianten toonden potentieel voor verbeterde prestaties door het combineren van BIO- en TECH-materialen.

TABLE SAM.1 Ranglijst van business-as-usual (BAU), biologische (BIO), technische (TECH) en hybride (HYBRID) varianten. In deze rangschikking is 1 de best presterende variant en 3 (keuken) of 4 (gevel) de slechtste.

Ontwerprichting	Component	Schaduwkosten	MFA	TC	Notities
BAU	Façade	2	3	2	Middelgrote milieu-impact, lage investeringskosten
	Keuken	3	3	2	Hoge milieu-impact, lage investeringskosten
BIO	Façade	1	4	4	Lage schaduwkosten, hoog materiaalverbruik, lage investeringskosten, hoge totaalkosten
	Keuken	1	2	3	Lage schaduwkosten, hoog materiaalverbruik, lage investeringskosten, hoge totaalkosten
TECH	Façade	4	1	3	Geen materiaalverbruik, hoge investeringskosten, hoge schaduwkosten, gedeeltelijke vervangingen leiden tot kleine verhogingen in alle impacts, hoge totale kosten
	Keuken	2	1	1	Laag materiaalverbruik, hoge investeringskosten, gedeeltelijke vervangingen leiden tot kleine verhogingen in alle impacts, lage totale kosten
HYBRID	Façade	3	2	1	Middelgrote milieu-impact, lage totale kosten

Belangrijk is dat BAU-componenten consistent slechter presteerder dan circulaire varianten, wat wijst op het potentieel voor het verbeteren van de ecologische en economische prestaties via circulaire ontwerprichtingen. Deze studie benadrukte de noodzaak om materialen en circulaire ontwerpprincipes effectief toe te passen, met als doel de impact op het milieu te verzachten, de levensduur te verlengen en meerdere toekomstige cycli voor componenten, onderdelen en materialen te introduceren. Dit versterkt het belang van de transitie naar circulaire bouwcomponenten voor een duurzamere gebouwde omgeving.

Resultaten onderzoeksdoel 3

Deze studie richtte zich op het identificeren van keuzes die belanghebbenden hebben gemaakt in de richting van een haalbaar circulair ontwerp en de impact van die keuzes, met als doel ontwerpers, beleidsmakers en besluitvormers te ondersteunen in andere circulaire ontwerpprocessen. Er is een longitudinale case study uitgevoerd van een circulaire bouwcomponent, de CIK. De onderzoekers hebben actief meegewerkt aan het ontwerp van het CIK, dat wordt weergegeven in Figuur Sam.2, het supply chain-model en het bedrijfsmodel gedurende vijf fasen, waarbij alle beslissingen van belanghebbenden werden gedocumenteerd. Door deze beslissingen te analyseren en te reflecteren op het ontwikkelingsproces zijn vijf lessen getrokken.

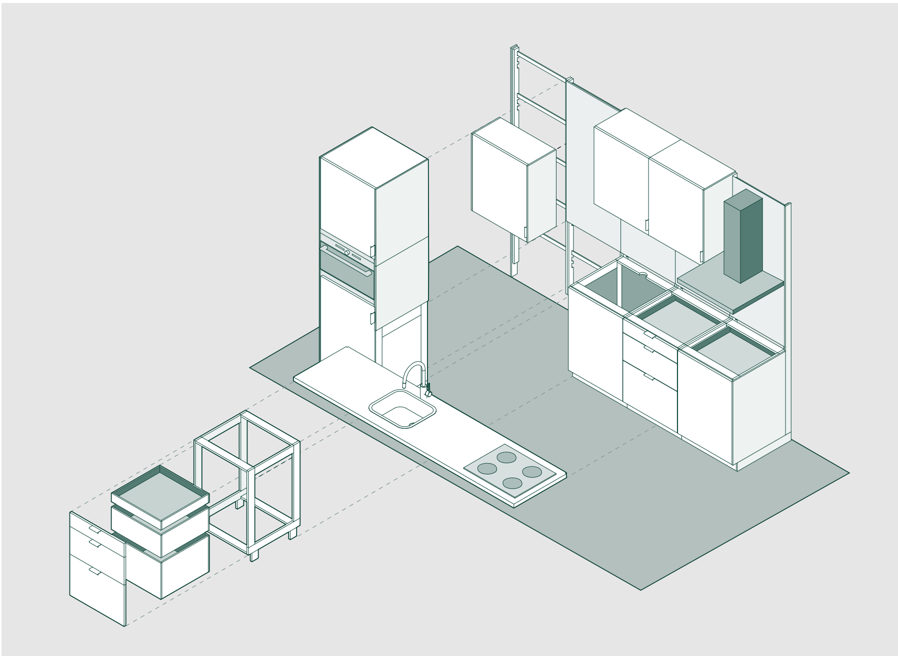


FIG. SAM.2 Het fysieke ontwerp van de CIK.

Les één benadrukte het belang van het prioriteren van haalbare circulaire ontwerpopties boven meer ideale circulaire opties, omdat de onmiddellijke implementatie van circulaire oplossingen gunstiger is voor een duurzamere gebouwde omgeving dan het uitstellen van de implementatie om een ‘meer circulair’ ontwerp te creëren. De tweede les onderstreepte het belang van de esthetiek van componenten voor brede acceptatie onder klanten en eindgebruikers, waarbij de noodzaak werd benadrukt om aan verschillende voorkeuren te kunnen voldoen. De derde les benadrukte de substantiële impact van beslissingen op detailniveau op de haalbaarheid en circulariteit van een component, waarbij gelijktijdig ontwerp op verschillende schaalniveaus werd aanbevolen. De vierde les benadrukte het belang van de participatie van belanghebbenden die de gehele keten representeren bij het op één lijn brengen van de waardepropositie en het garanderen van een effectieve projectfocus. Er werd voorgesteld om personen met optimale invloed, technische kennis en projecttoewijding erbij te betrekken. De vijfde les onthulde de noodzaak van voldoende tijd en middelen bij het overwegen van de integrale herontwikkeling van het fysieke ontwerp, het supply chain-model en het bedrijfsmodel.

Hoewel deze lessen misschien niet alle contexten volledig bestrijken, bieden ze wel inzicht in de besluitvorming tijdens de ontwikkeling van circulaire componenten, wat mogelijk kan bijdragen aan de toekomstige ontwikkeling van componenten.

Resultaten onderzoeksdoel 4

In dit onderzoek zijn zeven circulaire keukens, waaronder het CIK, geïdentificeerd en vergeleken om te bepalen welke typen circulaire keukens in de praktijk haalbaar zijn. Deze keukens zijn te zien in Figuur Sam.3a-g. Deze keukens werden vervaardigd door zowel gevestigde bedrijven als start-ups, waardoor verschillen in de mate van toegepaste innovatie zichtbaar werden. De gevestigde fabrikanten hadden de neiging zich nauwer aan te sluiten bij niet-circulaire keukenmodellen, terwijl start-ups radicalere innovaties implementeerden. Gedetailleerde informatie was vooral beschikbaar over het technische model, terwijl inzichten in industriële en bedrijfsmodellen relatief schaars waren.

Opvallend was dat de keukenontwerpen een tweedeling vertoonden op basis van materiaalkeuzes voor hun constructieve delen, met name tussen frameconstructies waarbij gebruik werd gemaakt van technische materialen (in dit geval staal) en op panelen gebaseerde constructies waarbij gebruik werd gemaakt van biologische materialen (verschillende typen variërend van multiplex tot cellulosepanelen). De CIK viel op door zijn bio-based framestructuur, die later door de fabrikant werd aangepast, wat de onhaalbaarheid ervan aangaf. Er werd ook een onderscheid opgemerkt met betrekking tot het gebruik van achterwanden, een kenmerk dat aanwezig is in zowel frame- als paneelkeukens.

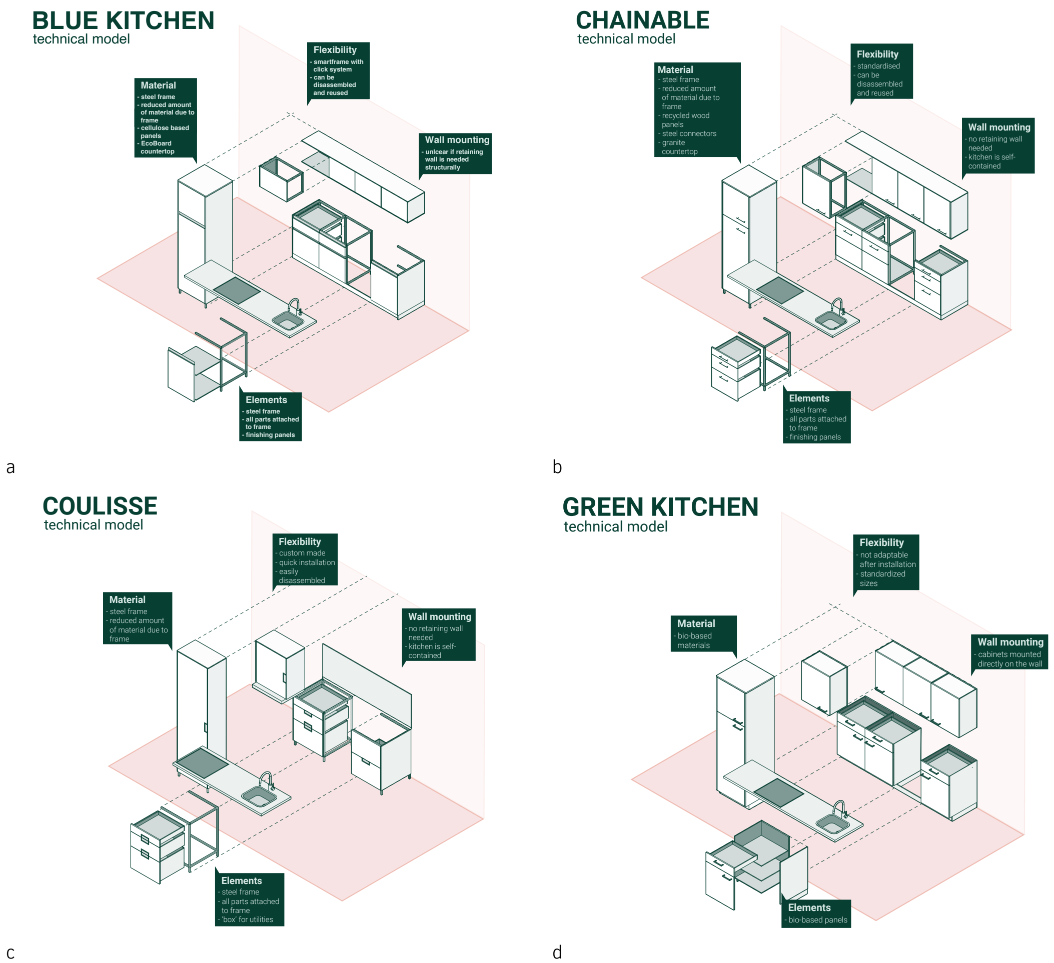
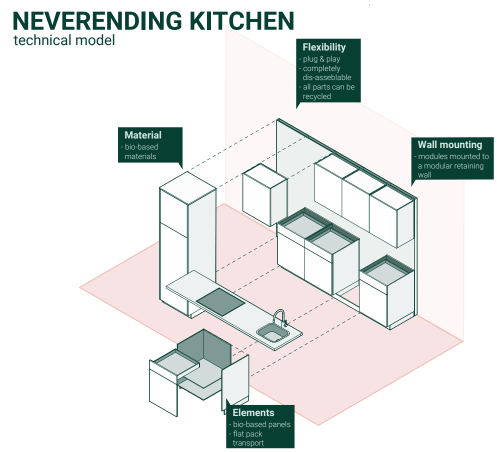


FIG. SAM.3 Technicsche ontwerpen van de (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, en (g) CIK.



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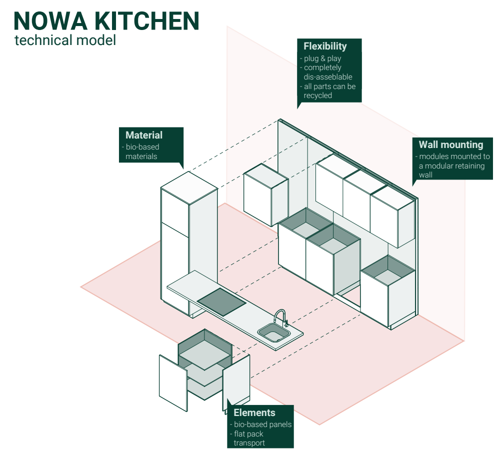

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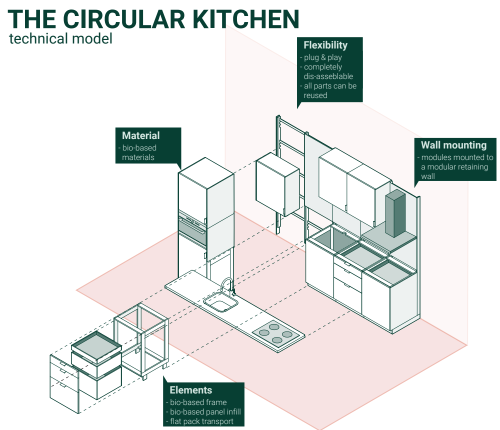

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FIG. SAM.3 Technicsche ontwerpen van de (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, en (g) CIK.

Alle onderzochte circulaire keukens gaven prioriteit aan circulaire ontwerpopties om het sluiten van toekomstige kringlopen te vergemakkelijken en zo hun milieuprestaties op de lange termijn te verbeteren. Het is echter cruciaal om te erkennen dat de haalbaarheid van circulaire keukentypen in de loop van de tijd kan veranderen, en dat de afwezigheid van bepaalde typen in de huidige praktijk niet noodzakelijkerwijs betekent dat ze onhaalbaar zijn. Bovendien, aangezien deze keukens recentelijk zijn ontwikkeld en geen enkele het einde van zijn levensduur heeft bereikt, blijft de mate waarin toekomstige kringlopen gesloten zullen worden en de daadwerkelijke voordelen die dat zal opleveren onzeker.

Hoewel dit onderzoek specifiek is voor de Nederlandse woningsector, biedt het waardevolle inzichten in haalbare technische modellen voor circulaire keukens. Dergelijke kennis kan de implementatie van toekomstige circulaire keukens vergemakkelijken, waardoor mogelijk de industriebrede standaardisatie wordt gestroomlijnd en de circulaire transitie wordt bevorderd. De studie benadrukt ook de ongelijkheid tussen ideale en haalbare circulaire ontwerpen in een onderzoekscontext, en circulaire keukens in de praktijk, waarbij het belang wordt benadrukt van het overwegen van marktimplementatie in dergelijke projecten.

Conclusies

De bouwsector speelt een cruciale rol bij het bevorderen van duurzaamheid, waarbij een verschuiving naar een circulaire economie (CE) het potentieel biedt om het verbruik van grondstoffen en afval te verminderen. Circulaire keukens onderscheiden zich als veelbelovende opties vanwege hun eenvoud in productie, bestaande standaardisatie, gestroomlijnde toeleveringsketens en gebruik binnenshuis, waardoor implementatie-risico's tot een minimum worden beperkt. Er kunnen verschillende strategieën worden gebruikt om circulaire bouwcomponenten zoals keukens te ontwikkelen, met als doel de kringlopen van grondstoffen te vernauwen, vertragen of sluiten.

Dit onderzoek was gericht op een haalbare circulaire keuken (CIK) die de impact op het milieu vermindert in vergelijking met de huidige, niet-circulaire keukens, waarbij woningcorporaties als primaire klanten werden benaderd vanwege hun aanzienlijke marktaanwezigheid en langetermijninvesteringsstrategieën. Om dit te bereiken zijn vier onderzoeksdoelen (RG's) gedefinieerd: het ontwikkelen van een LCC-methode voor de economische evaluatie van circulaire componenten

(RG1), het beoordelen van de ecologische en economische prestaties van circulaire bouwcomponentontwerpen (RG2), het trekken van lessen uit de keuzes van belanghebbenden bij de ontwikkeling van CIK (RG3), en het onderzoeken van de haalbare circulaire keukenontwerpen buiten het CIK-project (RG4).

Is het doel van het ontwikkelen van zo'n circulaire keuken bereikt? Was de CIK in de praktijk haalbaar en presteerde deze milieuvriendelijker dan de huidige, niet-circulaire keukens? En zo niet, welke strategieën zijn dan raadzaam om een betere circulaire keuken te ontwikkelen?

Conclusies over het ontwerpdoel

Alle geëvalueerde CIK-ontwerpen presteerden economisch en milieutechnisch beter dan de standaard niet-circulaire keukens. De laatste ontwerpvariant van de CIK, de TECH-keuken in Studie 2, behaalde de hoogste MFA-prestaties en de op een na hoogste in de CE-LCA. Omgekeerd blonk de BIO-keuken uit in CE-LCA en presteerde op één na best in de MFA. Terwijl het BIO ontwerpovereenkomsten vertoonde met niet-circulaire keukens, vereist de implementatie van TECH-ontwerpen substantiële veranderingen in de toeleveringsketen en het bedrijfsmodel. De onzekerheid die gepaard gaat met deze veranderingen heeft mogelijk negatieve gevolgen voor de milieuprestatie. Biologische ontwerpen bieden een grotere zekerheid qua milieuprestaties vanwege hun impact vroeg in de levenscyclus, onafhankelijk van de toekomstige toepassing van waardebehoudprocessen (VRP's), zoals hergebruik, herfabricage en recycling. Economische haalbaarheid staat voorop, waarbij belanghebbenden de nadruk leggen op kostenminimalisatie en kostenneutraliteit met niet-circulaire keukens – met een focus op initiële kosten. Ondanks de hogere initiële kosten bleek de meest aanpasbare CIK-variant gedurende langere perioden kosteneffectief, wat wordt bevestigd door het tweede onderzoek waarin TECH- en BIO-keukens werden vergeleken. De haalbaarheid in de echte wereld was echter beperkt, zoals werd waargenomen in onderzoeken drie en vier. Woningcorporaties geven nog steeds spaarzaam prioriteit aan de totale kosten (of total cost of ownership (TCO)), en massaproductie van CIK's vergt aanzienlijke investeringen in nieuwe productiefaciliteiten. Bovendien viel het besluit om deze investeringen te doen samen met onvoorziene negatieve feedback die werd ontvangen na het plaatsen van demonstratiekeukens in verschillende woningen. Bijgevolg slaagde het CIK er niet in om de onderzoeksfase te ontstijgen. Kortom, het ontwerpdoel werd niet bereikt en de CIK werd niet toegepast in de echte wereld. Desalniettemin werden de lessen uit het CIK-onderzoeksproject gebruikt om een ander, minder ambitieus circulair keukenontwerp verder te ontwikkelen dat in de nabije toekomst moet worden geïmplementeerd.

TOC

Reflecties

Dit onderzoek heeft circulaire keukens uitgebreid onderzocht in vier onderzoeken, en heeft inzichten opgeleverd die verder gaan dan individuele bevindingen. Dit laatste deel presenteert daarom drie inzichten: het verbeteren van de haalbaarheid van circulaire keukens, het ontwerpen voor een circulaire gebouwde omgeving en het vergroten van de rol van de circulaire economie op het gebied van duurzaamheid. Deze reflecties bieden implicaties voor de praktijk en suggereren mogelijkheden voor toekomstig onderzoek.

Reflecties op betere, meer haalbare circulaire keukens

Zoals uit de paragraaf "Conclusies over het ontwerpdoel" kan worden geconcludeerd, was het CIK-ontwerp niet haalbaar in de context waarin toegepast zou moeten worden. Maar hoe kan een circulaire keuken in deze context haalbaar zijn? En hoe zou die haalbare circulaire keuken toch betere milieuprestaties kunnen opleveren dan de huidige standaardkeuken?

Onderzoek vier toont de uiteenlopende benaderingen van start-ups en gevestigde fabrikanten bij het ontwikkelen van circulaire keukens. Terwijl start-ups radicaal innoveren, kiezen gevestigde fabrikanten, zoals de producent van het CIK, voor stapsgewijze verbeteringen (buiten een onderzoekscontext). Dit suggereert dat bij het streven naar grootschalige implementatie, die alleen haalbaar is met grote productiecapaciteit, prioriteit moet worden gegeven aan de haalbaarheid van het ontwerp, terwijl de milieuprestaties nog steeds verbeteren in vergelijking met de huidige, niet-circulaire keukens. Haalbaarheid wordt bereikt door de initiële kosten te verlagen en productiemethoden en toeleveringsketens af te stemmen op huidige industriestandaarden. Het verbeteren van de milieuprestaties omvat het toepassen van materialen met een lage impact of een langere levensduur, het vertragen van potentiële lussen door standaardisatie, modulair ontwerp en demonteerbare verbindingen, en het vergemakkelijken van reparaties en vervangingen waar mogelijk voor minimale kosten.

Voor fabrikanten die zich richten op geleidelijke groei in plaats van onmiddellijke grootschalige marktacceptatie, wordt radicale innovatie voor optimale milieuprestaties haalbaar. Dit houdt in dat grondstofkringlopen vooraf worden vernauwd en toekomstige kringlopen worden vertraagd en gesloten via verschillende

TOC

ontwerpstrategieën. Ontwerpbeslissingen kunnen gebaseerd zijn op de haalbaarheid van de totale kosten, en ontwerpen kunnen productiemethoden, bedrijfsmodellen en toeleveringsketens toepassen die verschillen van de huidige industriestandaard. Desalniettemin is het verzekeren van productie, verkoop, hergebruik en recycling van cruciaal belang, waarbij voortdurende inspanningen gericht moeten zijn op het verbeteren van de financiële levensvatbaarheid om het marktaandeel, en daarme de milieu-winst, te vergroten. Deze prioriteiten zijn weergegeven in Figuur Sam.4.

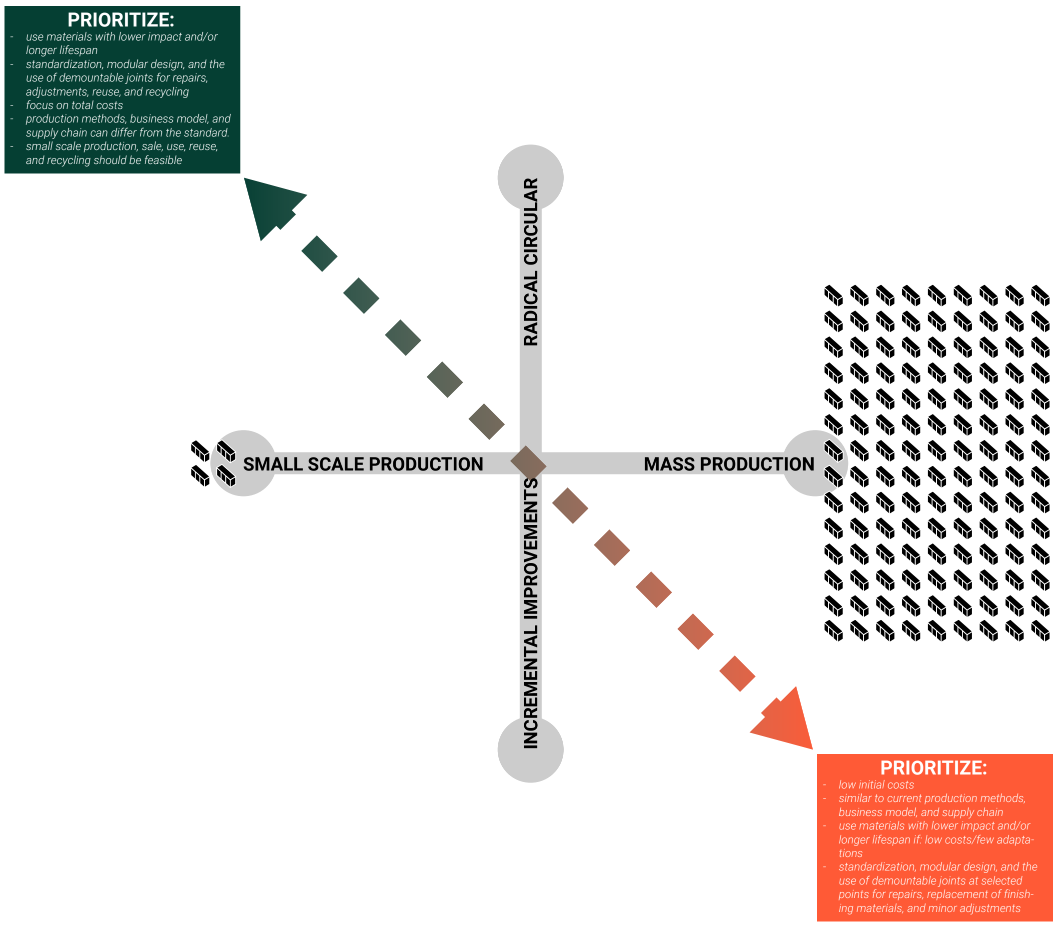

FIG. SAM.4 Circulaire ontwerpprioriteiten gebaseerd op de beoogde initiële productieschaal

Reflecties op ontwerpen voor een circulaire gebouwde omgeving

De productie van gestandaardiseerde modulaire bouwcomponenten als producten vereist een aanzienlijke heroverweging van ontwerpmethodologieën vanuit zowel product- als gebouwontwerpperspectieven. Hoewel wetenschappers op het gebied van de ontwerptheorie erkennen dat veel ontwerpfasen in de praktijk de neiging hebben elkaar te overlappen of gelijktijdig plaatsvinden (Milton & Rodgers, 2011), stellen product- en architectuurontwerptheorieën doorgaans een ontwerpproces met meerdere, elkaar opvolgende fasen voor (Ginting, 2020; Roozenburg & Eekels, 1995; Ulrich & Eppinger, 2008). In de eerste fasen is het ontwerp abstract (of globaal) en in de daaropvolgende fasen krijgt het geleidelijk meer gedetailleerde specificaties – convergerend van globaal naar gedetailleerd.

Uit de derde studie van dit proefschrift blijkt echter dat het succesvolle ontwerp van modulaire bouwcomponenten sterk afhankelijk is van beslissingen met betrekking tot verbindingen, productiemethoden en materialen die conventioneel in de latere fasen van het ontwerpproces worden genomen. Daarom zijn de conventionele ontwerpmethoden mogelijk niet toereikend en is een alternatieve aanpak nodig. Deze aanpak geldt zowel voor ontwerpen op gebouw- als op componentniveau.

Ontwerpers moeten vroegtijdig het gewenste niveau van modulariteit bepalen en de focus binnen het ontwerpproces daarop aanpassen. Een volledig gestandaardiseerd modulair gebouw of onderdeel vereist vanaf het begin een gedetailleerde ontwerpbenadering, divergerend richting de globale schaal. Enkele voorbeelden van deze aanpak zijn al te zien in de Nederlandse sociale woningbouwsector, bijvoorbeeld in de nieuwbouw modulaire woningen van de Bouwstroom (Aedes & VTW, 2022). Omgekeerd kan een volledig op maat gemaakt gebouw de traditionele convergerende ontwerpbenadering volgen. Ontwerpen die noch een gestandaardiseerde modulaire aanpak volgen, noch een volledig op maat gemaakte aanpak, vereisen mogelijk zowel het globale als het gedetailleerde niveau als startpunt van het ontwerpproces. Figure 1.10 toont dit voorstel voor een dergelijke selectie van ontwerpmethoden op basis van de mate van gestandaardiseerde modulariteit. Net als bij conventionele ontwerpfasen kunnen ontwerpiteraties heen en weer gaan tussen fasen – een ontwerpproces is zelden lineair. Daarom geeft deze figuur slechts een of meerdere startpunten voor het ontwerpproces aan, en een prioriteit en algemene richting.

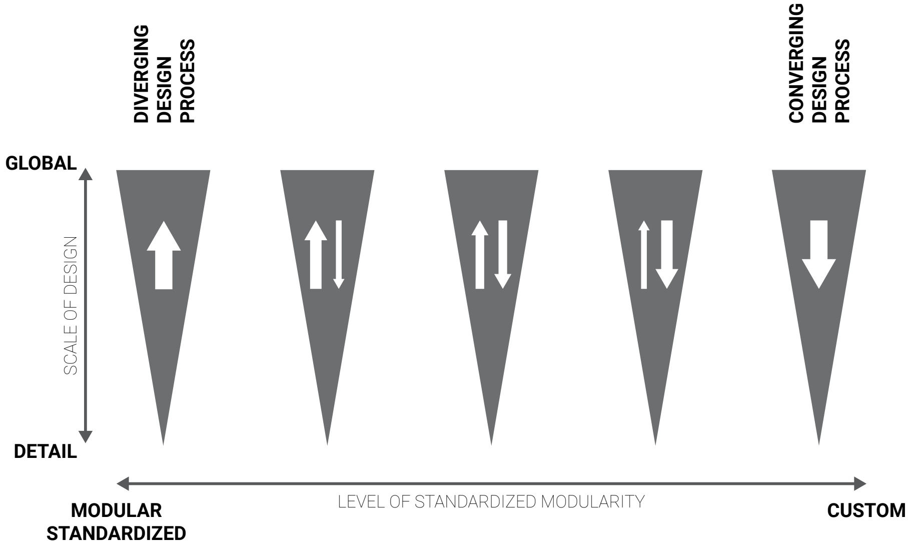

FIG. SAM.5 Implicaties van de mate waarin gestandaardiseerde, modulaire bouwcomponenten worden toegepast op het ontwerpproces, waarbij witte pijlen de richting van het ontwerpproces impliceren. De rechtse situatie weerspiegelt de huidige, traditionele praktijk, en de links een situatie die geoptimaliseerd is voor modulariteit.

Reflecties op het vertragen en sluiten van grondstoffenkringlopen

De CE biedt potentiële oplossingen om het gebruik van grondstoffen, de negatieve gevolgen voor het milieu en de verspilling in de gebouwde omgeving terug te dringen, maar het blindelings nastreven van circulariteit kan de milieuproblemen verergeren. Dit onderzoek benadrukt de noodzaak om onderscheid te maken tussen circulaire strategieën bij het bevorderen van duurzaamheid binnen de gebouwde omgeving. Uit studie 2 blijkt dat niet alle circulaire ontwerpopties de milieuprestaties verbeteren en soms zelfs het gebruik van grondstoffen en de afvalproductie vergroten. Bovendien vereisen circulaire componenten vaak hogere investeringen vooraf, met alleen potentiële voordelen op de lange termijn. Studie 3 identificeert uitdagingen bij het ontwikkelen van componenten voor toekomstige VRP's, waarvoor veranderingen in bedrijfsmodellen, toeleveringsketens en ontwerpmethodologieën nodig zijn. Hoewel er haalbare veranderingen bestaan, worden deze vooral waargenomen bij kleinschalige productie. Ontwerpen voor toekomstige VRP's introduceert onzekerheid vanwege het verre tijdsbestek waarin ze milieuvoordelen opleveren en de afhankelijkheid daarbij van samenwerking met belanghebbenden op de lange termijn. Componenten die afhankelijk zijn van toekomstige VRP's hebben mogelijk meerdere gebruikscycli nodig om superieure milieuprestaties te bereiken, wat de onzekerheid over hun voordelen vergroot.

Daarom benadrukt dit onderzoek het belang van het prioriteren van strategieën met onmiddellijke milieuvoordelen vanwege de risico's en uitdagingen die gepaard gaan met het behalen van voordelen op de lange termijn door middel van bouwcomponenten die zijn ontworpen voor toekomstige VRP's. Strategieën als Refuse, Rethink en Reduce, samen met het vervangen van materialen met een hoge impact door hernieuwbare materialen met een lage impact en het vertragen en sluiten van bestaande materiaalkringlopen zijn cruciaal voor het consequent bereiken van een duurzamere gebouwde omgeving. Concluderend kunnen we stellen dat niet alle circulaire benaderingen gunstig zijn voor de milieudoelstellingen op de korte of lange termijn, vanwege het gebrek aan verbetering van de milieuprestaties of de haalbaarheid ervan.

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1 Introduction

1.1 Towards a sustainable built environment

In recent years, numerous reports have highlighted the long-lasting and, in some cases, irreversible consequences of global warming surpassing 1.5°C. For instance, the destruction of entire ecosystems and a fourfold increase in the negative economic impact of additional heating and cooling effects before the year 2100 serve as alarming examples (IPCC, 2018; World Green Building Council, 2019).

Although housing is one of the fundamental needs of mankind, the building sector accounts for between 25% and 40% of energy-related global greenhouse gas (GHG) emissions, of which 72% is caused by operational energy use, and 28%[1] is caused by energy used in the material production and construction stage (embodied GHG emissions, or embodied carbon) (International Energy Agency (IEA), 2018; Ness & Xing, 2017; WEF, 2016; World Green Building Council, 2019) . Moreover, the building sector is the world's largest consumer of raw materials (Pomponi & Moncaster, 2017), accounting for 40% of all material consumption. These numbers are set to increase, as the global building stock is expected to double by 2050 (International Energy Agency (IEA) & Global Alliance for Buildings and Construction., 2019), and the total global extraction of primary materials is expected to triple by 2050 (Gallego-Schmid et al., 2020). Consequentially, 90% of biodiversity loss would be caused by resource extraction and processing (United Nations Environment Programme (UNEP) et al., 2019). Simultaneously, the sector is experiencing resource scarcity (Eberhardt et al., 2021), which also leads to increasingly volatile and higher raw material prices (Gallego-Schmid et al., 2020).

1 The World Green Building Council has also reported that "these figures may be higher as they do not include transport to site and chemical conversion process emissions released during the manufacturing of a number of key construction materials."

Finally, around 10-15% of the materials used in buildings are wasted during construction (Eberhardt et al., 2021; Gallego-Schmid et al., 2020), and the building sector is responsible for 40% of all global waste (Ness & Xing, 2017). More than a billion tons of construction and demolition waste[2] is expected annually from 2020 onwards in the European Union (EU) (Jiménez-Rivero & García-Navarro, 2017).

Therefore, a transition to a more sustainable built environment is paramount to ensure the stability of the global economy and natural ecosystems. Geissdoerfer, Savaget, Bocken, & Hultink (2017, p. 759) present a comprehensive definition of sustainability as " the balanced and systemic integration of intra and intergenerational economic, social, and environmental performance." Previous research and efforts in the building industry have predominantly concentrated on decreasing the operational energy consumption and emissions of buildings (Ness & Xing, 2017). However, reducing resource consumption can lead to both a reduction of (embodied) GHG emissions, waste production, and biodiversity loss (Kennedy et al., 2007; Ness & Xing, 2017; Pomponi & Moncaster, 2017; Wijkman & Skånberg, 2015). Consequentially, strategies towards a more sustainable built environment need to include a reduction in resource consumption.

1.2 A circular built environment

The Circular Economy (CE) could offer a solution to achieving a more sustainable built environment by minimizing resource use, environmental impacts, and waste. Geissdoerfer et al. (2017, p. 759) state that the 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". Slowing loops means to extend the lifespan of a building, a building component (such as a façade or roof), subcomponent (such as a window frame including glazing) or part (such as glazing); narrowing loops is to reduce resource use or enhance resource efficiency; closing loops is to recycle materials from end-of-life back to production (Bocken et al., 2016). These loops can both be 'open' and 'closed', influencing the overall shape

2 Half of this amount is excavation material.

of a CE system. Closed loops, as seen in recycling theory and circular supply chains, involve the recycling or reuse of resources within a closed network of partners (Genovese et al., 2017). This approach allows for greater control over resource flows and incentivizes the development of easily repairable and reusable designs. On the other hand, an open-loop CE involves the circulation of resources between users through platforms and companies that offer make, use, and re-make services (French & Laforge, 2006). While this facilitates ongoing access to resources, it may pose challenges in terms of stakeholder fragmentation and resource control.

Various authors have argued that a CE – like sustainability – should include the ‘triple bottom line’ of economic, environmental, and social performance (Geissdoerfer et al., 2017; Hunkeler et al., 2008; Sassanelli et al., 2019). Nevertheless, a focused approach to circularity is adopted in this dissertation, prioritizing the environmental and economic. The social performance is of critical importance for achieving overall sustainability, however, its inclusion adds complexity that would have reduced the feasibility of this research[3].

Value retention processes (VRPs) (also called R-imperatives) such as repair, reuse, remanufacture, recycle, follow from the strategies of slowing, narrowing, and closing loops and operationalize the CE (Blomsma & Brennan, 2017; Nasr et al., 2018; Reike et al., 2018). Figure 1.1 shows the visualization of the CE in the ‘Butterfly Model’, in which VRP’s are included. Multiple R-frameworks have been proposed, ranging from 3 to 10 R-imperatives, in which the 3R framework generally includes (1) Reduce, (2) Reuse, and (3) Recycle, while the frameworks that include more R-imperatives vary in which R’s are included, and in their definition. The exact origins of the R-frameworks remain difficult to trace (Kirchherr et al., 2017; Sihvonen & Ritola, 2015), and consensus on which framework should be used is lacking. For this dissertation, the R-framework and the definition of the R-imperatives of Reike et al. (2018) and Nasr et al. (2018) were adapted to specifically consider building components, see Table 1.1 for and overview.

3 Attempts were made to include the tenants, who would be the end-users, in the research through interviews regarding their acceptance of the circular kitchen. However, due to the COVID-19 pandemic delayed the kitchen placements and complicated contact with tenants.

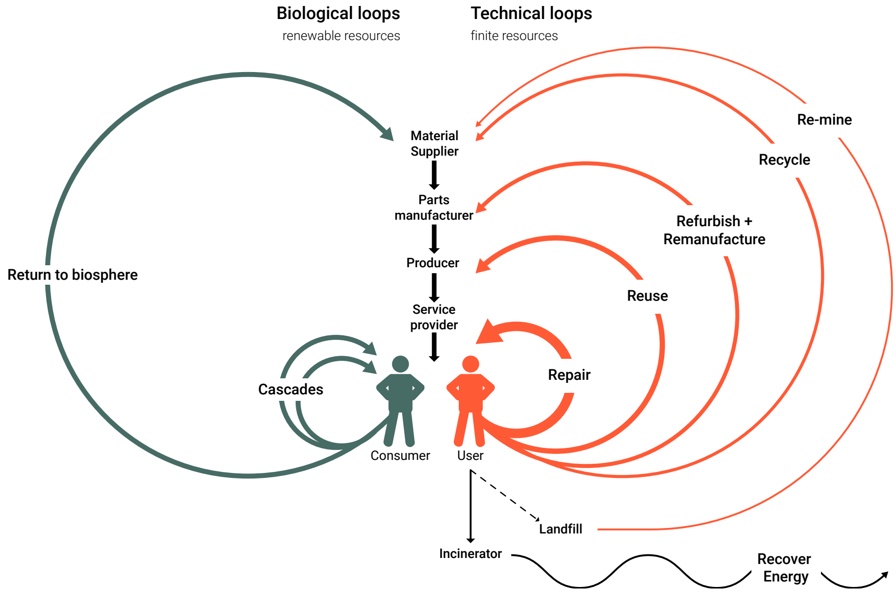

FIG. 1.1 CE system diagram, adapted from the Ellen MacArthur Foundation (2017) and Reike et al. (2018)

TABLE 1.1 Value Retention Processes adapted from Reike et al. (2018) and Nasr et al. (2018).

	R#	VRP	Definition
Closing loops	R9	Re-mine	Extracting materials from landfills and other waste plants
	R8	Recover energy	Producing energy by incinerating materials
	R7	Recycle	Processing used products/components, subcomponents, and parts into secondary materials that can be re-applied elsewhere, without retaining the original product structure.
Slowing loops	R6	Repurpose (Rethink)	Adapting discarded products/components, subcomponents, and parts for new functions, giving them a distinct new lifecycle
	R5	Remanufacture	Disassembling, checking, cleaning, and repairing or replacing parts of a multi-part product/component in an industrial process to bring it up to its original state
	R4	Refurbish	Replacing or repairing many subcomponents/parts of a multi-part product/component while maintaining its overall structure, resulting in an upgraded product/component
	R3	Repair	Restoring a product/component to its working order, addressing minor defects and replacing broken parts, with the aim of extending its lifespan and functionality
	R2	Reuse/Resell	Selling previously owned products or using them again without significant modifications or repairs
Narrowing loops	R1	Reduce	Use less (primary) materials per product/component or use fewer products/components in total.
	R0	Refuse	Refrain from buying and producing

1.3 The building component approach in the dutch context

1.3.1 Circularity the Netherlands

The Netherlands has expressed the ambition to create a 'fully circular' economy by 2050, and to reduce primary resource use – defined as minerals, fossil, and metals – with 50% by 2030 (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). In 2017 the Government signed a nation-wide agreement to accelerate the transition to the circular economy (VNO-NCW et al., 2017). Since then – the beginning of this research – the government has published or commissioned multiple reports on the realization of a circular built environment. In 2018 a 'transition agenda' for a circular built environment was published (Transitieteam Circulaire Bouweconomie, 2018) describing how a strategy to reach this goal set for 2050 in the built environment in three stages: (1) making an inventory of what is needed to reach the goal, which would take place between 2018 until 2021, (2) reaching 50% of the end-goal between 2021 and 2030, and (3) reaching the final goal between 2030 and 2050. Building on this transition agenda, the 'transition team circular built environment' published a report describing a roadmap to reaching the goals for 2030 (Transitieteam Circulaire Bouweconomie, 2022). This roadmap was developed in collaboration with existing initiatives across the building and infrastructure sector. Some examples are the Betonakkoord and the Staalakkoord, that aim to make concrete and steel more sustainable in the construction industry, respectively (Betonakkoord Voor Duurzame Groei, 2018; Bouwen met Staal, 2022), Duurzaam GWW that aims to make rail, ground, water and road construction more sustainabile (Stuurgroep van de Green Deal Duurzaam GWW, 2021), and Platform CB'23 that aims to connect all parties in the building sector with circular ambitions to draw up national, construction sector-wide agreements on circular construction before 2023 (Platform CB'23, n.d.).

This multitude of initiatives, and the increasing number of CE conferences, networks, consultancy firms, and publications dedicated to promoting circularity in the Netherlands shows that the CE has gained momentum. The alignment between governmental policy on one side and stakeholder interest on the other creates a favorable environment for innovative research and implementation of circular practices in the built environment. The Dutch context offers opportunities to explore and evaluate different approaches, strategies, and technologies that contribute to the transition towards a circular built environment. By capitalizing on these factors, valuable insights can be gained, enabling the identification of effective solutions and the advancement of circularity not only within the Netherlands but also globally.

1.3.2 The Dutch housing sector

Residential buildings constitute the majority of the Dutch real estate, accounting for over 87% of all registered addresses in the country (CBS, 2023a). Within this housing sector, imminent renovation efforts to reduce operational energy use, combined with housing availability challenges, are expected to generate substantial embodied environmental impacts. Plans are in motion to insulate 3.5 million homes, transition 1.5 million homes to gas-free installations (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a), and an estimated one million homes need to be constructed to fulfill the housing demand (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022b). To ensure compliance with national climate change mitigation policies and to prevent exceeding the levels of embodied impacts as agreed upon in the National Climate Agreement (National Climate Agreement – The Netherlands, 2019), regulations for the environmental impact of new buildings will become stricter in the coming years, insulating homes with renewable resources will be stimulated (Kamerbrief over Beleidsagenda Normeren En Stimuleren Circulair Bouwen, 2022), and the government states that the applied renovation solutions should align with the principles of the circular economy (CE) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a).

Housing associations (HAs) in the Netherlands, owning and managing 2.3 million of the 8 million homes in the country (CBS, 2023b), play a significant role in achieving a circular built environment. Their substantial demand provides incentives for supply chain partners to develop circular alternatives, and their long investment perspective makes them well-suited for implementing CE principles. Additionally, the adoption of circular business models may lead to cost savings resulting in lower Total Costs of Ownership (TCO). The cost savings achieved through circular business models can be allocated towards improving housing affordability, enhancing the condition of additional dwellings, and increasing the number of newly built homes, thereby benefiting a greater number of residents and ensuring the long-term sustainability of their housing stock. Therefore, this research primarily focuses on the application of the CE within the Dutch housing associations, while recognizing the potential transferability and benefits of these solutions to other sectors as well.

1.3.3 An integral approach

Authors such as Bocken et al. (2016), Mendoza et al. (2017), Pomponi and Moncaster (2017), Saidani et al. (Saidani et al., 2017), and van Stijn (2023) highlight the need for an integral approach to circular design. Most authors argue that developers and designers should not only focus on the physical design (or technical model) of a circular product, component or part, but should also consider the business model to incentivize circular use. For example, if it is significantly cheaper to discard and buy a new product, component or than it is to reuse one, it will be unlikely that it will be reused – even though its physical design might allow for easy reuse. Similarly, if no stakeholder will collect or organize the reuse of the product, component, or part, it will most likely not be reused either. Therefore, the supply chain (or industrial model) should be considered as well.

1.3.4 The building component approach

Several authors argue that achieving circular design requires a "systems approach" (Bocken et al., 2016; Kirchherr et al., 2017; Pomponi & Moncaster, 2017), which involves considering the entire design system, ranging from the macro to the micro-scale. The design system for the built environment can be divided in multiple ways. Jager's model illustrates the relationship between the building system and the product level by dissecting the building into products and parts (Jager, 2002). Brand's theory, based on the idea that buildings change at different rates, identifies different layers or components within a building system that have varying lifespans (Brand, 1994). By considering the interactions and varying lifespans of these layers, adaptability, longevity, and reduced environmental impact over time can be ensured. The design system that is applied in this research can be seen in Figure 1.2.

However, redeveloping a whole building system to be circular is not a feasible goal within a 4-year research project. Therefore, this research applies a building component approach to creating a circular built environment while considering the interactions with other layers, and as such is part of a recent school of research. Arguments to apply this approach differ between authors. For example, (van Stijn, 2023) – who developed 8 circular building components – argues that the building component approach offers the most potential to narrow, slow and close loops. According to Azcarate-Aguerre (2023), the component approach can simplify the implementation of different business models. Azcarate-Aguerre (2023) conducted research on the implementation of a Product-Service System approach for one component of the building: the facade, aiming to enhance the circularity and clean energy transitions in new buildings and extensive renovations.

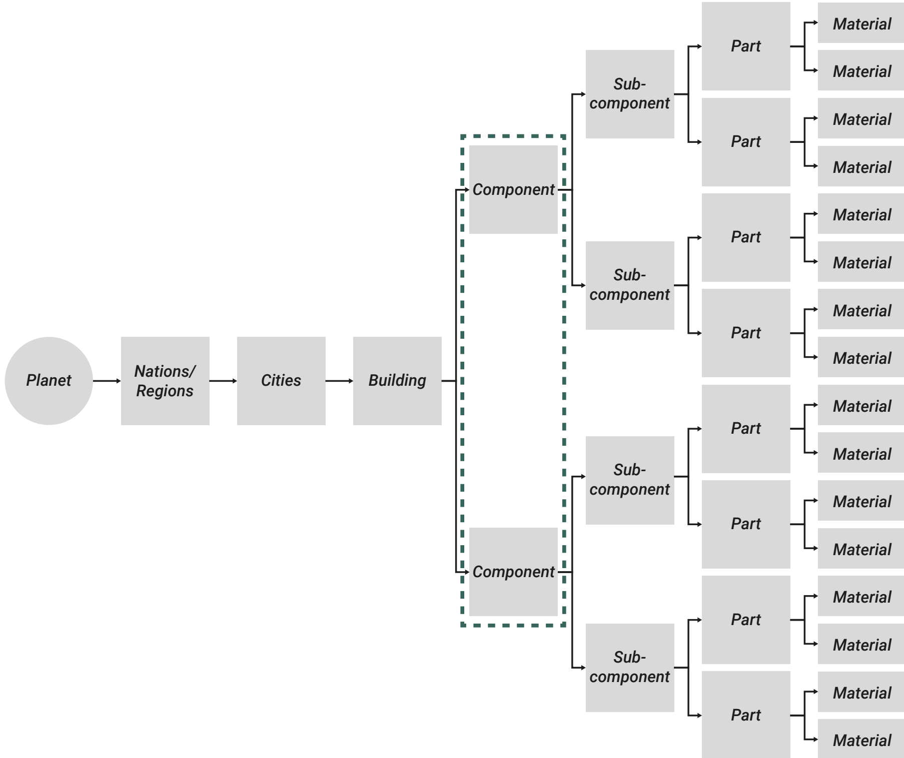

FIG. 1.2 Systems approach for circular design in the built environment: focusing on building component level

Furthermore, the maintenance and construction practices in both existing and new buildings often follow a component-based approach. These components, which have diverse functional requirements, are generally produced by different stakeholders in various locations and assembled on-site. Throughout the building's lifespan, these components undergo maintenance and replacement at different intervals due to their varying lifespans. This component-based approach provides an opportunity to implement targeted CE strategies that align with specific demands and benefits of the component. Consequently, a component approach, in which building components are substituted by circular components during renovation, maintenance, or new construction, can be a viable way to transition to a circular built environment.

1.3.5 Circular kitchen

A building consists of many components, such as a roof, façade, elevator, and a kitchen. These components differ in terms of complexity, lifespan, context-specificness, costs, investment risk, supply chain fragmentation, approach of application (project-wise versus continuous processes), and production method (one-off versus mass production) (van Stijn et al., 2023). This research is designed around the development process of a circular kitchen (the CIK), while generating knowledge from and for other circular building components as well.

While the environmental impact benefits of circularizing an individual kitchen may not be as substantial as those of a façade, the potential for successful kitchen implementation – i.e. widespread market adoption – could be higher. This higher likelihood of successful kitchen implementation offers the potential for more substantial overall environmental benefits.

There are several reasons why the likelihood of a circular kitchen being successful can be higher. First, kitchens have a relatively low complexity, generally being applied in similar indoor circumstances and not facing any weather conditions. Having to account for fewer parts that each have their specific function in the component, and having a less fragmented supply chain than most other building components decreases the risk of the components not being feasible. In this research, feasibility is defined as the extent to which application in practice is achievable. Second, kitchens are largely standardized as a result of ergonomics, and are mass produced. The application of a system of standardized modular parts to benefit VRPs is, therefore, more feasible. Third, their relative low investment costs for the clients makes investment in a circular kitchen more likely, as the financial risk is reduced. Due to the relative low costs of kitchens, prototyping, which is seen as beneficial for the development of circular components (Dokter et al., 2023), becomes more feasible for the kitchen manufacturers. Finally, due to the relatively short service life of kitchens and their frequent replacement (approximately 20 years in the Netherlands), there is a continuous demand for their production. This presents a favorable opportunity for investing in machinery to manufacture kitchens and their components.

1.4 Problem statement

There are many ways to develop circular building components such as a circular kitchen. Strategies for narrowing, slowing, and closing loops can be applied either separately or in combination, different types of materials can be applied, and circular variants for the technical model, industrial model, and business model can be developed. According to a circular building component design tool developed by van Stijn & Gruis (2019) – based on an extensive review of design frameworks for CE – there are 127 design options for the technical model, 92 options for the industrial model, and 125 options for the business model. As these options could theoretically all be combined, there are 3,58 ´ 10^{103} unique circular designs for a building component[4].

However, not all of these outcomes are desirable. For example, some designs might not reduce resource use, waste, and GHG emissions compared to linear building components, and thus might not contribute to a more sustainable built environment. Furthermore, some designs might have high investment costs, or a high total of all the costs that occur during their lifespan, and would not be feasible. Therefore, researching circular building components is needed to gain insights into the desirability and feasibility of different designs.

Although the number of articles published on the subject of CE had risen from under 20 publications in 2013 to over a 100 in 2016 (Geissdoerfer et al., 2017), research on applying the principles of CE in the built environment was still in its infancy (Ness & Xing, 2017). It was unknown which designs for circular building components would have the best environmental performance in theory – i.e., reduce resource use, waste, GHG emissions the most. Neither was known which designs for circular building components would have the best economic performance in theory – i.e., have the lowest total costs throughout the lifespan of the component. Furthermore, not all of the possible designs would be feasible in practice. Barriers for the implementation of circular design options in the built environment can be found in literature (see Adams et al. (2017), Akinade et al. (2020), Cruz Rios et al.

4 In a theoretical scenario where a circular component design allows for various combinations of options (the total number of options being 127+92+125=344 options), the total number of unique options is calculated as 2^344=3.58×10^103. This number includes the possibility of not applying any circular design options, which could result in a linear design or the strategic decision to ‘refuse’ building a component. Notably, if similar combinations can lead to multiple different designs, the number of possibilities becomes even higher.

(2021); Hart et al. (2019), or Kanters (2020) for example). Although these barriers are useful, designers, policymakers, and other decision-makers that influence the implementation of circular building components could benefit from knowledge of the relative importance of these barriers in the development process. Moreover, they could benefit from in-depth analysis of when and how the barriers (re)occur in our real-world case, how they were or could be overcome, and how they in-fluence the feasibility of a component. However, there were very few examples of circular building components at the start of this research. For example, when one would search for a circular kitchen online in 2018, the only images that would be found were those of a kitchen that has a concentric shape, which can be seen in Figure 1.3.

FIG. 1.3 The Acropolis concentric kitchen, made by Snaidero (Snaidero Rino Spa, n.d.).

Therefore, the following gaps can be identified: (1) a lack of knowledge on which circular building component designs are the most circular and how they can be made feasible, and (2) a lack of circular building components that can be applied in practice to reduce waste, resource consumption, and GHG-emissions. The subsequent section outlines how this research aims to fill these existing gaps.

1.5 Dissertation goals & methods

To address the gaps identified in Section 1.4, this research has a design goal and research goals. The development of the circular building component aimed to address the absence of such components in practice. The research goals were designed to support the development of the CIK while also generating valuable methods and knowledge.

1.5.1 Design goal

The design goal of this research is twofold. First, the CIK aims to improve the environmental sustainability of kitchens compared to the current market standard. Second, to ensure environmental improvements across the building sector, it strives for widespread market adoption by being feasible for both manufacturers and clients. This means meeting functional requirements similar to, or better than the current market standard and being economically viable throughout the entire lifecycle of the kitchen, including production, purchase, ownership, and possible VRPs. The design goal (DG) can, therefore, be described as follows:

DG: To develop a Circular Kitchen that is feasible in practice and performs better environmentally than non-circular kitchens.

The development of the CIK is primarily focused on its application by Dutch HAs, given the favorable context for circular building component development in the Netherlands, as outlined in section 1.3.1. HAs are a logical target group for such components, as explained in section 1.3.2. However, it is important to acknowledge the potential transferability and broader benefits of the CIK, as well as the knowledge gained from its design process, to other sectors as well.

The development of the CIK was done in co-creation with multiple organizations, companies, and individuals that have a role in the social housing kitchen supply chain: the stakeholders. These stakeholders include, for example, HAs, a kitchen manufacturer, parts and material suppliers, a kitchen appliances manufacturer, and a contractor (CO) – for a full list see Table 1.2.

TABLE 1.2 List of stakeholders involved in the CIK project.

Organization	Role
TU Delft*	Researchers
Chalmers University of Technology*	Researchers
EIT Climate-KIC*	Funder
AMS-Institute*	Knowledge institute/Funder
Bribus Keukens*	Kitchen manufacturer
ATAG*	Appliances manufacturer
Topline maatwerkbladen BV	Worktop manufacturer
Dirkzwager groep*	Contractor
Waterweg Wonen*	Housing association
Eigen Haard*	Housing association
Ymere*	Housing association
Stichting Woonbedrijf SWS*	Housing association
Woonstad Rotterdam	Housing association
Portaal*	Housing association

**Stakeholders who were committed partners in these projects.*

1.5.2 Research goals

Four research goals were identified to support achieving the design goal and to simultaneously develop methods that are applicable to circular building components and generalizable knowledge. Figure 1.4 shows the relation of the design goal and research goals in the CIK research project.

This research aims to develop circular kitchens that improve on environmental performance compared to non-circular kitchens while being feasible. Therefore, assessment of designs for this circular kitchen should consider both their environmental impact and feasibility. Economic viability plays a pivotal role in the latter aspect: if the production cost of a component is too high, manufacturers might avoid production, and if the component itself is overly expensive, clients might hesitate to invest. Evaluating circular building components requires methods that assess them within a Circular Economy framework. Van Stijn's research (2023) presents an appropriate method for evaluating the environmental performance of circular building components, subsequently applied to assess the CIK designs. However, a method for the economic evaluation of circular building components was not available at the outset of this research. Hence, the first research goal (RG1) is formulated as follows:

RG1. Develop an LCC method that determines the economic performance of circular building components.

This LCC method was developed and tested using the CIK case, generating input for design-decision making that is needed to reach the design goal, while showing whether such a component can be (economically) feasible and offering a method that can be applied to other components as well. A method to determine the environmental performance of circular building components was developed by van Stijn et al. (2021), and the environmental assessment of CIK variants was done van Stijn et al (2022). However, the comparison of the economic and environmental performance of CIK variants (and of other components) was still needed to aid decision making in the CIK project, and to generate knowledge on which types of components yield the best environmental and economic performance. Thus, the second research goal (RG2) is as follows:

RG2. Identify which types of circular building component variants perform best environmentally and economically.

In the development of feasible circular building components, economic and environmental performance are crucial, but they are not the sole determining factors. Many authors have conducted case studies and interviews to identify barriers and enablers for a circular built environment (see Appendix C for a literature review of these studies). However, to effectively address these barriers, decision-makers require a deeper understanding of their relative importance, their occurrence in real-world cases, and their impact on component feasibility. Such knowledge can inform better design, policy-making, and decision-making processes. Therefore, the third research goal (RG3) is as follows:

RG3. Draw lessons from stakeholders' choices in the CIK development that can aid the future development of feasible circular building components.

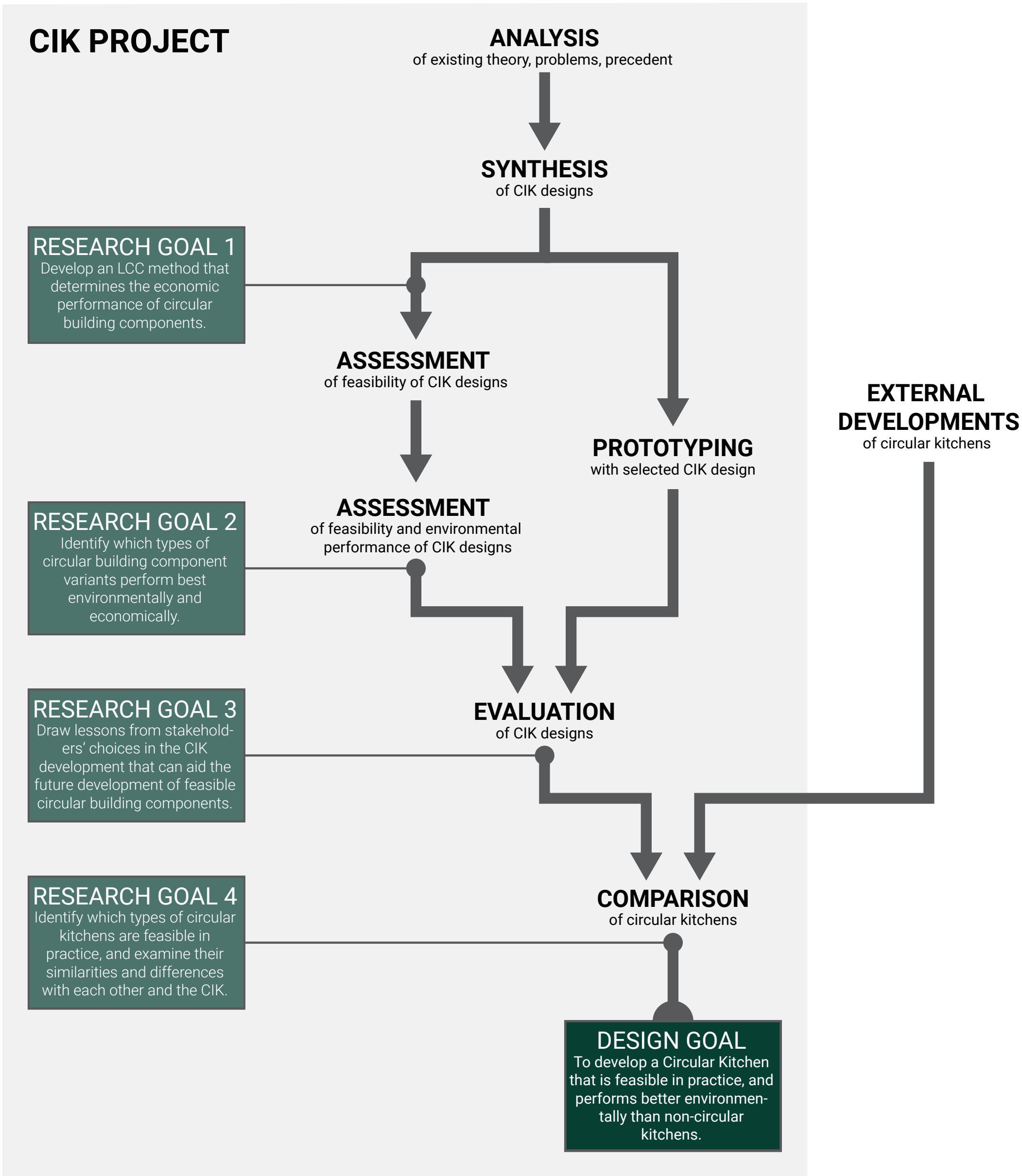

FIG. 1.4 Relationship between design goal and questions, design process and the research goals

Finally, it is important to note that the CIK is developed as part of a funded research project. This distinction may result in different design outcomes compared to circular kitchens developed outside of a research context, where profitability is more likely to be the primary focus. Such circular kitchens have been developed during the CIK research project. Analyzing these kitchens can yield valuable insights into the feasibility of different circular kitchen types: which designs have made it from an experimental phase to market adoption? Furthermore, it allows for the validation of choices made during the development of the CIK in terms of its viability within the current market. Therefore, the fourth research goal (RG4) is as follows:

RG4. *I*dentify which types of circular kitchens are feasible in practice, and examine their similarities and differences with each other and the CIK.

1.6 Approach and methods

1.6.1 Action Research Through Design in a pragmatic approach

At the start of the CIK project, no examples of circular kitchens existed – if defined as a kitchen that as a kitchen that incorporates a technical model, industrial model, or business model that aims to narrow, slow, or close resource loops. Thus, the optimal design solution for circular kitchen could only be identified by cycles of designing and assessing newly made designs. Consequently, the outcomes of the research are both derived from practice and valuable for practice (Frankel & Racine, 2010): it explains, and facilitates acquiring and applying knowledge for future design activities (Downton, 2003). Thus, this research can be categorized as Research-through-Design (RtD) (Frankel & Racine, 2010; Jonas, 2007). It moves past the existing, and aims to generate knowledge on solving problems in the built environment by designing.

On the other hand, this research is done by actively collaborating with stakeholders through co-creation, and thus intervening in the existing reality to bring about change and learning. Therefore, it can alos be characterized as action research (AR)(Adelman, 1993; Huang, 2010). AR aims to understand and transform social systems through a reflective cycle of planning, acting, observing, and reflecting (Carr

& Kemmis, 1986; Järvinen, 2007) and focuses on generating practical knowledge within specific contexts by involving key stakeholders in the research process.

Therefore, the research approach is characterized as "Action Research-through-Design" (ARtD), integrating elements from RtD and AR. This approach was also applied and substantiated by van Stijn (2023), who worked on making building components circular, and also researched the case of the CIK. By combining RtD and AR, this research approach goes beyond the empirical. It actively engages stakeholders and designers in developing and testing the CIK, fostering collaboration and knowledge exchange. This ARtD approach aims to address real world challenges by attaining the design goal, while simultaneously contributing to the body of knowledge concerning these challenges through this practical implementation.

1.6.2 A pragmatic approach

This research employs a combination of AR and RtD, as detailed in Section 1.6.1.: it generates knowledge by creating design solutions. As this approach is not widely established, it is vital to clarify the approach used to generate this knowledge, which can be described as the paradigm. Similar to van Stijn (2023), a specific form of pragmatism – a designerly form of pragmatism – was applied. This section provides insight into what this involves.

A paradigm comprises three essential components requiring definition: (1) ontology (pertaining to the nature of truth or reality), (2) epistemology (concerning how we confirm truth or reality), and (3) methodology (outlining the steps taken) (Guba, 1990). In the following sections, these components will be defined in the context of this research.

1.6.2.1 Ontology

This research is oriented towards facilitating human problem-solving, specifically in addressing environmental impact within the built environment. Its focus is not on the quest for an absolute truth or reality but on finding effective solutions to the problem (Powell, 2001). In this context, the solution to a problem within a specific context is regarded as a form of reality. Given that both the problem and its context are subject to change, the reality of a solution can evolve accordingly. Hence, the concept of reality remains subject to ongoing debate, negotiation, or interpretation.

The fundamental objective of design is to transition from the existing reality to a preferred one (Simon, 1997). For example, this transition might involve a shift from traditional to circular kitchens. A designerly form of pragmatism embraces this concept by recognizing the potential for changes in reality. Rather than fixating on the current state of affairs, it takes possible, probable, and desirable future realities into account. These future realities are intrinsically tied to the research's design goal, which seeks to develop a Circular Kitchen that is feasible in practice, and performs better environmentally than non-circular kitchens. Possible futures are created through the design of variants for the CIK (see synthesis in Figure 1.4). By assessing whether these design variants reduce environmental impacts in comparison to the current standard, the desirability of these envisioned futures is gauged, as outlined in Research Goal 2. Assessments of the feasibility of these design variants determine the likelihood of these futures, as delineated in Research Goals 1, 2, and 4.

1.6.2.2 Epistemology

Within the framework of RtD, encompassing both design and research components, the approach to confirming reality may vary between these two components. The research component aligns well with the pragmatist paradigm, adapting validity criteria based on the chosen research problem and method (Lenzholzer et al., 2013). For quantitative research methods, factors like reproducibility, generalizability, validity, and reliability apply, while qualitative methods or highly contextualized cases require adherence to qualitative research criteria (van Stijn, 2023).

Criteria for the design component should also be considered. These criteria reflect the rigor of the design process itself, and include purposefulness, reliability, consistency, transparency, and usability (Nijhuis & de Vries, 2019). Rather than assessing the quality of the design, they evaluate the coherence and argumentation within the design process, allowing for a clear understanding of the goals, means, choices, and reasoning behind the design (Bardzell et al., 2016; Nijhuis & de Vries, 2019). To achieve this, criteria such as “strength of logic” and “recoverability” are recommended, focusing on the logical reasoning and making the design process comprehensible for critical analysis (Biggs & Büchler, 2007; Checkland & Holwell, 1998; van Stijn, 2023). The latter highlights the importance of planning the design process and effectively documenting and analyzing design activities in RtD (Bardzell et al., 2016; van Stijn, 2023).

1.6.2.3 Methodology

The research commenced with a design process that raised numerous questions. Some of these questions found answers within existing literature, while others lacked relevant theories. Four research questions emerged from these inquiries, and these questions formed the basis of the research goals. Given the diversity of these research goals, the research methods employed varied per goal.

For a valid Research through Design (RtD) approach, it is essential to understand the design process and how it feeds and drives the research (as detailed in Section 1.6.2.2). Nevertheless, the overarching approach remained consistent (see Figure 1.4). This section outlines the design methodology and provides a concise overview of the methods applied for each research goal.

A systematic design approach was employed to structure the development and testing of circular building components. This approach consisted of various phases that result from integrating Wamelink et al.'s (2010) building design and realization process models, Roozenburg and Eekels' (1995) product innovation phases model, and Technology Readiness Levels: 'proof-of-concept,' 'prototype,' 'demonstrator,' and 'market implementation.' Each phase involved four activities based on the Basic Design Cycle (Roozenburg & Eekels, 1995): 'analysis', 'synthesis', 'simulation' (or test), and 'evaluation'. Notably, the 'initiative' and 'proof of principle' phases, which typically occur in this approach, were completed before this specific dissertation. See Figure 1.5 Systematic design approach for an overview of these phases and cycles. Additionally, while the design process didn't follow a linear path as planned, requiring multiple iterations and adjustments, this systematic design approach enhanced the understanding of the process.

Four steps were undertaken to achieve RG1, which aims to create an LCC method for evaluating the economic performance of circular building components. First, the essential requirements for a tool applicable to circular building components were determined. Second, a comprehensive review and assessment of existing tools were conducted to ascertain their suitability for assessing circular building components. Third, building on the findings from the tool assessment, existing models were modified and customized to align with the specific needs of assessing circular building components. This led to the development of the CE-LCC (Circular Economy Life Cycle Cost) model. Finally, the CE-LCC model's effectiveness and reliability were validated by subjecting it to testing through the assessment of various variants for the CIK.

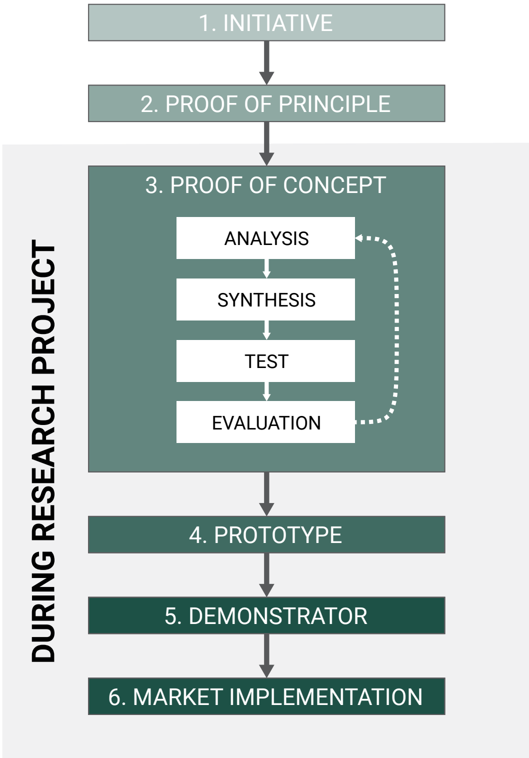

FIG. 1.5 Systematic design approach

After reviewing the literature on the economic and environmental assessment of circular building components, four steps were undertaken to achieve RG2. First, different designs were selected for two building components, namely the CIK and the circular renovation façade (Circular Skin). These designs were intended for either a biological loop, a technological loop, or a combination of both. The economic performance of these design variants was then assessed in comparison to a standard, business-as-usual (BAU) design representing current practices. This assessment utilized the CE-LCC model and integrated the results with the environmental performance data from van Stijn et al. (van Stijn et al., 2022). Following this analysis, which circular pathway (the biological or technical) resulted in the 'most circular' building components was determined. Finally, the outcomes were reflected on to identify potential enhancements for the development of biological, technical, and hybrid circular building components.

To achieve RG3, first, a circular building component (referred to as the CIK) was developed between 2017 and 2022. Throughout this timeframe, meetings were documented in summary form. Subsequently, a dataset was created, encompassing an inventory of decisions made by stakeholders during the development process, based on the summarized records. These decisions were subject to systematic and iterative analysis, and a reflection on the development process was conducted. Lessons learned were subsequently derived through the combination of this reflection and analysis (see Section 4.2.2 for a more detailed description). In the subsequent phase, the findings were validated with the involved stakeholders in the development process, and this validation was employed to refine the lessons learned.

Four main steps were undertaken to achieve RG4. First, existing circular kitchens that were available or would soon to be available in the Dutch housing market were identified through inquiries with relevant stakeholders and online search engines. Second, data were collected from manufacturers' websites and publications regarding these kitchens, while data for the CIK were sourced from this research project. Both quantitative and qualitative data was collected, and in a third step, quantitative and qualitative analysis was done. In the quantitative analysis, data was coded as "available" (A), "partially available/unclear" (PA), or "not available" (NA), offering insights into manufacturer focus and data availability for this study. The qualitative analysis involved examining design choices for technical, industrial, and business models to identify similarities and differences between the circular kitchens. Fourth, semi-structured interviews were conducted with selected manufacturers, chosen based on specific criteria, to validate and enhance the qualitative data (for the interview guides see Appendix D). Finally, the qualitative data were refined, and typologies of feasible circular kitchens for the Dutch housing sector were developed based on observed similarities and differences

1.7 Dissertation outline

This dissertation consists of 6 chapters, and is structured as follows:
Chapter 2 explores the possibilities for economic assessment of circular building components, and subsequently, a circular economy life cycle costing model (CE-LCC) for building components is developed. Chapter 3 applies CE-LCC and combines the outcomes with the outcomes for environmental performance from van Stijn et al. (2022) to determine which pathway (the technical or biological) of the CE yields the best 'circular performance'. Chapter 4 investigates which specific stakeholder choices throughout the development process led to a CIK design that was considered 'feasible' to implement in projects and practice. Five lessons are drawn from this investigation that could aid future developments of circular building

components. Chapter 5 compares circular kitchens that were implemented in practice outside of the scope of the CIK development process to identify which types of circular kitchens are feasible in practice. Chapter 6 summarizes and discusses the findings per research goal. Additionally, it concludes on the design goal: if it is achieved, and if not, how it could possibly be achieved. Finally, three new insights are presented, derived from reflecting on the research outcomes as a whole.

Some studies in this dissertation were published using personal pronouns such as 'we', while restrictions for the use of personal pronouns were set for other publications. In this dissertation, the use of personal pronouns is avoided in line with the later publications.

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

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ABSTRACT

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

when considering multiple interest, lifespan and remanufacturing and recycling scenarios. Although, the model could benefit from further research and application, it can support the transition towards a more sustainable (building) industry.

KEYWORDS Circular economy, Life cycle costing, Life cycle assessment, Building components, Built environment, Net present value

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

2.1 Introduction

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

The principles of a Circular Economy (CE) offer a step towards a sustainable built environment, by contributing to resource efficiency and effectiveness, reducing resource use and waste and therefore lowering environmental impact. CE, according to Geissdoerfer et al. (2017, p. 759), is “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops”, in which slowing loops is to lengthen the use of a product, closing loops is to recycle materials, and narrowing loops is to reduce resource use or achieve resource efficiency (Bocken et al., 2016).

The transition towards a circular built environment will require integral changes in the design, supply chain and business model of products[5] (van Stijn & Gruis, 2019). Therefore, tools and methods to support industry in this process are needed, which in general can be divided in two main types of methods: generative and evaluative (de Koeijer et al., 2017). Generative tools support the development of design proposals, while evaluative tools are used to assess the developed designs. The focus in this article is on an evaluative method.

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

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

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

2.1.1 Towards Circular Life Cycle Costing

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

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

2.1.2 Limitations of current approaches to Life Cycle Costing

There are three main approaches to LCC: Conventional LCC (C-LCC), Environmental LCC (E-LCC) and Societal LCC (S-LCC). C-LCC was introduced in the 1930s by the US Department of Defense to include operating and maintenance cost in public procurement (De Menna et al., 2018; Dhillon, 2009; Heralova, 2017). It has a single stakeholder perspective (producer or consumer) and does not always consider the complete life cycle; end of life (EOL) scenarios are not included (see Section 2.2). Multiple stakeholders can be included in E-LCC, which aims to complement the environmental life cycle assessment (LCA) with cost calculation. S-LCC can enlarge the boundaries of analysis further by including direct and indirect costs covered by society (De Menna et al., 2018; Hunkeler et al., 2008).

As stated, VRPs in the Circular Economy are carried out by a number of stakeholders (i.e., product manufacturer, customer, end of life actors (see Section 2.2) or other involved stakeholders).

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

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

None of the existing LCC methods meet all of the requirements to assess CE products. Therefore, to support the development of circular products, we adapt existing LCC techniques to (1) consider products as a composite of components and parts with different and multiple use cycles, (2) include processes that take place after the end of use, (3) provide practical and usable information to all stakeholders, and (4) facilitate alignment of the functional unit and system boundaries with LCA. In this paper, we develop an LCC method for the Circular Economy (CE-LCC) based on existing LCCs and apply it to a case of a circular building product.

2.2 Method

2.2.1 Linear versus circular processes

To make an LCC, processes that result in costs need to be defined. What these processes are and where they take place is determined by the design, industrial and business model for the product. A transition to CE affects all three, since material loops are narrowed, slowed and closed. While narrowing material loops does not affect the type of processes that take place or their location, slowing and closing loops have considerable consequences. To slow material loops, products are designed for product-life extension, in which the use period of goods is extended through the introduction of service processes such as reuse, maintenance, repair and upgrading. To close material loops, products are designed to be disassembled and recycled in a technological and biological cycle (see Table 2.1).

TABLE 2.1 Design strategies for the Circular Economy as proposed by Bocken et al. (2016)

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

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

VRPs in the Circular Economy are carried out by a number of stakeholders (i.e., product manufacturer, customer, end of life actors or other involved stakeholders). We have adapted this overview in four ways (as seen in Table 2.2). First, to create space for additional in- formation, we have removed three columns, containing object, owner and function. Although these columns were removed, the information they provided has been included in this article. Second, we have added two columns to the overview, containing possible stakeholders and the selected stakeholder for the VRP in the CE-LCC model, which will be further explained in section 2.2.5. Third, to enable most of the VRPs in the overview, product collection at the end of life or end of use is needed. This is represented through adding 'collect' in the key market stakeholder activities where relevant. Finally, Nasr et al. (2018) illustrated the difference between a number VRPs in a clear way. We have adapted these illustrations and have expanded them to illustrate all the VRPs defined in this paper in the last column of Table 2.2. The adapted overview is applied in this paper and forms the starting point for the allocation of processes to stakeholders.

2.2.2 Time value

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

Therefore, all costs in the CE-LCC model should be considered at present value (PV). Since stakeholders apply different discount rates (International Organization for Standardization [ISO], 2017), discount rates are defined per stakeholder. All costs in the model are discounted as described in Equation 2.1:

$$PV_{SH\,x} = \frac{FV_{SH\,x}}{(1 + i_{SH\,x})^t} \qquad \text{EQ. 2.1}$$

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

2.2.3 Model development

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

2.2.4 Use cycles

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

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

Since multiple use cycles take place on the component and part level within a use cycle of the product, the functional and technical lifespan of the components and parts can differ in the CE-LCC model. Since this affects the calculation of total cost (TC) for a product as well, we have applied a hierarchy: the TC of a product is calculated as seen in Equation 2.2:

$$TC = \sum_{k=m}^{n} CC_m + CC_{m+1} + CC_{m+2} + \cdots + CC_{n-2} + CC_{n-1} + CC_n \qquad \text{EQ. 2.2}$$

in which it is the sum of the total costs per component (CC), which is the sum of the total costs per part (PC), as can be seen in Equation 2.3:

$$CC = \sum_{k=m}^{n} PC_m + PC_{m+1} + PC_{m+2} + \cdots + PC_{n-2} + PC_{n-1} + PC_n \qquad \text{EQ. 2.3}$$

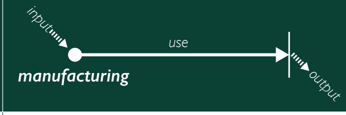
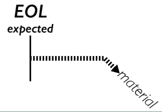
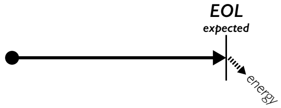
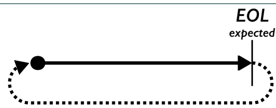
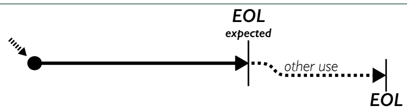
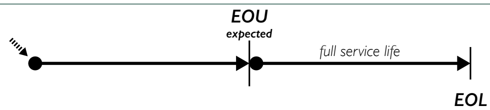
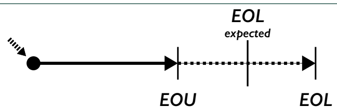
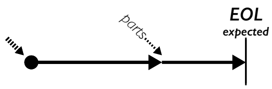
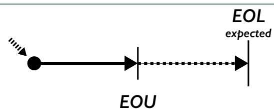
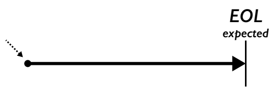
2.2.5 Stakeholder Domains

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

TABLE 2.2 Value Retention Processes adapted from Reike et al. (2018) by adding possible and selected stakeholders, illustrated as proposed for R2, R4

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

, R5 in Nasr et al. (2018).

	Possible Stakeholder (for allocation of costs)	Selected stakeholder for cost allocation in CE-LCC model	Process illustration  *EOU: End Of Use* *EOL: End Of Life*
	Third Parties	-	
	Third Parties	Third Parties (EOU Actors)	
	Manufacturer, Third Parties	Manufacturer	
	Third Parties	Third Parties (EOU Actors)	
	Manufacturer, Third Parties	Manufacturer	
	Manufacturer, Third Parties	Third Parties (EOU Actors)	
	Customer, Third Parties	-	
	Customer, Manufacturer, Third Parties	Manufacturer	
	-	-	
	-	-	×

TOC

The stakeholder domains in which VRPs take place is case specific and depends on the business and industrial model. However, VRPs have been allocated to set domains to make the CE-LCC model operational. If the VRP domains of a case do not match the set domains of the CE-LCC model, the costs for that VRP can be moved to the correct domain without having a significant impact on the model structure. Table 2.2 shows the stakeholder domains in which the VRPs can take place, and where they are allocated in the CE-LCC model. The allocation is based on how suitable the product, component or part is after the VRP for its original function and its lifespan. If the same function and lifespan can be achieved, the VRP is allocated to the manufacturer, as it could benefit the manufacturer financially without having to divert from their core business. In the model, R0 and R1 (refuse and reduce) are not allocated since they describe the reduction or absence of a financial transaction rather than a transaction and therefore cannot be included in an LCC (Hunkeler et al., 2008). R2 (reuse/resell) is assumed to occur when EOU is not EOL, given that collection takes place. Although R2 can take place in all domains, it is assumed that the manufacturer will engage in contracts that ensure recovery through collection after EOU. Therefore, R2 takes place in the domain of the manufacturer. R3 (re-pair) is defined as the replacement of deteriorated parts, which is in- cluded by considering products as composites of components and parts in the CE-LCC model and therefore does not need allocation to a do- main. According to Nasr et al. (2018), the difference between refurb- ishment and remanufacturing lies in the standardization of the process, the setting in which the process takes place, and the expected state after the process. While refurbishment (R4) is seen as taking place in a non-factory or non-industrial setting, being non-standardized and offering life extension, remanufacturing (R5) is seen as a standardized, factory process offering a new full service-life afterwards. Therefore, R4 in the CE-LCC model takes place in the domain of EOU actors and R5 takes place in the domain of the manufacturer. R6 (repurpose) takes place in the domain of EOU actors, since it implies a (irreversible) change in function. R7 (recycle) is used in the definition of recycling materials that can then be applied as secondary materials. Following Bradley et al. (2018), it is allocated in the domain of the manufacturer, as it can imply a saving compared to the acquiring of virgin materials for the manufacturer. R8, as R6 implies a permanent change in function to fuel for energy production and therefore takes part in the domain of EOU actors. As R9 concerns urban mining or landfill mining, it is a VRP that extends beyond the level of a product, its component or parts. Therefore, it cannot be included in the CE-LCC model. Figure 2.1 shows the structure for calculating costs per part that forms the basis of our CE- LCC model, applying multiple use cycles and various domains of sta- keholders that are involved in the life cycle of a circular product.

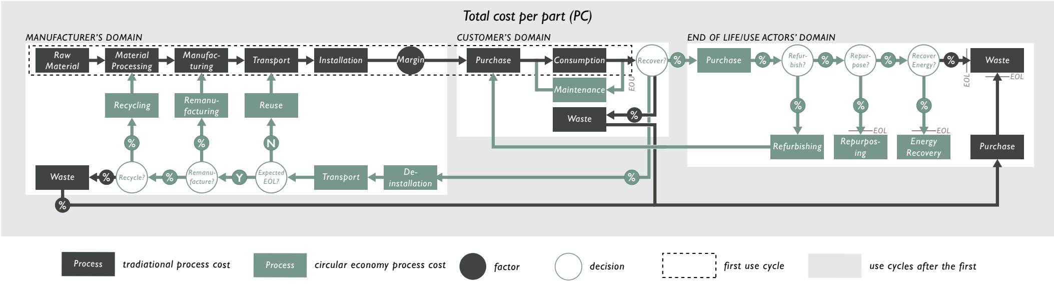


FIG. 2.1 The overall structure of use cycles of a part in the CE-LCC model.

The CE-LCC model calculates the total cost that arises from a product. Therefore, the outcome of the CE-LCC model is the total costs made for a product by all stakeholders involved throughout period of time: the sum of the costs for the whole product from each of the domains, as can be seen in Equation 2.4:

$$TC = TC_{MAN} + TC_{CUS} + TC_{EUA} \quad \text{EQ. 2.4}$$

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

2.2.6 Manufacturers Domain

Cost calculation for parts is done differently per stakeholder and is therefore specified per stakeholder domain. Since the costs for the customer are influenced by the costs made by the manufacturer, the costs for the manufacturer need to be determined first. These costs are determined as described in Equation 2.5:

$$PC_{MAN} = PC_{MAN\,0} + \sum_{t=1}^{t=P+1} \frac{PC_{MAN\,t}}{(1+i_{MAN})^t} = \sum_{t=0}^{t=P+1} \frac{PC_{MAN\,t}}{(1+i_{MAN})^t} \quad \text{EQ. 2.5}$$

where, the PC for the manufactures is calculated as the sum of the costs for the part per year. The model is aimed at the initial implementation of CE products and therefore excludes the cost benefit of the VRPs in the first use cycle, taking place at t = 0. The initial manufacturer's costs can be split up into costs for (raw) materials, material processing, manu- facturing, transport and installation. Equation 2.6 shows the calculation of PC_{MAN} at t = 0:

$$PC_{MAN\,t} = C_{rma} + C_{mpr} + C_{man} + C_{tra} + C_{ins}$$ EQ. 2.6

For every use cycle after the first (t > 0), the costs for raw material, material processing, manufacturing, transport and installation are reduced by the savings made through VRPs as described in Equation 2.7:

$$PC_{MAN\,t} = C_{rma}(1 - A_7 - A_5 - A_2) + C_{mpr}(1 - A_5 - A_2) + C_{man}(1 - A_2) + C_{tra} + C_{ins} + C_{rrr}$$ EQ. 2.7

in which the A values relate to the VRPs. VRPs in the model require extra costs to be made, such as de-installation and transport, but reduce the costs for raw materials, production and/or manufacturing, de- termined by the type of VRP. These costs are defined as seen in Equation 2.8:

$$C_{rrr} = A_{0\,MAN}(A_1(C_{din} + C_{tra}) + A_2(C_{din} + C_{tra} + C_{rmn}) + A_3(C_{din} + C_{tra} + C_{rec}) + A_{99\,MAN}(C_{wad}))$$ EQ. 2.8

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

$$If\ EOU = EOL, \qquad R_2 = 0$$ EQ. 2.9

$$If\ EOU \neq EOL, \qquad R_2 = 1$$ EQ. 2.10

in which the R_x is the expected average percentage of parts suitable for the VRP indicated as R0-R9 in Table 2.2.

When the technical life ends and R2 is 0, in a second step, it is de- termined which percentage of the parts can be remanufactured. In a third step, it is determined which percentage of the parts that remain can be recycled. Then, for the remaining amount of parts that cannot be reused, remanufactured or recycled by the manufacturer, costs occur for waste disposal by the manufacturer.

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

$$A_{0\,MAN} = 1 - A_{0\,EOUA} - A_{99\,CUS} \qquad \text{EQ. 2.11}$$

$$A_{0\,MAN} = R_{0\,MAN} \qquad \text{EQ. 2.12}$$

$$A_2 = (A_{0\,MAN})R_2 \qquad \text{EQ. 2.13}$$

$$A_5 = (A_{0\,MAN} - A_2)\,R_5 \qquad \text{EQ. 2.14}$$

$$A_7 = (A_{0\,MAN} - A_2 - A_5)\,R_7 \qquad \text{EQ. 2.15}$$

$$A_{99\,MAN} = A_{0\,MAN} - A_2 - A_5 - A_7 \qquad \text{EQ. 2.16}$$

where the amount collected by the manufacturer ($A_{0\,MAN}$) is determined directly by $R_{0\,MAN}$ (Equation 2.12), which also determines the amount the EOU actors collect (A_{0EOU}) and the amount of waste the customer has ($A_{99\,CUS}$)(Equation 2.11). R_2 determines the amount of reuse (Equation 2.13). The amount that is not reused can be remanufactured, depending on R_5 (Equation 2.14), and the amount that cannot be remanufactured can be recycled, depending on R_7 (Equation 2.15).

The amount of parts wasted by the manufacturer is then determined by the amount recovered, reused, remanufactured and recycled (Equation 2.16) All R_x values are entered into model, apart from R_2, which is determined as described above in Equation 2.9 and Equation 2.10.

2.2.7 Customers Domain

As stated in the previous section, the costs for the customer depend on the costs for the manufacturer. The costs for the customer are defined as described in Equation 2.17:

$$PC_{CUS} = PC_{MAN} \cdot M + \sum_{t=0}^{t=P+1} \frac{C_{con} + C_{mai} + A_{99\,CUS} \cdot C_{wad}}{(1 + i_{CUS})^t} \qquad \text{EQ. 2.17}$$

in which, to translate the manufacturers costs to the purchase costs for the customer, they are multiplied by M, the margin the manufacturer applies to account for profit and overhead that is not included in the other costs. The savings made through VRPs by the manufacturer are calculated into the price of purchase after the first use cycle, thus giving the customer an incentive for returning the parts at the EOU. Apart from the purchase costs, consumption (C_{con}) and maintenance costs (C_{mai}) are included in the calculation for the customer. Furthermore, the parts that are not recovered by the manufacturer or EOU actors at EOU cause waste disposal costs (C_{wad}) in the customers domain. As stated in Section 2.2.2, stakeholders can use varying discount rates. Therefore, in the calculation of the costs for the customer, a customer’s discount rate (i_{CUS}) is used.

2.2.8 EOU actors Domain

The EOU actors carry out the VRPs that are not executed by the manufacturer: refurbishment, repurposing and energy recovery. These VRPs are very likely to be executed by separate EOU actors. However, to make the model operational, the complexity has been limited and these actors are combined in a single domain. At the end of use, the assumption is made the EOU actors will acquire the parts at the costs of the residual value (V_r). The EOU actors’ costs are calculated as seen in Equation 2.18 and Equation 2.19:

$$PC_{EUA} = \sum_{t=0}^{t=P+1} \frac{PC_{EUA\,t}}{(1+i_{EUA})^t}$$ EQ. 2.18

$$PC_{EUA\,t} = A_{0\,EUA} \cdot V_r + A_4 \cdot C_{ref} + A_6 \cdot C_{rep} + A_8 \cdot C_{enr} + A_{99\,EUA} \cdot C_{wad}$$ EQ. 2.19

in which they have costs for refurbishment, repurposing, energy re- covery and at the end, for waste disposal. Just as in the determination of VRP related costs for the manufacturer, the A values of the EOU actors' VRPs are calculated as seen in Equation 2.20, Equation 2.21, Equation 2.22, Equation 2.23, and Equation 2.24:

$$A_{0\,EUA} = R_{0\,EUA}$$ EQ. 2.20

$$A_4 = (A_{0\,EUA})R_4$$ EQ. 2.21

$$A_6 = (A_{0\,MAN} - A_4)\,R_6$$ EQ. 2.22

$$A_8 = (A_{0\,MAN} - A_4 - A_6)\,R_8$$ EQ. 2.23

$$A_{99\,EUA} = A_{0\,MAN} - A_4 - A_5 - A_8$$ EQ. 2.24

in which the interdependency of the amount of parts that undergo a VRP is similar to Equations. 2.11-2.16, starting with the amount of parts recovered by the EOU actors, determined either by $R_{0\,EUA}$, or by $A_{0\,MAN}$ and $A_{99\,CUS}$, as seen in Equation 2.11.

2.3 Test-case: the Circular Kitchen

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

The CIK is currently being developed for the Dutch social housing sector by TU Delft and industry partners and is funded by EIT Climate-KIC and AMS institute. The aims of the CIK are to develop a market- ready circular kitchen that reduces the environmental impact of kitchens through slowing and closing loops, while remaining affordable and functional. Slowing and closing the loops is done through a separation in parts based on function (and related functional and technical lifespan). The CIK consists of a docking station to which kitchen modules can be attached. The modules consist of a construction (with a long lifespan) to which infill (with a medium lifespan) and finishing (with a short lifespan) can be attached. As opposed to current kitchens, no glue is used to connect the parts to each other. Instead, click-on connections are used that allow for tool-free assembly and disassembly. Therefore, parts of the kitchen can be easily remanufactured and re- cycled separately while offering more flexibility throughout the use period, thus prolonging the overall lifespan of the kitchen.

The CIK is capable of illustrating the effect of having a component with parts that differ in lifespan and type of lifecycle, as for example a façade would. Furthermore, the CIK offers a building component that is already designed for standardization and is mass-produced by a man- ufacturer, a key principle of CE (see Table 2.1). Moreover, the kitchen manufacturer's 80 years of experience with mass-production allows for more accurate data to be used than currently possible for most other CE building components.

2.3.1 Comparisons: Variants

As part of the development process of the CIK, three variants (see Figure 2.2), consisting of 4 lower cabinets, 4 wall cabinets, and a high ca- binet, were proposed to the stakeholders involved. Variant 1 consists of a frame construction made of modified timber, while variants 2 and 3 consist of a more traditional panel construction of durable plywood. Furthermore, in variants 1 and 2, the construction and finishing parts are separated into two layers, while variant 3 has panels that function both as construction and finishing. Figure 2.2 shows these CIK variants and the business as usual (BAU) kitchen.

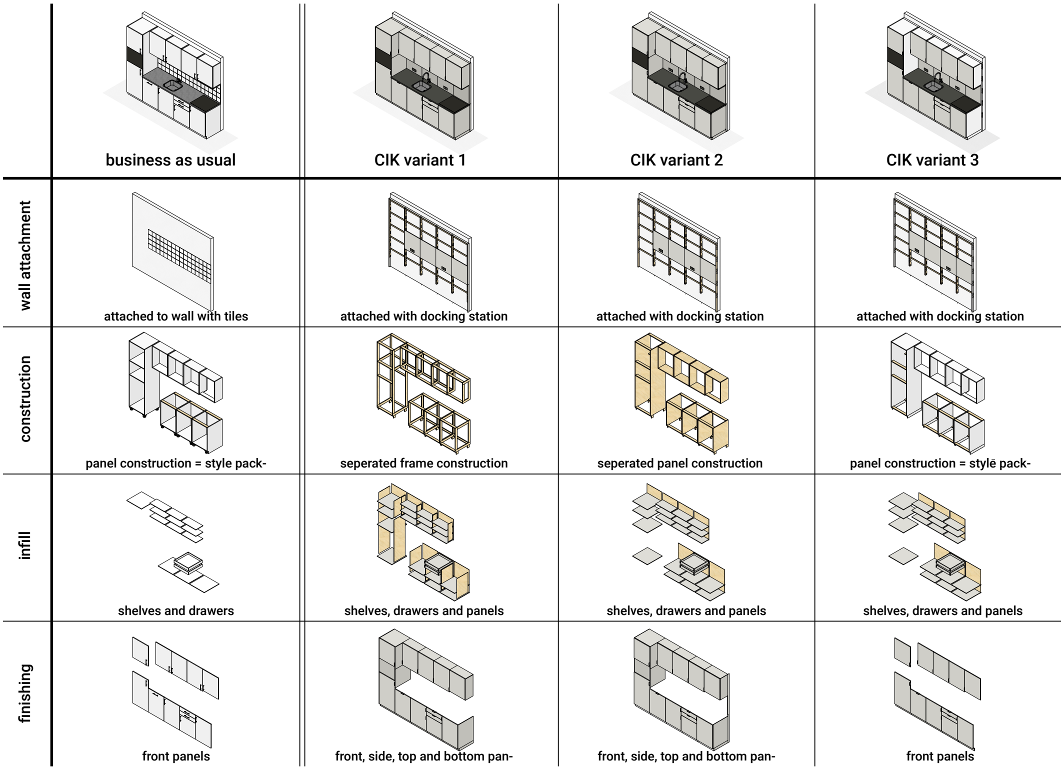


FIG. 2.2 Overview of the variants compared, shown in both the assembled setup (top row) and the functional layers displayed separately (bottom 4 rows).

All the input data was gathered from the stakeholders involved in the CIK project. Where no data was available, estimations were made by the stakeholders. To test the sensitivity of a number of parameters in the model, the CIK variants and the business-as-usual case were compared over a period of 75 years in three types of scenarios: (1) different interest rates, (2) different expected lifespans of parts, and (3) different percentages of remanufacturing (R5) and recycling (R7). Table 2.3 shows these scenarios and the altered parameters.

TABLE 2.3 Overview of values used in the three comparisons of the CIK variants and the BAU kitchen.

	vari- ant	comparison 1: interest rates			comparison 2: technical lifespan in years					comparison 3: VRPs in percentages					
		I1:	I2:	I3:	L1: BAU & CIK 75%	L2: BAU & CIK 100%	L3: BAU & CIK 125%	L4: BAU 100%, CIK 75	L5: BAU 100%, CIK 125%	V1: 75%		V2: 100%		V3: 125%	
										R5	R7	R5	R7	R5	R7
customer interest rate manufacturer interest rate	All All	4,5% 3%	2% 2%	-0,50% -0,50%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%	4,5% 3%
all	0				15	20	25	20	20	0%	0%	0%	0%	0%	0%
construction	1				60	80	100	60	100	0%	75%	0%	100%	0%	100%
construction	2				48	64	80	48	80	0%	8%	0%	10%	0%	13%
construction & style package	3				30	40	50	30	50	45%	8%	60%	10%	75%	13%
connectors	1,2,3				26	35	44	26	44	0%	0%	0%	0%	0%	0%
infill	1,2,3				30	40	50	30	50	23%	8%	30%	10%	38%	13%
infill	1,2,3				15	20	25	15	25	0%	60%	0%	80%	0%	100%
style package	1,2,3				30	40	50	30	50	23%	8%	30%	10%	38%	13%

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

Throughout the 75-year period, variables that determine the dis- count-value, such as the interest rate and inflation, might change. While the Social Housing Guarantee Fund (WSW) is expecting the interest on Dutch 10-year bonds to rise to 4.5% within 20 years (Autoriteit Woningcorporaties, 2018), the recent rise in negative yield bonds (Ainger, 2019) has led others to believe that low, or even negative yields, might stay (Harding, 2019). Since interest rates have a profound influence on the investments companies make, three scenarios for comparison were compared: (I1) 4.5%, (I2) 2% and (I3) -0.5% (based on Dutch 10-year state bonds in September 2019 (IEX, 2020)) nominal interest, all with an inflation of 2% (based on data from CBS (2020)). The discount rate for the scenarios was calculated as seen Equation 2.25:

$$i = \frac{1 + nominal\ interest}{1 + inflation} - 1 \qquad \text{EQ. 2.25}$$

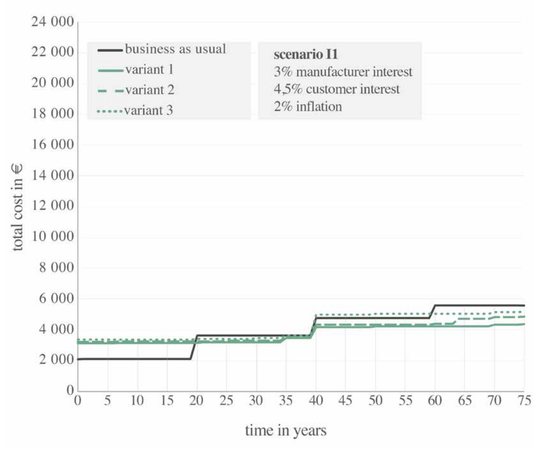


FIG. 2.3 Comparison scenario I1 of total costs for three CIK variants and the business as usual case

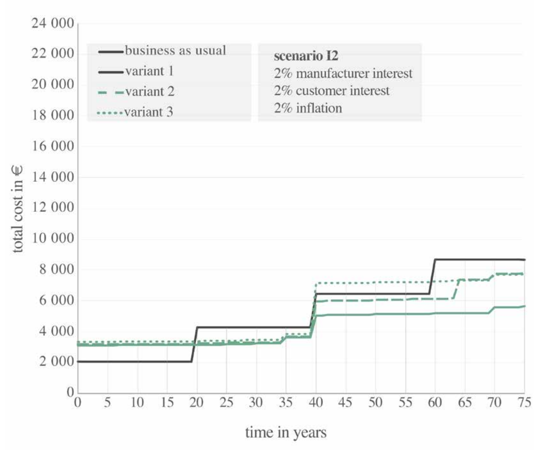


FIG. 2.4 Comparison scenario I2 of total costs for three CIK variants and the business-as-usual case

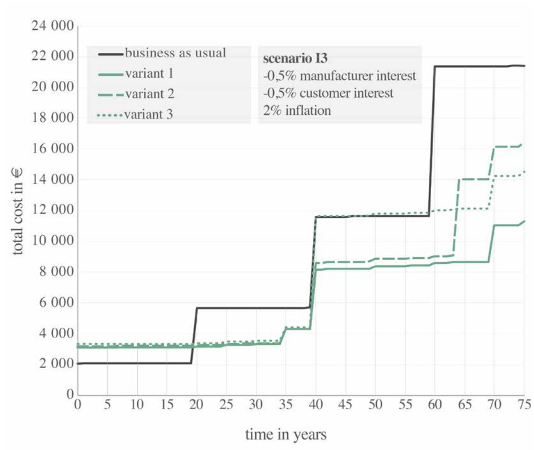


FIG. 2.5 Comparison scenario I3 of total costs for three CIK variants and the business-as-usual case

The associated total costs for each scenario can be plotted using the model as seen in Figure 2.3, Figure 2.4, and Figure 2.5 (International Organization for Standardization [ISO], 2017). The BAU kitchen has the lowest TC up to year 20 due to the lower investment costs. However, BAU kitchens are expected to be fully replaced every 20 years. Therefore, from year 20 onwards, the circular variants have a lower TC in all scenarios, with the exception of variant 3 from year 40-60, which shows a steep rise in TC at year 40. This is due to the replacement of the layer that is both the construction and the finishing that is expected to happen around this time. The TC of variant 2 closely resembles that of variant 1, up to the moment where the construction is expected to be replaced. Variant 2 uses a panel construction that consumes more, and a different type of material than frame construction of variant 1. In the 2% and -0.5% interest scenarios, the TC of variant 2 even rises above that of variant 3. Even though the interest rates have significant influence on the results, variant 1 has the lowest TC at all timepoints after 20 years in all interest scenarios.

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

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

As with the first comparison, the associated total costs for each scenario can be plotted using the model as seen in Figure 2.6, Figure 2.7, Figure 2.8, Figure 2.9, and Figure 2.10. Since the lifespans are altered, the point in time at which the CIK variants have lower TC changes. In scenario L1 (Figure 2.6), where the BAU kitchen has a lifespan of 15 years (75% of the original estimate), the TC of the BAU kitchens exceeds that of the CIK variants after 15 years, except for variant 3 in between year 30 and 45. In scenario L3, where the lifespans have been set at 125% of the original estimates, the difference in TC between the CIK variants and the BAU decreases, and variant 3 has a higher TC than the BAU after 50 years, but ends up lower at 75 years again. Scenario L1, L2, and L3 show that the difference in TC decreases if the lifespan of all materials increases. Furthermore, if the materials for the CIK variants have a lifespan of 75% of the estimated values, as in scenario L4, then the BAU kitchen has a lower TC than variant 2 and 3 throughout most of the period.

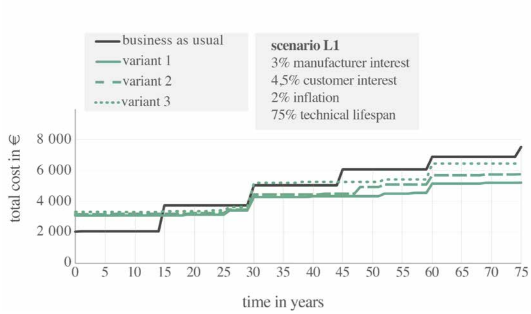


FIG. 2.6 Comparison scenario L1 of total costs for three CIK variants and the business-as-usual case.

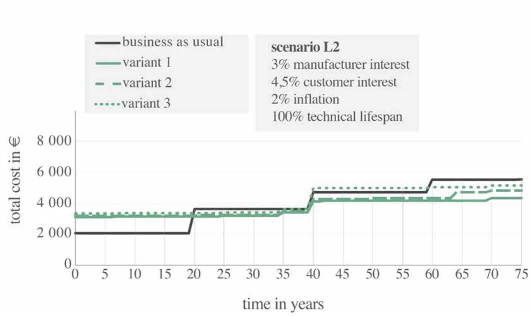


FIG. 2.7 Comparison scenario L2 of total costs for three CIK variants and the business-as-usual case.

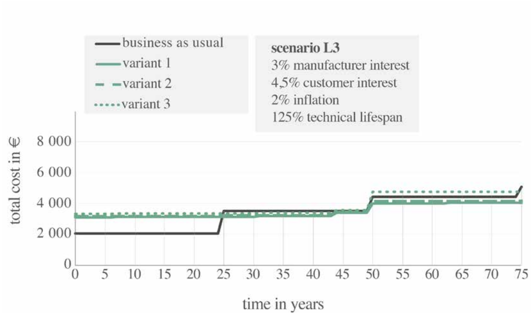


FIG. 2.8 Comparison scenario L3 of total costs for three CIK variants and the business-as-usual case.

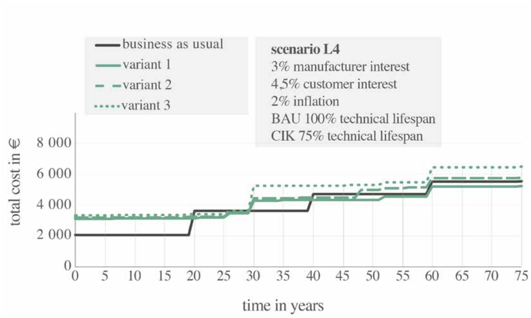


FIG. 2.9 Comparison scenario L4 of total costs for three CIK variants and the business-as-usual case.

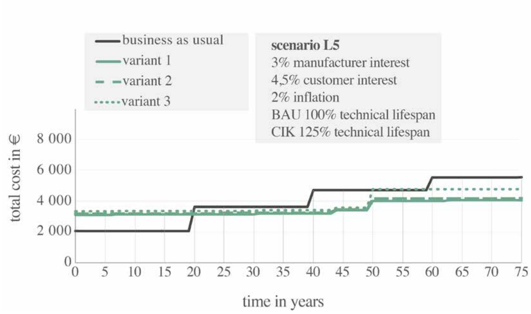


FIG. 2.10 Comparison scenario L5 of total costs for three CIK variants and the business-as-usual case.

However, if the CIK variants last longer than estimated (scenario L5), they consistently have a lower TC than the BAU kitchen after 20 years, except for variant 3 between year 50 and 60. The comparison of these scenarios shows that the expected technical lifespan of the parts used has a significant impact on the TC outcomes for the variants. However, even though variant 1 does not consistently have a lower TC than the BAU throughout the period in scenario L4, it does have a lower TC after 75 years.

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

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

As in the previous comparisons, the associated total costs for each scenario are plotted and can be seen in Figure 2.11, Figure 2.12, and Figure 2.13. These figures show that both reducing the VRPs to 75% and increasing them to 125% has only a minor impact on both the absolute and relative outcome. The TC of the kitchens compared only show very minor differences throughout time.

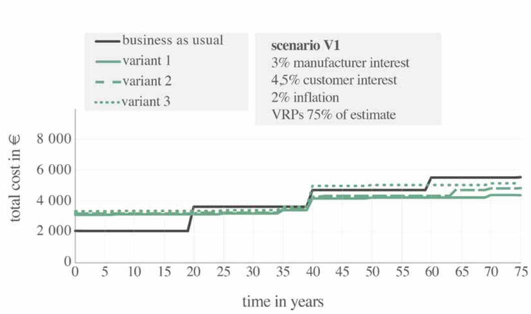


FIG. 2.11 Comparison scenario V1 of total costs for three CIK variants and the business-as-usual case.

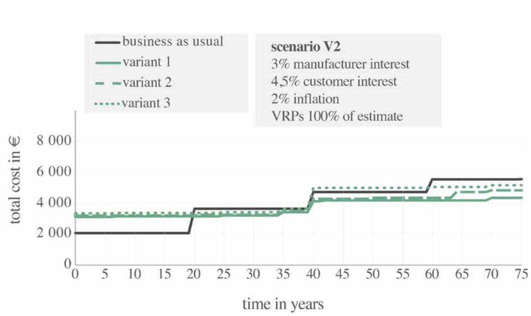


FIG. 2.12 Comparison scenario V2 of total costs for three CIK variants and the business-as-usual case.

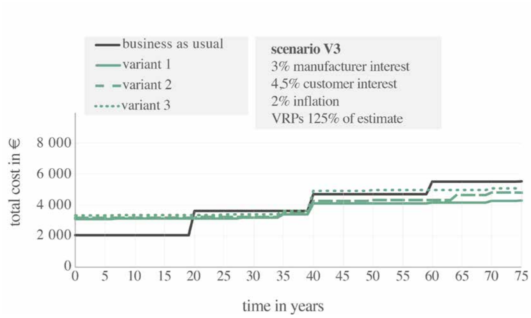


FIG. 2.13 Comparison scenario V3 of total costs for three CIK variants and the business-as-usual case.

2.3.5 Summary of results

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

2.4 Discussion

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

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

Moreover, as the model will generally be applied to long periods of time, changing costs over time (due to resource scarcity, increased waste-costs, etc.) will probably occur. To assess the degree of uncertainty associated with the results, dynamic modeling or further sensitivity analysis should be conducted. This form of risk management should constitute an integral part of the process (Boussabaine & Kirkham, 2008).

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

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

2.5 Conclusion

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

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

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

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3 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.

KEYWORDS Circular economy, Building components, Life cycle costing, Life cycle assessment, Circular pathways, Circular design strategies

3.1 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 & 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).

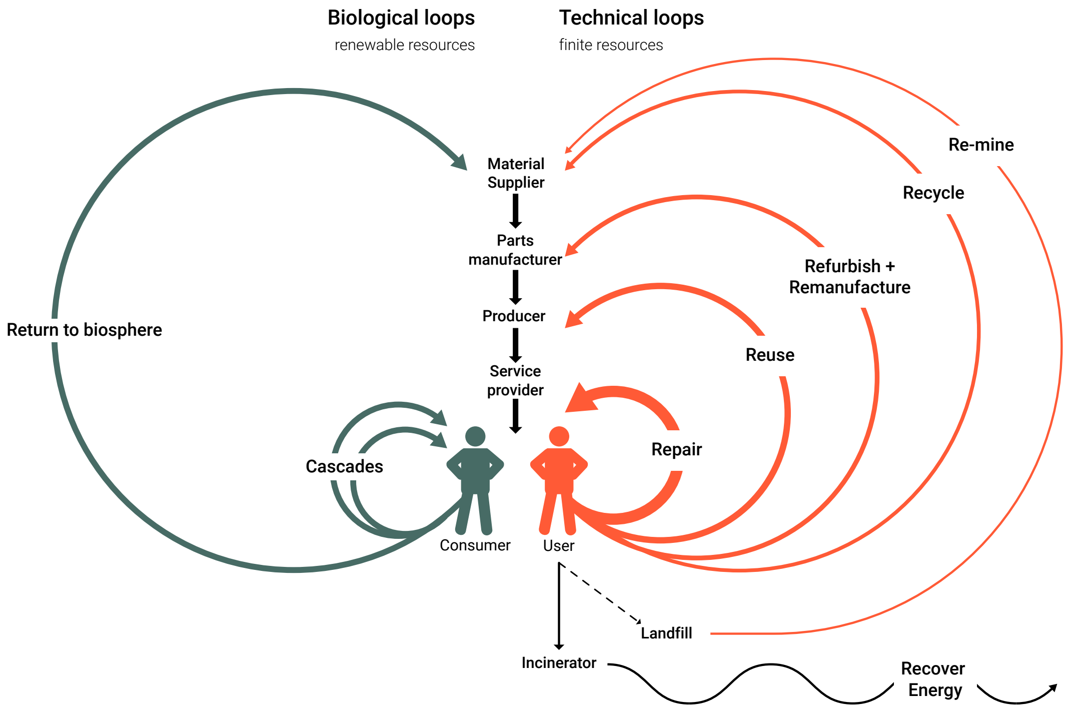

FIG. 3.1 CE system diagram, adapted by authors from the Ellen MacArthur Foundation (2017b) and Reike et al. (2018).

Slowing and closing loops can be achieved in different ways (van Stijn et al., 2022; van Stijn & 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. Figure 3.1 shows the circular loops in an adapted version of the CE 'butterfly model' by the Ellen 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., 2020, 2022).

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 busi- ness 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 de- sign (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.

3.2 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), and 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; Eberhardt et al., 2020b; van Stijn et al., 2021). Moreover, LCA and MFA can assess large sets of impact categories and indica- tors. 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 & 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.

TABLE 3.1 Precedent studies comparing environmental or economic performance of circular design options in building components.

Author	Building component	Circular design options compared	
Buyle et al. (2019)	Interior partitioning wall	4 BAU designs and 3 demountable and reusable designs	
Cruz Rios et al. (2019)(Cruz Rios et al., 2019)	External framed wall	1 single-use wood-framed wall and 1 reusable steel framed wall	
De Wolf (2017)	Building structure	BAU design and material efficient design with low carbon materials	
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	
Geldermans et al. (2019)	Interior partitioning wall	Adaptable design (modular; demountable); bio-based and non-virgin materials.	
Quintana-Gallardo et. al (2021)	External wall	rice straw panel and conventional double brick 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	
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	

Assessment method		Design option(s) with the best performance	
Environmental	Economic	Environmental	Economic
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;
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.	-
LCA (embodied carbon only)	-	• Choosing low carbon materials and optimizing the structural efficiency to reduce the material quantity in the building structure.	-
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.	-
Circ-flex design guidelines and Activity-based Spatial MFA	-	• Combining design for adaptation with bio-based and reversible fiber composite materials.	-
LCA	-	• The biological rice straw panel external wall	-
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 in medium cycles
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.	-

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TABLE 3.1 Precedent studies comparing environmental or economic performance of circular design options in building components.

Author	Building component	Circular design options compared	
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	
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	
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	

	Assessment method		Design option(s) with the best performance	
	Environmental	Economic	Environmental	Economic
	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.	
	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.	-
	-	CE-LCC		• The demountable design with a separate frame, infill and finishing has the lowest LCC outcome in all scenario’s

Life Cyle Costing (LCC) is an appropriate method for assessing economic performance that can be applied to calculate the costs of a design variant over time (Davis 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 3.1 summarizes precedent studies that compared the environ- mental 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 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 con- ventional 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.

3.3 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 eco- nomic 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.

3.4 Results

In the following subsections, this research's results are presented and reflected upon. Subsection 3.4.1 describes the CIK and Circular Skin design variants. Subsection 3.4.1.1 elaborates on the goal, scope, and lifecycle inventory of the CE-LCA, MFA, and CE-LCC. Subsections 3.4.3 and 3.4.4 show the results of the environmental and economic assessment of the variants respectively. To provide further support to these results, subsection 3.4.5 elaborates on the outcomes of the sensitivity analysis. The results are interpreted in subsection 3.4.6 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.

3.4.1 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 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 3.2 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.

TABLE 3.2 Overview of the developed circular building components, their material composition, design strategy, supply chain and business model.

		Material	Mass [kg]	Rel-ative mass	Material character-ization	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**				

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TABLE 3.2 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 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**				

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TOC

TABLE 3.2 Overview of the developed circular building components, their material composition, design strategy, supply chain and business model.

		Material	Mass [kg]	Rel-ative mass	Material character-ization	Design strategy	Supply chain	Business model
CIRCULAR SKIN	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**				

3.4.1.1 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. Figure 3.2 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.

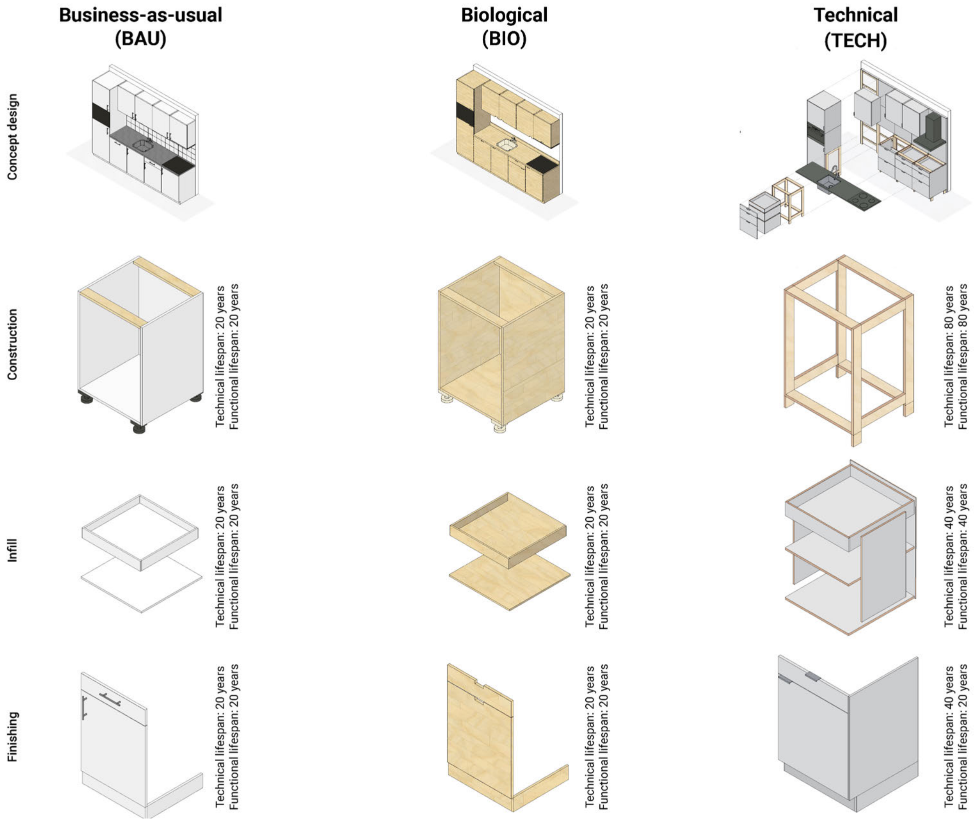

FIG. 3.2 The Circular Kitchen design variants, divided according to functional layers.

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.

3.4.1.2 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). Figure 3.3 visualizes the technical models of the Circular Skin variants. In-situ application or off-site prefabrication is possible for each of the variants.

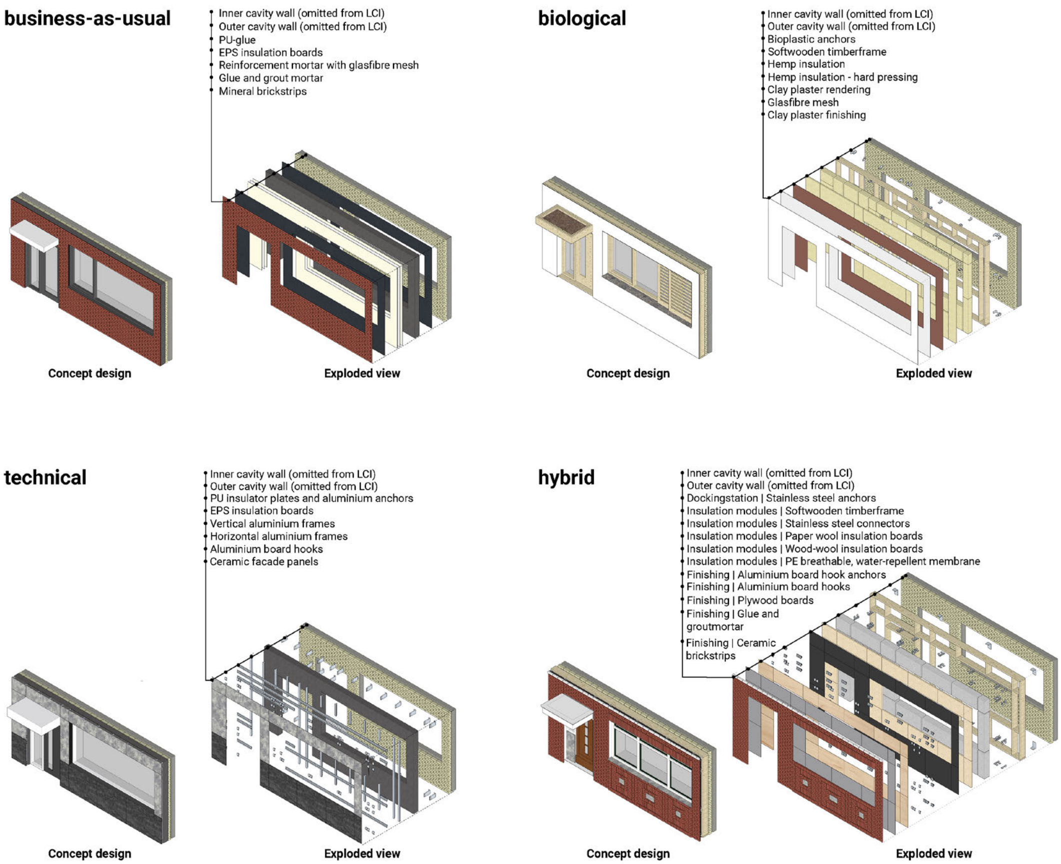

FIG. 3.3 The Circular Skin design variants, including an exploded view.

TOC

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 re-pair, 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 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 brick-strip 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 sub-components are disassembled and their materials are either recycled, downcycled, or incinerated at EOL.

3.4.2 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.

3.4.2.1 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 facade. As the kitchen configurations in social housing are quite homogeneous, a lower cabinet was considered representative of the whole kitchen. A section of facade for a reference terraced dwelling was considered representative of the facades.

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 facade, the FU is the use of a 'specific' renovation facade for the reference facade, with an insulating value of approximately Rc 5.0 m2K/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 facade variants.

The scope definition in CE-LCA differs from the EN 15978 (2012) standard. In the system boundary, all cycles within the building component, its subcomponents, parts, and materials are encompassed. This includes cycles both inside and outside of the building component system, as outlined by van Stijn et al. (2021). For instance, in the TECH kitchen, multiple reuse cycles of the kitchen fronts in other kitchens were considered, along with the downcycling of front materials and incineration for energy recovery. The system boundary for CE-LCC was aligned as closely as possible with CE-LCA. It encompasses the total costs for a product system over a defined period, including costs during manufacturing, use, end-of-use (EOU), and end-of-life (EOL), such as costs for realizing value retention processes (VRPs) and potential waste costs. However, it excludes cycles external to the building component system, such as VRPs occurring in open loops by partners outside of the component's value chain. The scope of MFA was confined to the building component's use cycle, focusing on the direct import and export of that cycle. In CE-LCA, MFA, and CE-LCC, capital goods like production and VRP facilities and machinery were not considered within the scope.

3.4.2.2 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.

3.4.3 Environmental performance

3.4.3.1 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, 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. (2020a) – 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.

3.4.3.2 Circular Economy Life Cycle Assessment results

The results of the CE-LCIA of van Stijn et al. (2022) are shown in Table 3.3. 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.

The GWP allocated to the Circular Skin and CIK has been plotted in Figure 3.4 and Figure 3.5, 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.

TABLE 3.3 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
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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}
LCA	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							
SHADOW COSTS	Global warming potential	0.05	€ 48.88	€ 15.87	€ 26.65	€ 18.92	€ 7.41	€ 3.00	€ 3.75
SHADOW COSTS	Ozone layer depletion potential	30	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
SHADOW COSTS	Photochemical ozone creation potential	2	€ 0.39	€ 0.33	€ 0.28	€ 0.28	€ 0.10	€ 0.04	€ 0.06
SHADOW COSTS	Acidification potential	4	€ 11.26	€ 8.82	€ 9.25	€ 6.55	€ 2.39	€ 1.40	€ 1.34
SHADOW COSTS	Eutrophication potential	9	€ 5.36	€ 29.05	€ 6.62	€ 6.69	€ 2.00	€ 1.10	€ 1.08
SHADOW COSTS	Abiotic depletion potential for elements	0.15	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 271.41	€ 129.72	€ 129.25
SHADOW COSTS	Abiotic depletion potential for fossil fuels	0.00007696	€ 1.05	€ 0.22	€ 0.48	€ 0.32	€ 0.00	€ 0.00	€ 0.00
SHADOW COSTS	Fresh water aquatic ecotoxicity potential	0.03	€ 8.85	€ 3.48	€ 194.85	€ 54.82	€ 2.49	€ 0.54	€ 1.21
SHADOW COSTS	Human toxicity potential	0.09	€ 25.69	€ 11.23	€ 43.92	€ 52.10	€ 16.38	€ 2.43	€ 8.56
SHADOW COSTS	Marine aquatic ecotoxicity potential	0.0001	€ 127.29	€ 30.11	€ 274.17	€ 137.17	€ 17.01	€ 5.26	€ 8.37
SHADOW COSTS	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**

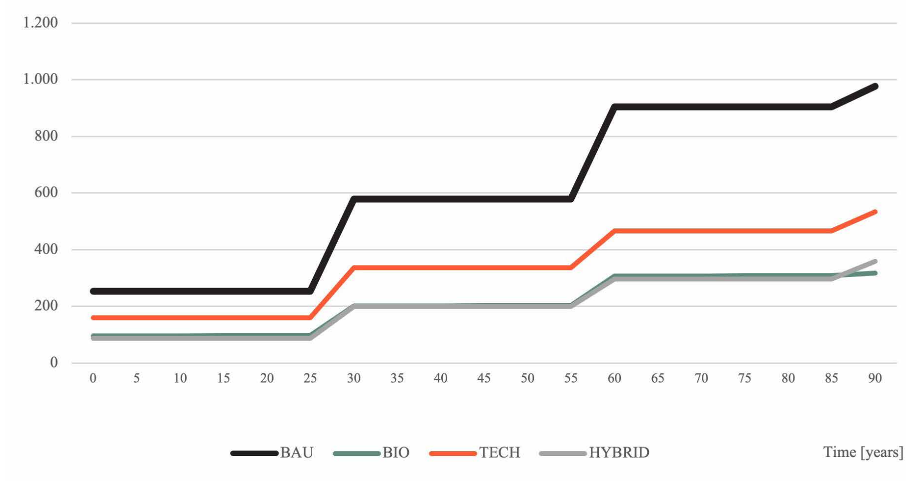

FIG. 3.4 Global warming potential allocated to Circular Skin business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants in time.

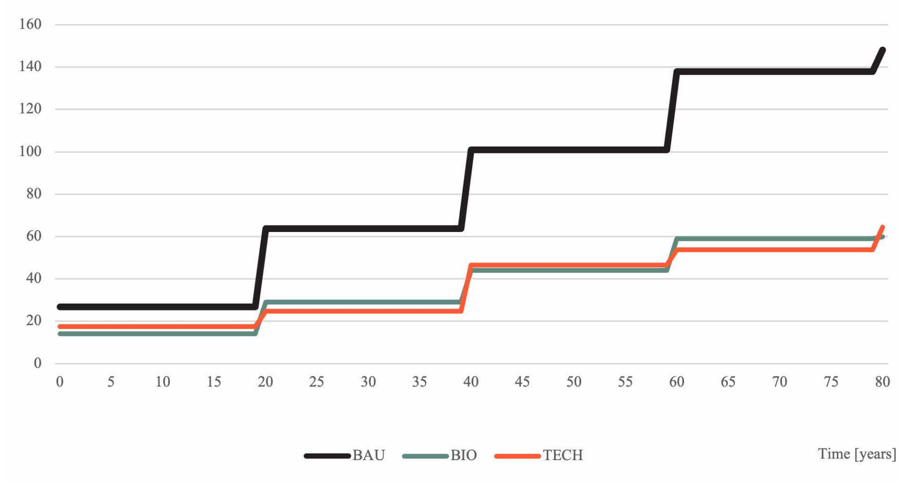

FIG. 3.5 Global warming potential allocated to Circular Kitchen business-as-usual (BAU), biological (BIO), and technical (TECH) variants in time.

3.4.3.3 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.

3.4.3.4 Material Flow Analysis results

TABLE 3.4 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

The results of the MFA of van Stijn et al. (2022) can be seen in Table 3.4. 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%.

3.4.4 Economic performance

3.4.4.1 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.

3.4.4.2 Circular Economy Life Cycle Costing results

TABLE 3.5 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	€ 1,624	€ 1,993	€ 2,672	€ 1,658	€ 141	€ 216	€ 155
	Total installation costs	€ at NPV	€ 1,504	€ 1,445	€ 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	€ 3,486	€ 4,296	€ 4,208	€ 2,793	€ 218	€ 292	€ 189
CUSTOMER	Purchase price	€	€ 1,587	€ 1,762	€ 3,275	€ 2,168	€ 110	€ 153	€ 201
	Total material costs	€ at NPV	€ 1,473	€ 1,815	€ 2,726	€ 1,616	€ 180	€ 276	€ 230
	Total Installation costs	€ at NPV	€ 1,374	€ 1,319	€ 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	€ 3,152	€ 4,510	€ 4,027	€ 2,685	€ 276	€ 372	€ 270
	Total costs	€ at NPV	**€ 6,638**	**€ 8,806**	**€ 8,235**	**€ 5,477**	**€ 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.

The results of the CE-LCC are shown in Table 3.5. 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.

TOC

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).

Figure 3.6 and Figure 3.7 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.

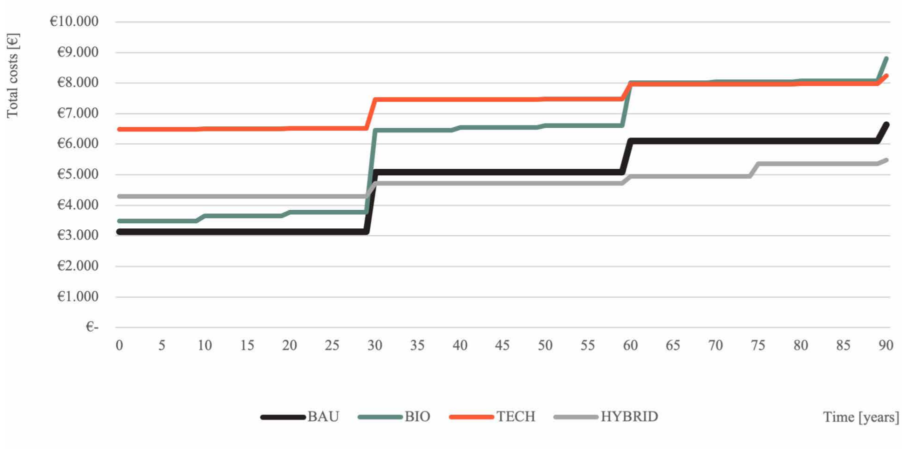

FIG. 3.6 Total costs for the Circular Skin business-as-usual (BAU), biological (BIO), technical (TECH), and hybrid (HYBRID) variants plotted over time.

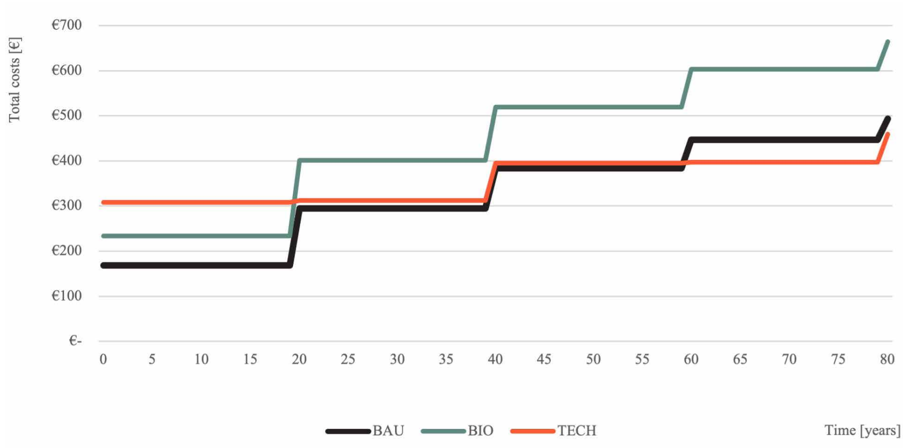

FIG. 3.7 Total costs for the Circular Kitchen business-as-usual (BAU), biological (BIO), and technical (TECH) variants plotted over time.

3.4.5 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.

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 Appendix A. 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.

3.4.6 Interpretation of the result: the technical or biological loop?

TABLE 3.6 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**

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 3.6), 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 %. 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.

TABLE 3.7 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

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 3.7. 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.

3.5 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 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 ((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.

3.6 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.

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4 Cooking Up a Circular Kitchen

A Longitudinal Study of Stakeholder Choices in the Development of a Circular Building Component

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ABSTRACT The built environment can be made more circular by gradually replacing building components with more circular components during construction, renovation, or maintenance. However, many different design options can be seen as circular. Although there is a growing number of studies about circular design options, research on what makes these options feasible or not feasible in practice is limited. This type of research requires intensive, long-term involvement with practitioners. Therefore, this article presents a longitudinal case study of an exemplary circular building component: the circular kitchen. The researchers actively engaged in a co-creation with industry partners to develop a circular kitchen design, supply chain model, and business model. All the choices made from initiative to market implementation were documented. Five lessons were drawn from an analysis of the stakeholder choices that can aid the future development of feasible circular building components: about ambition, aesthetics, design scale, participation, and focus.

KEYWORDS circular economy; circular design; building components; kitchen; circular kitchen; kitchen design; co-creation; case study

4.1 Introduction

The built environment is said to be responsible for a substantial part of all human-induced emissions, resource use, and waste (Ness & Xing, 2017). A transition to a more sustainable built environment is therefore paramount. By increasing resource efficiency and effectiveness, and reducing resource use and waste, the circular economy (CE) could offer the means to do so.

Geissdoerfer et al. (Geissdoerfer et al., 2017) (p. 759) describe a CE as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops”. In this context, slowing means using materials longer, closing means recycling at the end-of-life, and narrowing means reducing resource use or achieving resource efficiency up front (Bocken et al., 2016), which can be done through value retention processes (VRPs) such as reuse, repair, refurbishing, and recycling (Reike et al., 2018; Wouterszoon Jansen et al., 2020). To realize VRPs, components, parts, and materials should be considered from a systems perspective, focusing not only on the physical design (or technical model), but also on the supply chain (or industrial model) and business model (van Stijn & Gruis, 2019).

A gradual transition to a circular built environment can be achieved by replacing building components with circular components during renovation, maintenance, or construction. Many different CE design options can be applied to a circular building component’s physical design, supply chain, and business model. For example, a component can have a modular design, to be reused and updated—slowing loops in the future. However, it can also be made of biodegradable renewable resources, or be lightweight—narrowing loops now (Wouterszoon Jansen et al., 2022). Multiple aids have been developed to support this decision-making process, distinguishing between generative and evaluative methods (Bocken et al., 2014; de Koeijer et al., 2017). Generative methods, such as the parameter-based tool presented by van Stijn and Gruis (van Stijn & Gruis, 2019), support the integration of CE options during design synthesis. Evaluative methods, on the other hand, assess the ‘circular performance’ of a design. Examples of such methods are the environmental assessment method of circular economy life cycle assessment (CE-LCA) (Eberhardt et al., 2020; van Stijn et al., 2021) and the economic assessment of circular economy life cycle costing (CE-LCC) (Wouterszoon Jansen et al., 2020, 2022). When applying these methods, these studies found that purposeful application and combinations of circular design options led to better performance.

However, to assure a successful transition to a more circular built environment, the components have to be applied in practice. The extent to which this application is achievable is defined as ‘feasibility’ in this study. Many authors have investigated the feasibility of applying circular economy (design) principles in the built environment (Adams et al., 2017; Akinade et al., 2020; Azcarate-Aguerre et al., 2018a, 2022; Chang & Hsieh, 2019; Charef et al., 2021; Condotta & Zatta, 2021; Cruz Rios et al., 2021; Galle et al., 2021; Ghisellini et al., 2018; Giorgi et al., 2022; Guerra & Leite, 2021; Hjaltadóttir & Hild, 2021; Huang et al., 2018; Kanters, 2020; Selman & Gade, 2020; Torgautov et al., 2021). They have identified challenges or barriers, and—to a lesser extent—drivers, enablers, or opportunities (an overview of these studies is included in Appendix C). The majority of studies have researched feasibility at the construction industry level or building level. Only Azcarate-Aguerre et al. (Azcarate-Aguerre et al., 2018b, 2022) focus on the building component level and study a façade. Some studies analyze the feasibility of a particular circular design option or limit the feasibility scope. For example, Azcarate-Aguerre et al. (Azcarate-Aguerre et al., 2018b, 2022) focus on façade servitization models whilst Akinade et al. (2020) look at design for deconstruction. Condotta and Zatta (Condotta & Zatta, 2021) take a policy and regulatory perspective and Charef et al. (Charef et al., 2021) adopt the socioeconomic and environmental perspective.

However, most authors have opted for a literature study, studied completed cases, or interviewed one or multiple stakeholders (once). These studies conclude with a list of identified barriers (see Appendix C). Although these barriers are useful, designers, policymakers, and other decision-makers that influence the implementation of circular building components could benefit from knowledge of the relative importance of these barriers in the development process. Furthermore, they could benefit from in-depth analysis of when and how the barriers (re)occur in a real-world case, how they were or could be overcome, and how they influence the feasibility of a component.

Therefore, we present a longitudinal study of the development process of a circular building component: the circular kitchen (CIK). This study is limited to the kitchen as a building component, and, however important, does not include the sustainability of the activities that take place in the kitchen, such as cooking. The CIK was developed for the Dutch social housing sector in co-creation with multiple organizations, companies, and individuals that have a role in the social housing kitchen supply chain: the stakeholders. These stakeholders include, for example, housing associations (HA), a kitchen manufacturer (KM), parts and material suppliers, a kitchen appliances manufacturer (AM), and a contractor (CO)—for a full lists see Table 4.1. In this study, we aim to identify the stakeholders’ choices that led to a feasible CIK and go beyond a list of barriers by deriving lessons learned from in-depth analysis to support decision-makers in the future development of circular building components.

TABLE 4.1 List of stakeholders involved in the CIK project.

Code	Organization
RI1	research institute
F1	funder/research institute
RI2	research institute
F2	funder
KM	kitchen manufacturer
AM	appliances manufacturer
CO	contractor
PM	paint manufacturer
HA1	housing association
HA2	housing association
HA3	housing association
HA4	housing association
HA5	housing association
RE	real estate investor
WM	worktop manufacturer
CM	connector manufacturer

4.2 Materials and Methods

This study was conducted in several steps. In the first step, we developed a circular building component (the CIK) between 2017 and 2022. During this period, we documented the meetings in summaries. In the second step, we developed a dataset that includes an inventory of the choices made by the stakeholders in the development process based on the documented summaries. We analyzed these choices systematically and iteratively (see Section 4.2.2) and reflected on the development process. We then derived lessons learned by combining reflection and analysis. In the third step, we validated our findings with the stakeholders involved in the development process. The validation was then used to refine the lessons learned. In the following sections, we will elaborate on the methods applied in each step.

4.2.1 Developing the CIK

The CIK was developed for and with Dutch HAs, as they own nearly one-third of the housing stock (Sociaal en Cultureel Planbureau, 2020) in the Netherlands and have high ambitions of achieving circularity (*Lente-Akkoord 2.0 | Lente-Akkoord 2.0*, n.d.). Their experience with long-term collaborations and a long-term investment perspective makes them favorable candidates for implementing circular principles. Furthermore, other practice stakeholders that are part of the kitchen supply chain were involved in the development process. Table 4.1 shows a full list of the stakeholders involved in CIK development.

The CIK was developed in multiple stages, as seen in Figure 4.1, which we defined as the following: (1) 'initiative', (2) 'proof-of-principle', which includes sketch design and variants, (3) 'proof-of-concept', which includes conceptual and definitive designs, (4) 'prototypes', which includes mock-ups and full-scale prototypes, (5) 'demonstrators', which includes placements of fully functional kitchens in real-world dwellings, and finally (6) 'market implementation', meaning upscaling and application in multiple projects. The development process mostly took place in phases 2 to 5. However, the initiative in phase 1, and the end goal of market readiness in phase 6 are significant for this study and are therefore included.

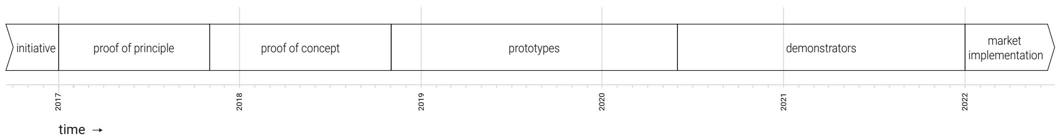

FIG. 4.1 CIK development phases through time.

During all these phases, co-creation workshops were organized. The researchers played an active role in the process, initiating collaborations and proposing and testing design variants together with stakeholders from practice. Therefore, their expertise and background should be described: both researchers 1a (R1A) and 1b (R1B) have a back-ground in architecture, designed parts of the CIK, and developed generative and evaluative methods for circular building components. R1A and R1B also served as project leads for periods of time. The stakeholders took the lead in the product development toward the later stages, and the researchers provided additional knowledge and reflection. Summaries of the contact moments between the stakeholders, as well as presentations, drawings, and photos were documented. An overview of these contact moments can be found in Appendix C.

4.2.2 Stakeholder Choices

Our dataset includes an inventory of over 600 choices made by the stakeholders in the development. ‘Choices’ are defined as a consideration of or decision between two or multiple possibilities. Choices in our dataset can be about both the design (of the physical object, the supply chain, or the business model) and the innovation process.

Figure 4.2 shows the parallel processes to identify which stakeholder choices influenced the feasibility of circular design options: ‘zooming out’, ‘zooming in’, and induction. Once these parallel processes were completed, the outcomes were validated. The following paragraphs describe these processes in detail.

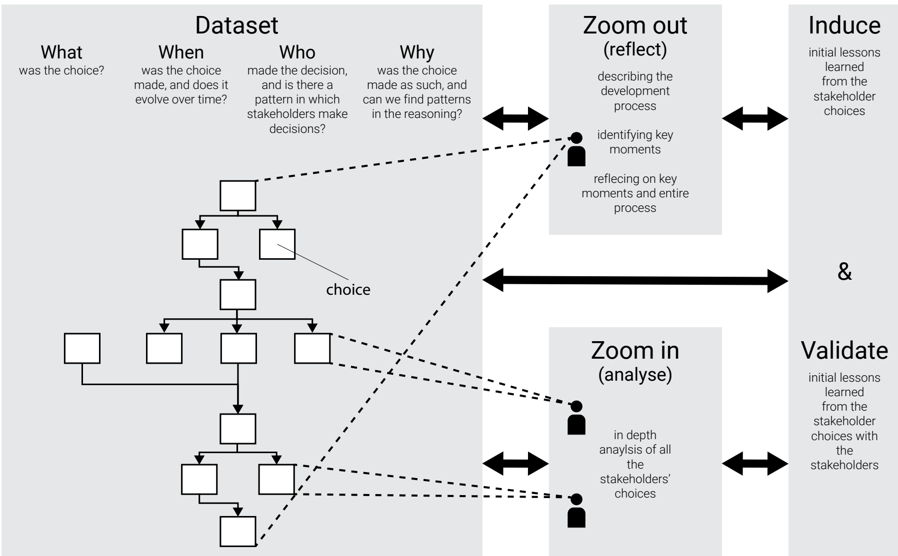

FIG. 4.2 Approach for reflection on and analysis of stakeholder choices to induce lessons learned.

When ‘zooming out’, we reflected on the process as a whole, based on the theories of ‘reflection on action’ by Schon (1983) and the action research cycle by Carr and Kemmis (1986). We described the CIK development process chronologically, a summary of which can be found in Section 4.3, and a full description in Appendix C. Summarizing allowed us to reflect upon the entirety of the process or choices in particular moments; it helped us to identify choices that were ‘key’ in developing feasible circular building components.

TOC

When ‘zooming in’, we analyzed single stakeholder choices in depth. We noted (1) what the choice was, (2) when the choice was made (according to the phases mentioned in Section 4.2.1), (3) who made the choice, and (4) why the choice was made as such, for which we can distinguish different categories of reasoning. These categories were added based on the studies on CE barriers in the literature review. Since most studies applied different frameworks, there was no existing framework that could include all categories. Therefore, rather than selecting a framework before the analysis, we added coding dimensions inductively, through the iterative reading of the existing frameworks provided in the literature studied (also described as emergent coding (Dahlsrud, 2008; Kirchherr et al., 2017)). Table 4.2 shows the categories of reasoning and the applied definition to clarify the differentiation between categories in our analytical framework. For example, the difference between ‘Societal and Cultural’ and ‘Social or Psychological’ is to whom the reasoning is related. Societal and cultural reasoning is based on the fit with what is (perceived as) the cultural norm, for example: “in the Netherlands, one should build with bricks”. Social or psychological reasoning is related to other stakeholders directly, for example: “we do not trust this supplier to be able to provide us with this product consistently”. The difference between ‘Value proposition’ and ‘Functional and Aesthetic’ should also be clarified. In our framework, reasoning based on the value proposition is about whether something is an added value for the stakeholders, and is based on their willingness to buy, supply, produce, or take part in the development of a product. For example: “This product has an acceptable life cycle cost and allows us to offer our tenants more customization, while it has a lower environmental impact.” Reasoning in the category of functional requirements is based on whether a product suffices for the intended use (aesthetics is seen as part of this but is mentioned separately since this inclusion is not straightforward). For example: “By using these connectors, the cabinet is not rigid enough, and will move if users push it”.

TABLE 4.2 Analytical framework.

Category of Reasoning	Subcategories (If Applicable)	Applied Definition
Environmental	Material	Stakeholders perceive a choice leads to more or less material flow.
	Impact	Stakeholders perceive a choice leads to more or less environmental impact.
Financial and Economic	Initial costs and profit	Stakeholders perceive a choice leads to higher or lower initial cost or profit.
	Life cycle costs	Stakeholders perceive a choice leads to higher or lower costs over the component's lifecycle due to (e.g.,) maintenance, longer lifespan, and end value.
	Risk	Stakeholders perceive a choice leads to more or less risk in the development and realization process, in the market potential, or availability.
	Value proposition	Stakeholders perceive a choice leads to a more or less desirable value proposition. This includes the perceived market fit of the component to clients' needs and the perceived fit of the component in the product portfolio and activities of other stakeholders.
Societal and Cultural		Stakeholders perceive that a choice leads to a better or worse fit with current (building) culture or societal norms—relating to society or culture as a whole
Behavioral	User behavior	Stakeholders perceive a choice fits more or less with how users behave with the component.
	Social or psychological	Stakeholders perceive a choice fits more or less with how they interact with other specific stakeholders including what they believe and trust.
Governmental and Regulatory		Stakeholders perceive a choice leads to more or less compliance with governmental policy or regulations.
Technical		Stakeholders perceive a choice for a component can or cannot be technically realized.
Functional and Aesthetic		Stakeholders perceive a choice to increase or decrease the aesthetic or functional properties of the component as affecting its fit for intended use.
Supply Chain		Stakeholders perceive a choice can or cannot be realized within the supply chain.
Information, Skills, and Educational		Stakeholders perceive a choice increases or decreases the need for additional information, skills, or education.

Focusing on the four questions of what, when, who, and why, we looked for recurring patterns. From the findings of the reflection and analysis, we derived lessons that could have improved the CIK and could be used when developing circular building components in the future. We emphasize that selecting and analyzing choices, reflecting on the process, and deriving initial conclusions occurred iteratively.

In the final step, we validated the key choices and lessons learned in a workshop with the stakeholders. In this workshop, we asked the stakeholders to list what they considered the key choices that influenced the feasibility of the CIK. Furthermore, we asked the stakeholders to list their lessons learned from the CIK development process. The researchers then presented what they considered the key choices and the lessons learned they derived. We then developed a complete list of key choices and lessons learned from the workshop's results.

4.3 Case Description

In social housing, the kitchen is replaced every 20 years on average. The kitchens consist of cabinets from melamine-coated chipboard panels which are glued together. These kitchens are rarely repaired or reused due to their low price. This causes unnecessary resource use, impacts, and waste generation. In the next paragraph, we will briefly describe the developed CIK and process. For a full description, see Appendix C.

A modular concept design for the CIK was developed (see Figure 4.3). This design combines strategies to slow and close material loops: kitchen modules can be attached to and detached from a docking station, to allow for changes in layout. The modules consist of a long-life frame, to which fronts, drawers and shelves can be connected. All of the connections in the design are made using tool-free click-on connectors, allowing for easy repair and adjustments in function and appearance. Durable plywood is used to prolong the lifespan of parts. After installing a circular kitchen, full replacement is no longer necessary, preventing future resource use, impacts, and waste. To incentivize the manufacturer to produce such a circular kitchen, a circular business model was developed: the docking station and the kitchen is sold to the HAs, and they are provided with a service subscription and a take-back guarantee. Additional kitchen modules, or alternative finishing options can be offered to tenants.

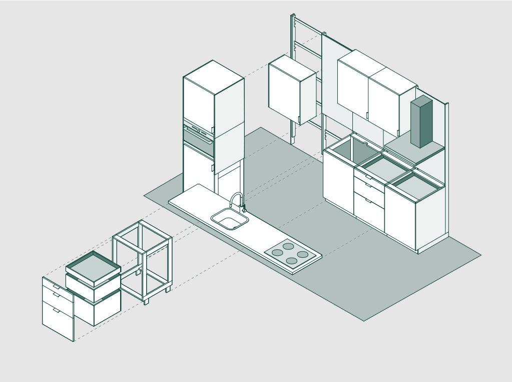

FIG. 4.3 CIK demonstrator technical design concept

FIG. 4.4 CIK demonstrator placed in a dwelling

The proof-of-concept of the kitchen was built to a first prototype, refined, and eight demonstrator kitchens were installed in dwellings (see Figure 4.4). The kitchen manufacturer has since been redeveloping the circular kitchen to remain closer to the current production process and business model. Instead of a frame, the kitchen cabinet is constructed from demountable panels. Through this design, they aim to facilitate the repair of parts in local shops. Instead of plywood, a more circular variant of chipboard is used.

4.4 Results

In the following section, we will elaborate on the findings from the development process. These findings will be divided into five categories that were derived from the iterative process of 'zooming in' and 'zooming out'.

4.4.1 Ambition

As the CIK was supposed to become a market-ready product at the end of the project, feasibility in the current market was an important end goal, and a balance between an ambition regarding circularity and feasibility had to be found. Although circularity and feasibility do not necessarily have a trade-off, in the CIK process, choices favoring a more circular CIK often lead to more radical changes in the design, business model, or supply chain, and can therefore be less feasible. The level of circular ambition fluctuated despite, or because of the feasibility requirement throughout the CIK process.

A high circular ambition was detected by many decisions made to improve material consumption, environmental impact, or costs throughout the lifecycle, and a low circular ambition was detected by few choices made to improve on these categories. Circular ambition was also detected by the extent to which circular design options are applied. Choices for the sake of feasibility are generally identified as choices to reduce risk, that align better with the cultural standards, with functionality, or can be produced in similar ways to current kitchens. Four major changes in circular ambition can be identified: (1) initiation of the project, (2) start of the international project, (3) realization of the first prototype, and (4) the evaluation of the demonstrator kitchens and the move toward market implementation. These changes can be seen in Figure 4.5.

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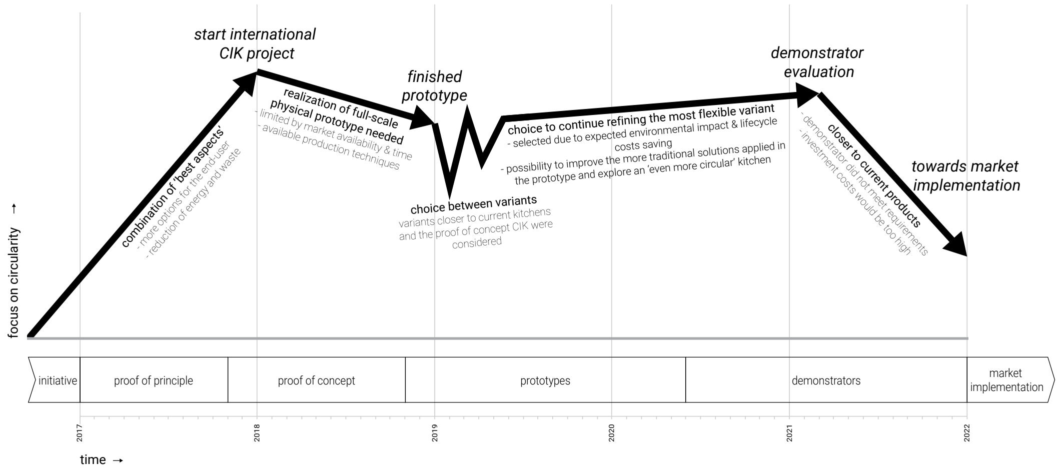

FIG. 4.5 Level of circular focus for the CIK through time. The position on the y-axis is determined relative to previous points and is not absolute.

4.4.1.1 Increase in Circular Ambition

The first change in circular ambition was caused by the initiative for the CIK project. Stakeholders were asked if they could lease kitchens instead of buying them and a one-year research project was started to define such a lease kitchen. During this one-year project, a proof-of-principle was developed for the CIK. Five variants were designed (for a full description, see Appendix C) and the group selected a combination of two ambitiously circular variants for the final proof-of-principle CIK: the plug-and-play kitchen, which facilitates circular loops and accommodates current and future needs by separating the kitchen into parts based on expected lifespan, and the 'all-CE kitchen', which includes appliances that reduce energy usage and waste. A business model and supply chain model to incentivize and organize all the loops for this design were developed as well (see Appendix C for a full description). Nevertheless, at this point, the radical innovative design that was selected was seen as feasible—on 'paper'.

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4.4.1.2 First Reduction in Circular Ambition

In the proof-of-concept phase, the proof-of-principle design had to be refined toward a first realizable full-scale prototype—which had to be delivered as part of the project's funding agreement before the end of 2018. Although the frame construction with separate infill and a style package was seen as challenging in relation to current production techniques, it was not seen as too challenging at first. However, minor changes had to be made to make the realization of the prototype possible in the short term: (1) appliances that were not yet developed could not be included, and the ambition shifted from reducing energy usage and waste to only reducing energy usage, (2) the materials were selected according to current and expected availability for mass production and could therefore not be experimental, (3) furniture panel-connectors could not be tailor-made in time, therefore existing connectors had to be found, and (4) the wall mounted cabinets were not expected to be rigid enough with a frame construction and were redesigned to have a conventional panel construction. These changes are seen as the first reduction in circular ambition in favor of feasibility.

4.4.1.3 Slight Increase in Circular Ambition after Success

After the realization of the full-scale prototype, the design of the CIK was re-evaluated. The added costs and complexity of a design that has a separated frame, infill, and style package led to the development of multiple variants that differed in the application of circular design options. To determine which variant would be further developed, preliminary CE-LCA, Material Flow Analysis (MFA), and CE-LCC results for all the variants were presented to the group (see Appendix C for a more detailed description). Subsequently, the group decided to further develop the variant that applied the most circular design options: a refined version of the prototype kitchen. Contrary to the prototype, this variant included wall-mounted cabinets that consisted of a frame, infill, and a style package—consistently applying the separation of parts based on function—and had the best 'environmental benefits to cost ratio', which was the main reason for its selection.

4.4.1.4 Decline in Circular Ambition toward Market Implementation

The selected variant was then developed into a demonstrator, of which 40 would be placed in dwellings. Due to the COVID-19 pandemic, however, the placement of demonstrators became more complicated and was delayed, and eventually, 10 demonstrators were built and placed. The placement of these demonstrators showed some limitations and complications in practice: (1) the kitchen did not allow for plenty of space behind the docking station for plumbing in real-life situations, (2) the adjustment of the feet was not satisfactory, (3) users were expected to reject the unfinished panels on the inside of the cabinets. Due to this feedback and the investments needed in the KMs production line to produce a kitchen like the demonstrator, the KM decided to remain closer to their current production process. The kitchen cabinet would be constructed from demountable panels, made of a more sustainable chipboard. Through this design, they aim to facilitate the repair of parts in local shops.

4.4.2 Aesthetics

To maximize the impact of the CIK, it was initially intended for the social housing sector, which makes up for 28% of the housing sector in the Netherlands (Sociaal en Cultureel Planbureau, 2020), and can structurally apply circular solutions as a part of a transition to a more sustainable housing portfolio. However, to realize this impact, the kitchen has to be applied and accepted by users. In this section, we describe one of the factors that played a key role in the acceptance: aesthetics. Discussion on the aesthetics of the CIK was detected in the dataset by choices made regarding the style package, materials, and other elements that determine the look of the kitchen.

4.4.2.1 Functional Requirements

Currently, housing associations provide their tenants with—mostly white—kitchens that consist of three base cabinets and three wall cabinets without appliances. In the proof-of-concept phase, the researchers, KM, and HAs met to determine the functional requirements for a kitchen for HAs. The researchers and KM wanted to go beyond statements such as ‘it has to be white’ and wanted to take the underlying reason as a starting point for the refinement of the proof-of-concept design.
Table 4.3 shows the requirements that were mentioned in this meeting that could influence the aesthetics of the kitchen, whether these are stated for the sake of aesthetics, or are a result of the kitchen’s functioning.

TABLE 4.3 Requirements for kitchens mentioned by HAs that influence the aesthetic of the kitchen directly.

Requirement	Reason	Aesthetic Reason	Functional Reason
the appearance must be as neutral as possible	to satisfy the largest group possible	X	
closed-off storage is desirable	visibility of belongings can be problematic	X	
closed-off storage is desirable	to make belongings harder to access for vermin		X
materials should be easy to keep clean (wipe with a cloth)	to make longer use more likely		X
materials must have a certain degree of scratch resistance	to make longer use more likely		X

The first two reasons in Table 4.3 can be explained by the role of housing associations: they provide housing for a varied group of tenants, with different backgrounds and tastes. Although the users might favor exclusivity and authenticity (Selman & Gade, 2020), the HA has to provide a single solution that is acceptable for all tenants. The latter three requirements have a significant influence on the aesthetics but were stated for functional reasons.

4.4.2.2 Acceptance of the Prototype

In the refinement of the proof-of-concept design, the list of functional requirements was one of the three pillars by which the CIK was assessed (together with environmental impact and life cycle costs). All the functional requirements, including those influencing the aesthetics of the CIK, were implemented in the design. Drawers were used instead of doors as much as possible in the base cabinets due to their better ergonomics and their expected longer functional and technical lifespan. Their use also eliminates the need for interior panels inside the cabinet that would need to have a finishing layer. Because the inside of the cabinet does not become fully visible, the appearance of the kitchen could be traditional, while the design was unconventional. The drawers were made out of a material with a layer that is easy to clean, and the design, therefore, met the requirements. Figure 4.6 shows the base cabinet with drawers of prototype 1, and Figure 4.7 shows the frame structure behind the drawers.

FIG. 4.6 CIK prototype 1

FIG. 4.7 CIK prototype 1 with a drawer opened to show the interior of the cabinet.

4.4.2.3 Rejection of the Demonstrator

After the prototype, the demonstrator was designed with a higher circular ambition (see Section 4.4.1). This included making the wall cabinets out of a frame with a separate infill and style package. The infill was designed so that the interior side panels did not need a finishing layer, while the horizontal panels did—since belongings would be stored on these panels. Figure 4.8 shows the interior of the wall cabinets of the demonstrator kitchens.

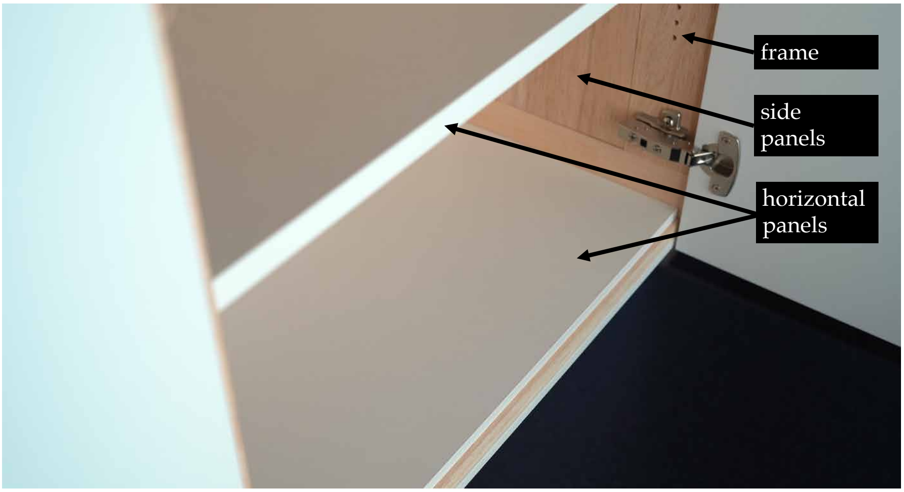

FIG. 4.8 Interior of the demonstrator wall cabinets.

After the placement of demonstrator kitchens in homes, one of the HAs was not completely satisfied with the kitchen. Among other reasons (see Appendix C), the HA noted that users were expected to reject the unfinished panels on the inside of the cabinets.

4.4.3 Design Scale

To lower the environmental impact of the CIK compared to conventional kitchens, while aiming for a similar lifecycle cost, the aim was to make the materials last as long as possible. By applying materials with a long technical lifespan (the maximum period during which it can physically function (Cooper, 1994)) where possible, some parts could be reused multiple times after the end of the functional lifespan (the period in which the object meets the functional demands of the user (Wamelink et al., 2010)), therefore lowering the environmental impact and costs over time (see (Wouterszoon Jansen et al., 2020),(van Stijn et al., 2022)). Therefore, the properties of the materials, and how they would be connected and disconnected, were of utmost importance. The first since the material should not only last as long as possible, but it also has to last without changes such as deformation and discoloration, and it must be available in the longer term. The latter is of importance since reuse can only occur if the parts can be connected and disconnected from each other multiple times, without loss of strength or stability.

TOC

4.4.3.1 Materials

In the proof-of-concept phase, the first selection of materials to use in the prototype had to be made. The KM stated that lifespan should be one of the main deciding factors. Furthermore, the material had to be available in 80 years and, as we have seen in the previous section, should be scratch resistant and easy to clean. Moreover, the material had to be available in larger quantities and would ideally be able to be processed in the KM's existing machines. Finally, the materials used would ideally be fully recyclable, with as little environmental impact as possible.

Due to the requirements for the material, there was no ideal material, and a compromise had to be made. Throughout the 5-year process, multiple novel materials were offered to be used in the CIK project. Finally, the KM concluded that they would most likely use sustainable chipboard, to save costs and reduce risks, because of their experience with it, and because it is readily available and affordable.

4.4.3.2 Connecting Materials

In the proof-of-principle design, the frame of the kitchen would be connected with custom-made parts, and the other part used—up to then undefined—click-on connectors. Due to the limited amount of time, until a full-scale prototype had to be realized, these connectors could not be developed within the project scope. Therefore, connectors that would facilitate assembly and disassembly multiple times with ease, and without loss of strength and stability needed to be found.

Once the materials had been narrowed down to a few options, mock-ups were made to test multiple connectors with these materials. In doing so, we found that the use of each connector required unique properties of the material it would be connecting. For example, one connector relied on expansion to fasten itself onto the material, which could therefore only be materials in which it could expand. Another connector needed a milling accuracy of 0.1 mm, and since milling depth is generally measured from the bottom of the panel, it needed panels that have a consistent thickness with a 0.1-mm accuracy. Any deviation from these requirements resulted in a connection that was either not strong or stable enough, or could not fully function—leading to failure to connect or disconnect.

4.4.4 Participants

Due to the duration of the CIK project, the participating employees of the partner organizations changed. Over the 5 years of the project and 108 meetings, 43 unique different persons from 16 organizations participated. Although for some organizations only one employee participated consistently throughout the project, some employees only took part for a shorter period and were replaced by a colleague. We found three deciding factors for the impact they had on the development: (1) their role within the organization and associated influence, (2) their technical knowledge, and (3) the degree to which their role allowed them to focus on the CIK project. We will elaborate on this impact, and on the effect of changing participants in the next section.

4.4.4.1 Consequences of Change in Participation

The replacement of participants from the KM is a striking example, especially since the KM plays a crucial role in the development, being the only organization that has specific knowledge of the technical design and parts of the supply chain. Figure 4.9 shows the involvement of three employees of the KM throughout the process, the effect their involvement had, and their influence, technical knowledge, and focus on the CIK project. KM1 (KM chief executive officer) was involved in the initiative and proof-of-principle phases. Since KM1 has the most influence within the KM, a support base within the organization was created, and decisions could be made quickly. However, KM1 lacked technical knowledge, and could not support the project team with specific knowledge. In the proof-of-concept phase, the manager of product and process development (KM 2) joined the CIK project. KM 2 had relatively high influence within the organization combined with ample technical knowledge, enabling fast decision-making for the technical side of the project—which was needed in this phase. However, in a later stage, KM 2 was assigned new tasks within the organization, and the focus on the CIK was reduced. Consequently, a product manager (KM 3) joined the CIK project team. KM 3 had limited influence in the organization and limited technical knowledge. The period in which KM 3 was the main participant for the KM in the CIK project was therefore characterized by low decisiveness and initiative from the KM's side. Toward the demonstrator phase, the KM appointed a dedicated 'business developer, circular kitchen' (KM 4). Although KM 4 lacked some of the technical knowledge of KM 2, the fact that KM 4 was dedicated to the CIK project, combined with more influence in the organization, caused the initiative and decisiveness of the KM to increase.

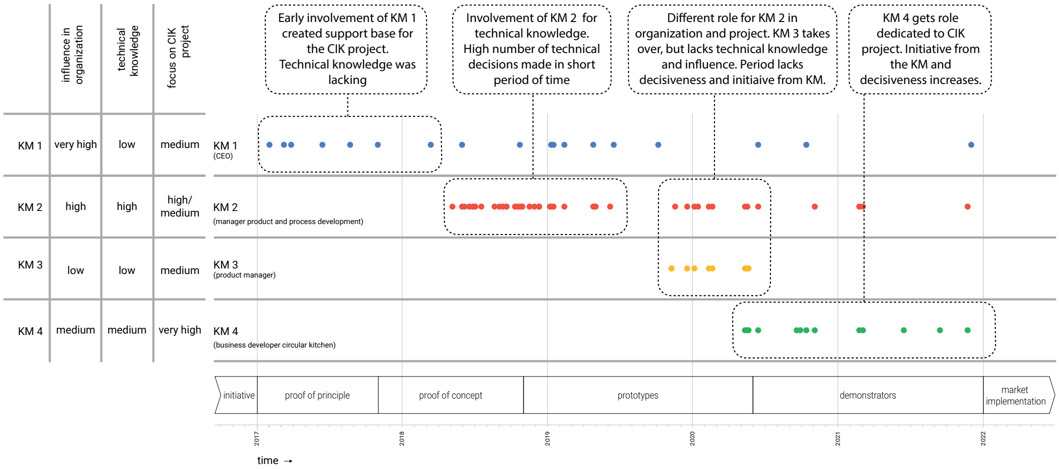

FIG. 4.9 Participation of the four different individuals from the KM involved over time, including their level of influence, technical knowledge, and focus on the CIK project.

4.4.4.2 Is the Future Supply Chain Fully Represented?

Table 4.4 shows the 16 organizations that participated in the CIK project. The inclusion of both the manufacturer and the client has led to better alignment of the value proposition; this improved the coordination among the stakeholders about what was possible and what was needed. For example, a synergy was found between modularity as a way to reduce environmental impact and material use, and a way to offer tenants customization of their kitchen. Notably, we did not include the end users (the tenants) in the list of organizations. However, a focus group was organized with tenants in the proof-of-principle phase.

Furthermore, Table 4.4 shows the lack of involvement of stakeholders that are involved in the raw materials stage, and end-of-life stage (such as material manufacturers and recyclers respectively). The inclusion of experimental, new materials, or new recycling techniques was, therefore, not explored to their full extent in the scope of the CIK project. Furthermore, the development of the supply chain and business models concept focused on the life cycle stages that were represented by the involved stakeholders.

TOC

TABLE 4.4 List of organizations participating, and organizations defined in the supply chain, in which X signals (current) full involvement in the product lifecycle stages, and / signals a partial involvement in the lifecycle stage.

Code	Organization	Role	Raw Material Stage	Materials Manu-facturing Stage	Product Manu-facturing Stage	Use Stage	End of Life Stage
RI1	research institute	researchers					
F1	funder/research institute	funder					
RI2	research institute	researchers					
F2	funder	funder					
KM	kitchen manufacturer	supplier			X		/
AM	appliances manufacturer	supplier			X		
CO	contractor	service provider				X	
PM	paint manufacturer	supplier		X			
HA1	housing association	customer				X	
HA2	housing association	customer				X	
HA3	housing association	customer				X	
HA4	housing association	customer				X	
HA5	housing association	customer				X	
RE	real estate investor	customer				X	
WM	worktop manufacturer	supplier		X	X		
CM	connector manufacturer	supplier		X	X		

4.4.5 Focus

Successful circular innovation often requires a change in three elements: (1) the physical design, (2) the supply chain, and (3) the business model of a building component (van Stijn et al., 2022). The CIK project started with the suggestion of shifting toward a new business model: leasing kitchens instead of buying them. Although all three elements were further developed, the effort that was put into these elements was not equal in some stages of the development. The next paragraph describes the development of the business model, supply chain, and physical design.

Figure 4.10 shows the meetings in which the design, business model, and supply chain were mentioned internally. Events are excluded, as they were used to present the ideas to a broader audience, and not to decide on potential changes. Furthermore, workshops and meetings that were linked to the project, but did not concern the kitchen itself were excluded as well (such as workshops discussing the development of kitchen appliances, outcomes of research, or meetings to plan for an event or website).

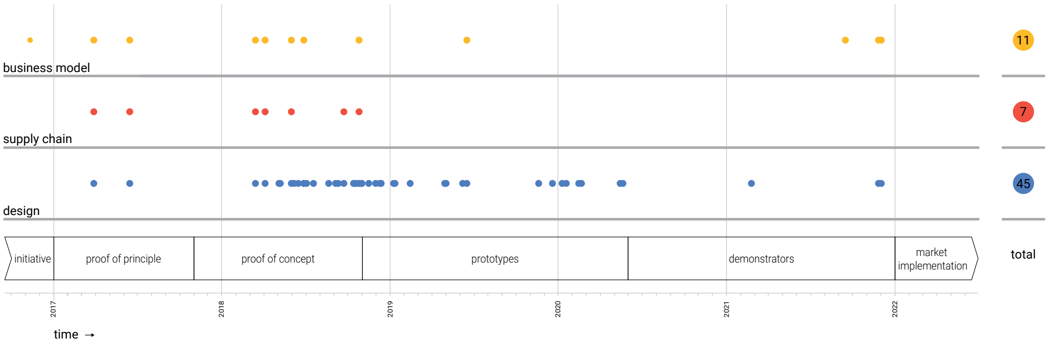

FIG. 4.10 Meetings in which the business model, supply chain, and design were discussed over time.

In Figure 4.10, we can see that the number of meetings in which the design of the CIK was discussed is by far the highest with 45 meetings. The business model and supply chain were only discussed in 11 and 7 meetings, respectively. Furthermore, we can see periods in which the focus on the design of the CIK was intensified, generally before a phase in which a new physical deliverable was needed (the prototype and demonstrator phases). During these periods, many decisions on the physical design of the kitchen were made to realize a full-scale version.

Furthermore, when the business model and supply chain model were discussed, they did not change significantly. The business model only switched from a lease model to a buy model in the proof-of-principle phase, and returning to a lease model was proposed in the prototype phase. The supply chain model did not change significantly at all after the proof-of-principle phase. Finally, preliminary ideas about tracking the parts were explored, but not elaborated on.

4.5 Lessons Learned

From the findings, we derive five lessons learned for developing circular building components, on the following topics: (1) ambition, (2) aesthetics, (3) design scale, (4) participation, and (5) focus. These lessons learned are not the only knowledge gained from the CIK development process, but we see them as the main points of attention that could have improved the CIK itself—whether to make it more circular or more feasible—and its development process. The following sections will describe these five lessons.

4.5.1 Lesson 1: Ambition

From Section 4.4.1, we can derive the first lesson learned from the analysis of the CIK project. We have seen a high circular focus at the start of the project, in which the best parts of all the proposed variants were selected and combined. However, throughout the process, we can identify two moments in which the circular focus decreases. Both of these decreases were mostly caused by the need to realize a fully functional component: the prototype was limited by the market availability of materials and the production techniques that were available. The changes from the demonstrator toward a market-ready CIK were limited by requirements set by the clients and possible investment costs for unconventional production methods.

In the CIK case, both decreases in circular ambition were caused by conditions that were known beforehand but were not seen as insurmountable. Although the ambitious variants chosen might have been seen as more circular, if they are not applied in practice due to lack of feasibility, the building practice does not become more circular at all, as sticking to the business-as-usual model is rarely the most circular option (Wouterszoon Jansen et al., 2022). However, we do recognize that what is feasible might change over time, and more ambitious designs might become more feasible later. Considering that lock-ins (see for example (Korhonen et al., 2018)) of non-circular or non-sustainable practices should be avoided at all times, we derive the following lesson: *prioritize implementing feasible circular options now, and improve to the most circular options over time.*

4.5.2 Lesson 2: Aesthetics

As can be seen in Section 4.4.2, not all requirements that led to a conventional aesthetic of the CIK were for the sake of aesthetics. We can distinguish two lines of reasoning when it comes to the required aesthetic for an HA's kitchen: (1) aesthetic to increase the expected acceptance among users, and (2) aesthetic as a result of functionality. However, both lines of reasoning ultimately have the same goal: user satisfaction, which is a crucial factor in the adoption of circular products—if the users are not satisfied, a transition to these products will not take place (Wastling et al., 2018). Although the 'most circular' design solution—on paper—might not be developed by trying to please as many users as possible, a design that is less circular but accepted by more users is more likely to be adopted. In turn, large-scale adoption of a product can make standardization more effective and reuse more likely. The lesson we can therefore derive is: *adjust the aesthetics to satisfy as many clients/users as possible.*

4.5.3 Lesson 3: Design Scale

For a circular design that relies on reuse through modularity, functioning reversible connections are paramount; if the parts cannot disconnect, they cannot be reused. In the CIK design, modularity was a key design element to decrease the environmental impact and life cycle costs. Another key design element was the material selection. Although both elements were considered from relatively early on, the assumption was made in earlier stages that it was a solvable problem, and the combination of material and connector was only tested in the prototyping phase. From this phase on, the combination of material and connector remained a challenge in the development of the CIK, and even led to reverting back to conventional materials, as a change in material—a detail-scale decision—would have large-scale consequences.

Conventional (architectural) design methods propose a converging design process, working from the larger scale without any detail or materialization, toward the smaller, more detailed scales in which materials and connections are ‘filled in’. However, the functioning of modular designs or designs that can be disassembled relies on the functioning of their details. Therefore, we derive the following lesson: *design at a large and smaller scale simultaneously or even design the details first.*

4.5.4 Lesson 4: Participation

The example of the KM’s participants in Section 4.4.4.1 shows that who is involved has a significant influence on the effectiveness of the process. This is especially true for the stakeholders that have a crucial role in the development, such as primary manufacturers. Furthermore, the example in Section 4.4.4.2 shows the importance of the participation of all the stakeholders that will have a role in the envisioned supply chain. These stakeholders each bring specific knowledge to the project and allow for better alignment of the value proposition between the stakeholders, making the component and its business model and supply chain more feasible, and possibly more circular. The lesson learned from these findings is, therefore: *involve people with the optimal amount of influence, technical knowledge, and focus on the project, and make sure all the relevant stakeholders are represented.*

4.5.5 Lesson 5: Focus

During the CIK development, a substantial focus on the physical design of the CIK can be seen. There are several factors that might have caused this focus. First, the requirements for the funding of the research project were to deliver a prototype in 2018 and to place demonstrators in real-world homes in a later phase. Second, the two main researchers involved in the development have a background in architecture, which could have led to a focus on the physical design. The involvement of certain stakeholders such as the kitchen manufacturer and a contractor, and the exclusion of others, such as a recycler (see also Section 4.4.4.2) could have affected the focus as well. Finally, the physical design of the product was the 'most urgent' problem to solve, since a fully functional product was needed now, while the changes in the supply chain accommodating CE loops would most likely be needed in more than 5 years. However, a system for tracking parts would have to be implemented from the sale of the first product. Furthermore, the business model should be defined when the product becomes available on the market since agreements regarding finances and liability should be agreed on before the sale.

In the CIK process, we have seen an attitude of "product first, and then we will figure out how to sell and reuse it". Although many authors state that the physical design, supply chain model, and business model should be developed integrally (Malabi Eberhardt et al., 2021; van Stijn et al., 2020), fully developing all three did not fit within the time and resources available for the CIK project, and eventually, the CIK's physical design was adapted to fit within the current supply chain and business model as much as possible. Since the environmental and economic performance of some designs can rely heavily on future cycles (Wouterszoon Jansen et al., 2022), these future cycles should be guaranteed in the design, business model, and supply chain model, from which we derive the following lesson: *plan for sufficient time and resources if the physical design, supply chain model, and business model are to be completely redeveloped integrally.*

4.6 Discussion

Our lessons learned can be used when developing circular building components in the future. However, there are several limitations to this study, and the lessons should not be applied without taking note of these limitations. First, some of the barriers found in the current literature can be recognized in the CIK development process (for an extensive list, see Appendix C). For example, the second most mentioned barrier—"additional time, labor and cost to design and construct circular design options" (Akinade et al., 2020; Charef et al., 2021; Cruz Rios et al., 2021; Giorgi et al., 2022; Guerra & Leite, 2021; Kanters, 2020; Torgautov et al., 2021)—and other barriers that were mentioned often—"circular design options and materials require higher initial investment" (Charef et al., 2021; Galle et al., 2021; Ghisellini et al., 2018; Guerra & Leite, 2021; Torgautov et al., 2021), and "risk or unwillingness to pay for long term financial benefits of CE that may not occur whilst up-front investment is needed"(Akinade et al., 2020; Charef et al., 2021; Galle et al., 2021; Selman & Gade, 2020)—align with the reasoning for the lesson about ambition. However, some barriers that are frequently cited in the literature are not represented in the CIK development. For example, the most commonly mentioned barrier—"lack of or ambiguous legislation and regulation for CE and circular design options" (Akinade et al., 2020; Condotta & Zatta, 2021; Cruz Rios et al., 2021; Ghisellini et al., 2018; Giorgi et al., 2022; Hjaltadóttir & Hild, 2021; Kanters, 2020; Selman & Gade, 2020)—is not reflected in our lessons. This could be caused by an absence of this barrier but also by regulations being considered implicitly by the stakeholders. Furthermore, barriers related to the use of non-virgin materials are not reflected directly in any of the lessons. Moreover, we do not claim that our lessons are the only lessons to be learned from our dataset; analyzing our dataset from other points of view may yield other results.

Second, since the five lessons were derived from the experiences of one case, we cannot claim that the lessons apply to all building components. The development of a circular structure (Malabi Eberhardt et al., 2021) can differ significantly from the development of a circular kitchen (van Stijn et al., 2020). Furthermore, the particular application of a lesson and the context in which it is applied influences its usefulness significantly. Since the CIK was developed in just one context—that of social housing in the Netherlands, with specific people from specific stakeholders, who did not comprehensively represent the supply chain—this could limit the generalizability of the research. Future research, involving more cases, in various contexts, should be done to further validate our findings.

Third, the lesson on ambition (lesson 1) might seem to suggest anything is better than business-as-usual. However, we stress that the focus on feasibility should be maintained within the context of striving to achieve the most circular outcome. Variants should be assessed using environmental and economic assessment methods to determine which variant is the most circular, within what is feasible. Furthermore, unsustainable lock-ins should be avoided. For example, if making an essential connector within a building component out of a low-impact, non-virgin material is not feasible now, and a material with high environmental impact has to be used, developers should design the possibility of replacing the high-impact material with a more sustainable alternative later, and not 'lock-in' the high impact material in the design.

Fourth, our lesson on participation (lesson 4), indicated a lack of participation from some stakeholders that were relevant to the CIK process. We would however also like to state the positive side, as many relevant stakeholders were involved in the process, and their active involvement contributed to gathering more realistic and relevant knowledge regarding the development of circular building components. Therefore, lesson 4 should not only be seen from the perspective of possible improvement for the CIK, but also from the perspective of how the CIK was already relevant to current practice while achieving a significantly better environmental and economic performance than the business-as-usual approach (Wouterszoon Jansen et al., 2022).

Finally, although our method analyzes stakeholders' choices, it does not offer a structured way to reflect on the learning process of individual stakeholders. By reflecting on the process as a whole, and through the validation of the outcomes with the stakeholders, however, we gained some insights into the learning process: (1) stakeholders transitioned from having no knowledge of the circular economy and being skeptical to becoming advocates. Most stakeholders became involved in other CE projects during or after the CIK project. (2) When asked to reflect on the process, multiple stakeholders stated that the involvement of a knowledge institute that is not affected by possible profit from the project, and funding that took away the financial risks for their businesses, provided them with an optimal learning environment. Nevertheless, the demonstrator kitchen that was developed did not turn out to be feasible in practice, for financial reasons among others.

This longitudinal study of one specific circular building component has shown that barriers to implementing CE principles can occur at different moments, can be overcome in many different ways, and that what is seen as feasible can change over time. Although the translation of multiple cases to barriers and enablers might be beneficial for the reach and generalization of these studies, valuable information can be lost. One can therefore ask whether long, complex development processes can, and should be reduced to barriers and enablers, or even to lessons learned, or whether a more holistic approach to such a single study is needed.

4.7 Conclusions

The built environment can be made more circular by gradually replacing building components with more circular components during construction, renovation, or maintenance. However, many different design options can be seen as circular, and knowledge of which design options lead to feasible components in practice can be beneficial for designers, policymakers, and other decision-makers in practice. Although existing studies provide a list of barriers that could indicate what does not make circular design options feasible, knowledge of the relative importance of these barriers, and when and why they occur remains limited. Therefore, we present a longitudinal case study of an exemplary circular building component: the CIK. The researchers actively co-created the CIK's design, supply chain model, and business model in multiple workshops and meetings, throughout five phases—from initiative to market implementation—and documented all the choices made. We then derived findings and initial lessons learned from the stakeholder choices, by iterative reflection on the process as a whole, and by in-depth analysis of the stakeholders' choices. These initial findings and lessons were then validated in a workshop with the stakeholders, and we presented the final findings and lessons learned in this article.

From the findings, we derived five lessons learned from the CIK process. First, we found that the circular ambition for the development of a component should always be framed within what is feasible, as implementing something more circular now is usually better than sticking to business-as-usual. Therefore, our first lesson is: *prioritize implementing feasible circular options now and improve to the most circular options over time*. Second, we found that the aesthetics of a component can determine the acceptance by clients and end users and that if the product is not satisfactory in terms of aesthetics, it will not be implemented broadly. Our second lesson is, therefore: *adjust the aesthetics to satisfy as many clients/users as possible.* Third, we found that decisions made on a scale that is traditionally considered toward the end of the development process in the built environment—the scale of details—generally has a significant impact on the feasibility and circularity of a component. Our third lesson is, therefore: *design at a large and smaller scale simultaneously, or even design the details first.* Fourth, we found that the participation of the relevant stakeholders is of great importance for the alignment of the value proposition, and the right focus and effectiveness of the process. Furthermore, who represents the stakeholders plays a significant role as well. Therefore, our fourth lesson is*: involve people with the optimal amount of influence, technical knowledge, and focus on the project, and make sure all the relevant stakeholders are represented.* Finally, we have seen a substantial focus on the technical, physical design of the CIK, while the supply chain and business model were considered to a lesser extent. Thus, the current supply chain and business models were mostly preserved, and we learned the following lesson: *plan for sufficient time and resources if the physical design, supply chain model, and business model are to be completely redeveloped integrally.*

Although we do not claim these lessons to be comprehensive, or applicable in all contexts, we believe they give an insight into the decisions when developing a circular component, and that they could help in the development of future components.

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5 Comparing Circular Kitchens

A Study of the Dutch Housing Sector

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ABSTRACT

The built environment can be made more circular by gradually replacing building components with more circular components during construction, renovation, or maintenance. However, many different design options can be seen as circular. Although there is a growing number of studies about circular design options, research on what makes these options feasible or not feasible in practice is limited. This type of research requires intensive, long-term involvement with practitioners. Therefore, this article presents a longitudinal case study of an exemplary circular building component: the circular kitchen. The researchers actively engaged in a co-creation with industry partners to develop a circular kitchen design, supply chain model, and business model. All the choices made from initiative to market implementation were documented. Five lessons were drawn from an analysis of the stakeholder choices that can aid the future development of feasible circular building components: about ambition, aesthetics, design scale, participation, and focus.

KEYWORDS

circular economy, circular design, building components, kitchen, circular kitchen, kitchen design, design comparison

5.1 Introduction

The built environment is responsible for a substantial part of all human-induced emissions, resource use, and waste globally (Ness & Xing, 2017). The Dutch housing sector will contribute significantly to these environmental impacts, as it is stands on the verge of a renovation wave to reduce operational energy use, and faces a crisis related to availability. Consequentially, 3.5 million homes are planned to be insulated and 1.5 million are set to transition to gas-free installations (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). While these renovations will decrease operational carbon emissions, they can significantly increase embodied impacts (Kennedy et al., 2007; Ness & Xing, 2017; Pomponi & Moncaster, 2017; Wijkman & Skånberg, 2015). To solve the housing crisis, one million homes are scheduled to be built in the next decade (Kences, 2021), further contributing to embodied impacts in the built environment. Hence, regulations on the environmental impact of new buildings will become stricter in the coming years (Kamerbrief over Beleidsagenda Normeren En Stimuleren Circulair Bouwen, 2022), and the government states that the applied renovation solutions should align with the principles of the circular economy (CE) (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022).

The CE is “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops” according to Geissdoerfer et al. (2017, p. 759). Narrowing loops aims to reduce resource use or achieve resource efficiency up front, slowing loops aims to use resources longer, and closing loops aims to (re)cycle end-of-life materials back to production (Bocken et al., 2016). Slowing and closing loops can be performed through value-retention processes (VRPs) such as reuse, repair, refurbishment, and recycling (Reike et al., 2018; Wouterszoon Jansen et al., 2020). To realize VRPs, components, parts, and materials should be considered from a systems perspective, focusing not only on the physical design (or technical model), but also on the supply chain (or industrial model) and business model (van Stijn & Gruis, 2019).

A gradual transition to a circular built environment can be achieved by replacing building components with circular components during renovation, maintenance, or construction. Kitchens are logical components to be made circular (Ollár et al., 2020); they have a relatively short lifespan (±20 years in the Netherlands) (Wouterszoon Jansen, van Stijn, & Eberhardt, 2022) and are produced as a standardized product. Furthermore, developing prototypes is seen as beneficial for the development of circular components (Dokter et al., 2023), which is relatively affordable for kitchens due to the low investment costs compared to a building façade, for example.

In line with the definition of the CE provided by Geissdoerfer et al., a circular kitchen can be defined as a kitchen that incorporates a technical model, industrial model, or business model that aims to narrow, slow, or close resource loops. Consequentially, kitchens can be made circular by applying many different CE strategies to their technical model, industrial model, and business model. For example, a kitchen can feature a modular design to facilitate reuse and updates, thereby slowing loops in the future. Alternatively, it can be constructed using biodegradable, renewable resources or lightweight materials, thereby narrowing loops in the present (Wouterszoon Jansen, van Stijn, & Eberhardt, 2022). However, not all designs are feasible in practice.

Knowledge of which types of circular kitchens are feasible in practice can facilitate future circular kitchen development, thereby accelerating the transition to a circular built environment. Therefore, this article aimed to determine which types of circular kitchens are feasible in practice. The circular kitchens that were analyzed (1) have been developed in the last 5 years and (2) are currently available or will soon be available—assuming that adoption in practice serves as an indicator of feasibility. It should be noted that the feasibility of circular kitchen types is context-dependent, varying between different countries (Wouterszoon Jansen, van Stijn, Gruis, et al., 2022). To ensure that the kitchens were compared equally, this research was limited to the Dutch housing sector.

5.2 Background

The number of articles published on the subject of CE has risen from under 20 publications in 2013 to over 100 in 2016 (Geissdoerfer et al., 2017) and has since continued to rise. Without claiming to be comprehensive, an overview of the relevant literature from this growing field of research will be provided in this section.

Numerous methods, tools, and frameworks have been developed to aid in the decision-making process when selecting from among various types of circular design options. These aids can be defined as either generative or evaluative (Bocken, Farracho, et al., 2014; de Koeijer et al., 2017).

Generative aids support the integration of circular strategies or options during the design process (van Stijn et al., 2022). Several authors have contributed to the development of design guidelines for a circular built environment, with an emphasis on achieving optimal environmental performance (Chiodo, 2005; Eberhardt et al., 2021; van Stijn et al., 2020, 2022; Zaman et al., 2023). A similar focus on environmental performance is found in the study by Kręt-Grześkowiak et al. (2023),who reviewed 70 articles that offer guidelines for design for disassembly and design for adaptability and proposed a design process framework. Mackenbach et al. (2020), on the other hand, proposed guidelines for circular buildings to overcome specific barriers. Other authors have focused on developing tools and frameworks for achieving a circular built environment. For example, Gillott et al. (2023) developed a CE design workflow tool that can be used in an early stage of the design process, while Minunno et al. (2018) applied a CE framework to the prefabricated building sector. Eberhardt et al. (2020) conducted a literature review to assess the applicability and readiness of strategies linked to the circular economy (CE) in the context of building construction. Additionally, some authors have developed or derived archetypes for CE business models (Bocken, Short, et al., 2014; Leising et al., 2018; Rosa et al., 2019; Urbinati et al., 2017). However, most of these articles did not study circular building components. Van Stijn et al. (2020 & 2022), Eberhardt et al. (2021), and Zaman et al. (2023) did develop aids specifically for circular building components, and van Stijn and Gruis (van Stijn & Gruis, 2019) reviewed 36 existing generative design aids and developed the "Circular Building Components Generator" (CBC generator), a generative tool for circular building components.

Evaluative aids help determine the "circularity" of a generated design, for which the environmental and economic performance is often assessed (Wouterszoon Jansen, van Stijn, & Eberhardt, 2022)— although some authors argue social performance should also be included (Hunkeler et al., 2008; Sassanelli et al., 2019). Life cycle assessment (LCA) and material flow analysis (MFA) are often seen as suitable methods to evaluate environmental performance (Corona et al., 2019; Pomponi & Moncaster, 2017; Sassanelli et al., 2019; van Stijn et al., 2021), while life cycle costing (LCC) is often seen as an appropriate method to evaluate economic performance (Bradley et al., 2018; Wouterszoon Jansen et al., 2020). However, these aids do not predict the feasibility of the practice of certain design options, as the complex context of the "real world" are simplified to measurable parameters or general design options.

Many authors have studied the feasibility of applying CE principles to this “real-world” by identifying barriers. Wouterszoon Jansen et al. (2022) provided an overview of these studies and concluded that only Azcarate-Aguerre et al. (2018 & 2022) focused on the building component level (a façade). Many of the authors have opted for a literature study, interviews with one or multiple stakeholders (once), or case studies of completed cases. Some authors have also conducted case studies of circular buildings or building components without identifying barriers as a goal. For example, Mangialardo et al. (2018) studied three cases of a building, while O’Grady et al. (2021) provided a thorough analysis of a prefabricated building, which they analyzed using a new circular-economy-based index for the built environment, proposing that this index could be used in the design stage of buildings. Kyrö et al. (2019) provided a case study of multiple relocatable buildings and detailed a framework to aid in the future development of such buildings. Leising et al. (2018) studied three cases (a newly built project, a renovation project, and a demolition project) and developed a collaboration tool. Maerckx et al. (2019) studied 14 cases of renovation or extension and derived multiple levers and obstacles, and Yan et al. (2019) studied examples of both types of building components from various continents.

However, only a few authors have specifically studied circularity in the kitchen industry. For example, Ollar et al. (2020) studied which aspects of stakeholders’ value propositions might contribute to circular housing design, with a focus on the kitchen, and Dokter et al. (2019) studied how co-creation can contribute to the implementation of a CE in the kitchen industry. For their Circular Kitchen (CIK) research project, Wouterszoon Jansen et al. (2022) developed and reflected on the development of a single circular kitchen over four years, deriving lessons for the development processes of other circular components. However, these authors either studied the circumstances under which a circular kitchen could be developed best or were limited to (single) kitchens that were in the design or development stage, and therefore did not derive feasible types based on multiple real-world cases.

None of the studies mentioned above provided insight into examples from practice, or their similarities and differences. Arguably, the knowledge of which types of technical models, industrial models, and business models would be feasible in practice for circular kitchens remains limited.

5.2.1 Circular Building Approaches and Circular Kitchens in the Dutch Housing Market

The Dutch building practice includes examples that can be regarded as proto-circular. For example, the "open building" by Habraken (1961) suggested separating buildings into layers (such as tissue, support, and infill), and standardized modules were introduced to allow for user customization and future upgrades. The industrial, flexible, and demountable building (IFD) (Maas & Van Gassel, 2003; Van Gassel, 2003) was built on the ideas of the open building and united flexibility with the industrialization of the building process. The "Slimbouwen" (Lichtenberg, 2005) is another example of separating the building into layers to improve the building process while allowing for future adaptations.

In more recent times, numerous instances of circular practices can be observed in the Dutch housing sector. These examples range from using "buildings as material banks" (for example, the "Circl" pavilion by ABN Amro (ABN AMRO, n.d.)), to bio-based construction systems (for example Iewan (Strowijk Nijmegen, n.d.), or "Kalkhennephuis" (Werkstatt, n.d.)), to flexible, movable container homes (for example, Finch modules (Finch Buildings, n.d.)).

Furthermore, multiple circular building components have been developed in the Dutch housing sector in previous years. Some of these components were developed in an academic setting, as part of a research project, such as the 2nd Skin Façade Refurbishment system (Azcárate-Aguerre et al., n.d.; Henry, 2018), the Façade Leasing Demonstrator (Azcárate-Aguerre et al., n.d.), the Circular Skin (van Stijn, 2023), the Circular dwelling extension, the Circular Net-Zero-Energy-Building (NZEB) renovation concept, and the CIK (Wouterszoon Jansen et al., 2022). Other components and products were developed independently of any academic research project. For example, The New Makers (TheNewMakers, n.d.) and Obimex developed circular interior partitioning walls (Obimex, n.d.), Phillips created a circular lighting solution called Signify (Signify Holding, n.d.), and Trebbe developed circular window frames (Trebbe Groep B.V., n.d.).

In addition to the CIK, several other circular kitchens have been developed in the Netherlands. Six circular kitchens were identified that are either available or soon to be available in the Dutch market. These kitchens were found by making inquiries with relevant stakeholders and by using Google search engines between August 2021 and May 2022, searching for "circular kitchen" and the Dutch translation of these terms. The CIK was included in the comparison, since it was intended to be implemented in practice, but will be implemented in a simplified version, being an example of a circular kitchen that generated knowledge and experience but was eventually not seen as feasible in practice. Table 5.1 gives an overview of these circular kitchens. Of these kitchens, four are produced by companies whose core business is kitchen production, and three are produced by companies that offer products outside of the kitchen sector. Furthermore, two of the manufacturers can be considered as well-established within the Dutch sector and have been manufacturing kitchens for over 10 years, while for the others, their circular kitchen is the first kitchen product they have produced. All of the circular kitchens were announced in the last 4 years, with the first circular kitchen being offered in 2018 (No Waste Kitchen), and some of the kitchens are not yet offered.

TABLE 5.1 Overview of the circular kitchens offered or announced for the Dutch housing market in 2022.

Kitchen Name	Kitchen Manufacturer	Kitchens as Core Business?	New or Established in the Kitchen Sector?	Announced	Available From	Data Collection
Blue Kitchen	Blue Kitchen	Yes	New	Unknown	unknown	company website, publications
Chainable Kitchen	Chainable	Yes	New	2020	2020	company website, publications, interview
Coulisse Kitchen	Coulisse	No	New	Unknown	unknown	company website, publications
Green Kitchen	DKG	Yes	Established	2021	2023	company website, publications, interview
NeverEnding Kitchen	Triboo	Unknown	New	2019	2019	company website, publications
No Waste Kitchen	The New Makers	No	New	2018	2018	company website, publications
the Circular Kitchen (CIK)	Bribus	Yes	Established	2017	will not become available as developed in the research prototypes	data provided by the research project, as published in (Wouterszoon Jansen, van Stijn, Gruis, et al., 2022)

5.3 Materials and methods

This research was conducted in five steps, as illustrated in Figure 5.1. In the first step, the existing circular kitchens that are either available or will soon be available to the Dutch housing market were identified by making inquiries with relevant stakeholders and using online search engines, for which the outcomes can be found in Section 5.2.1 and Table 5.1. Furthermore, the relevant literature was reviewed regarding evaluative and generative aids, circular building components and their feasibility, and circular kitchens. The evaluative aid that was utilized for gathering data and analyzing the selected circular kitchens was established in this step and is elaborated on in Section 5.3.1.

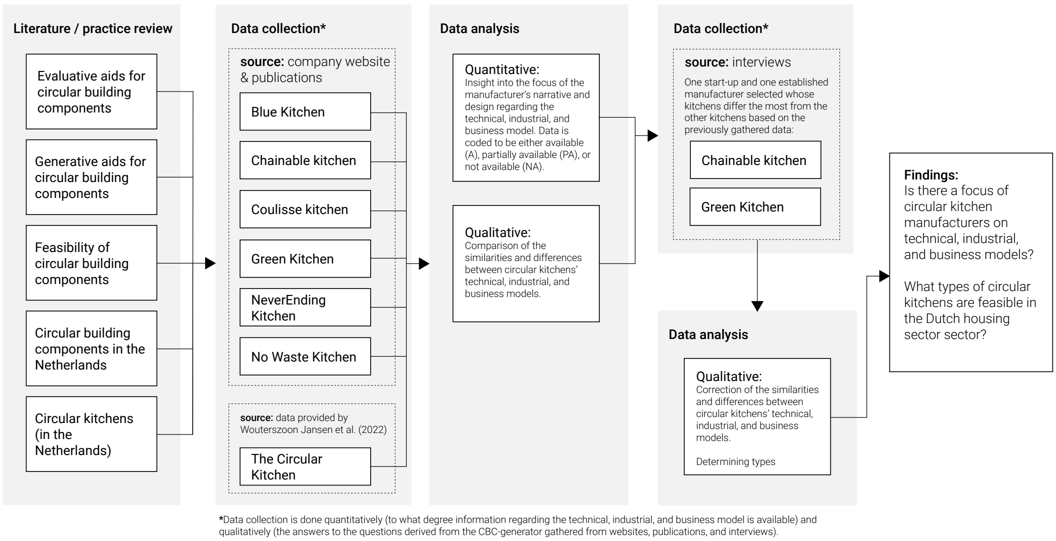

FIG. 5.1 Flowchart of the research approach of this study. Data for the Circular Kitchen were sourced from Wouterszoon Jansen et al. (2022).

In the second step, data were collected from the manufacturers' websites and publications about the kitchens. The data for the CIK were sourced from the existing research provided by Wouterszoon Jansen et al. (2022). Data collection (and analysis) was performed both quantitatively—to what degree information regarding the technical, industrial, and business model is available—and qualitatively—descriptions of the technical, industrial, and business model were gathered from websites, publications, and interviews.

In the third step, the data were analyzed. For the quantitative analysis, the data were coded according to three categories for availability and distinctness: available (A), partially available/unclear (PA), and not available (NA). The quantitative analysis provided insight into the focus of the manufacturer's narrative regarding their circular kitchen, which was assumed to be representative of the focus of the kitchen's design process, while simultaneously providing insight into the availability (and consequently, the representativeness) of the data utilized for this study. For the qualitative analysis, the similarities and differences between the circular kitchens were determined based on the design choices that were made for the technical, industrial, and business model.

In the fourth step, semi-structured interviews were conducted. Since not all manufacturers were available for interviews, a selection was made based on pre-existing data. Two of the six manufacturers (excluding the CIK) were selected based on two criteria: the type of manufacturer (one start-up and one established manufacturer were chosen) and the extent to which their kitchens demonstrated differences compared to the other kitchens, as determined through quantitative and qualitative analysis. The outliers were then selected. The purpose of these interviews was to verify the accuracy and comprehensiveness of the qualitative data from the other sources and to correct the similarities and differences that were found based on these sources. An interview guide (see Appendix D) was developed based on the evaluative aid that was selected for data gathering and analysis. Both interviews ($n = 2$) were conducted digitally through Zoom in Dutch, and the audio was recorded with the permission of the participants. The interviews were transcribed and coded in Microsoft Excel (see Appendix D).

In the fifth step, the qualitative data were corrected, and typologies of feasible circular kitchens for the Dutch housing sector were derived based on the similarities and differences that were found.

5.3.1 The CBC Generator as An Evaluative Aid

To conduct a comparative analysis of circular kitchens, an evaluative aid is needed. However, the existing evaluative aids generally compare the (quantitative) circular performance of circular kitchens, and this study aimed to compare the designs for the circular kitchen's technical model, industrial model, and business model. Therefore, LCA, MFA, or LCC were not applied. Rather, an evaluative aid was needed that categorized the design options for the technical model, industrial model, and business model.

The CBC Generator (van Stijn & Gruis, 2019) offers such a framework based on parameter option matrixes and design canvasses. The parameter option matrixes allow design teams to "mix and match" design options and create different variants for circular building components. This "mixing and matching" is performed by filling the design canvasses for the technical, industrial, and business models with the selected parameter options.

Nonetheless, the CBC generator was originally designed as a generative tool, while this study required an evaluative framework. Consequently, the CBC generator was modified and repurposed to serve as an evaluative tool for this study; instead of selecting parameter design options to construct a technical model, industrial model, and business model, the existing designs for these models were analyzed and deconstructed into sub-parameters based on the qualitative data that were collected. For example, if text descriptions and images were gathered that illustrate how the wooden panels of a circular kitchen can be disassembled from the steel frame, then the parameter options to "separate parts at the material boundary", to "separate support and infill", and to "use separable connections" can be used to deduce that biological and technical materials were used. Furthermore, the availability of information regarding the sub-parameters for the technical model (27 sub-parameters in total), the industrial model (9 sub-parameters in total), and the business model (10 sub-parameters in total) constitutes the input for the quantitative analysis. Figure 5.2 illustrates the use of the CBC generator as a generative tool (as it was originally developed), and as an evaluative tool (as it was used in this study). The interview guide was based on the parameters and sub-parameters provided by the CBC generator as well (see Appendix D for the relation between the CBC generator sub-parameters and the interview questions).

As the CIK was developed using the CBC generator, the process was merely reversed: it is known from the CIK research data which parameters were selected in the development of the technical, industrial, and business models.

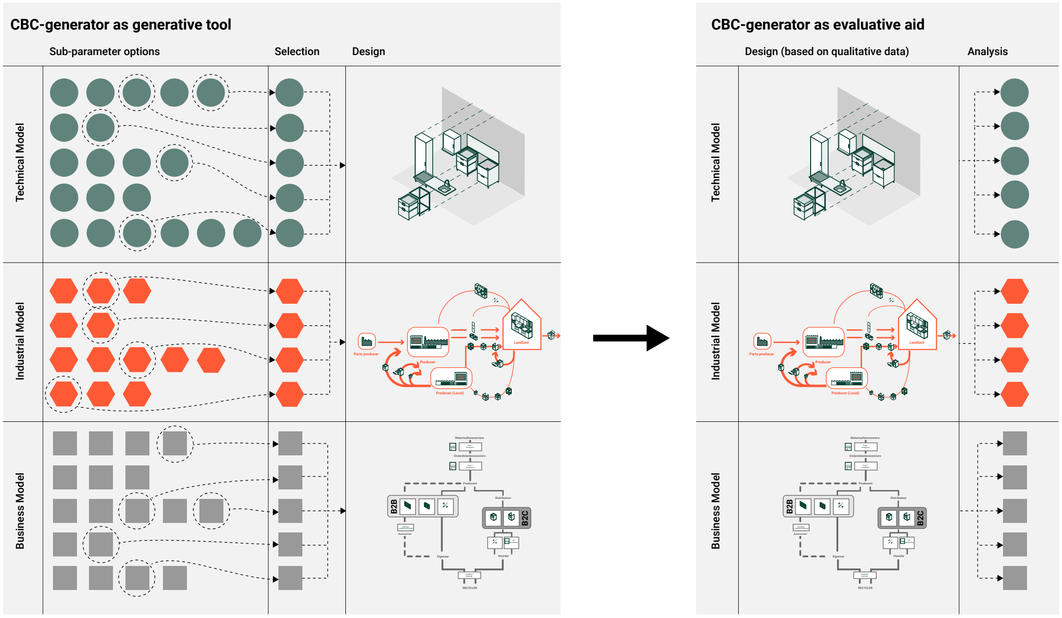

FIG. 5.2 Original use of the CBC generator (left) and adapted use of the CBC generator (right) for this study.

5.4 Results

This article aimed to determine which types of circular kitchens are feasible in practice. To do so, circular kitchens that are available or will soon be available in practice were analyzed and compared to find differences and similarities.

The results are discussed in three parts. First, the quantitative analysis of data availability is discussed. The availability of the data gives insight into the narratives of manufacturers regarding their kitchens. This narrative is assumed to represent the focus of the kitchen's design process and gives insight into whether more focus on the technical model, industrial model, or business model is feasible. Second, the outcomes of the interviews are elaborated on. These interviews functioned to verify the accuracy and comprehensiveness of the qualitative data from the other sources and to correct the similarities and differences that were found based on these sources. Finally, the similarities and differences between circular kitchens are discussed, and which types of circular kitchens are feasible in the current Dutch practice is determined.

5.4.1 Availability of Data for Sub-Parameters on Manufacturers' Websites and Publications

Table 5.2 shows whether data regarding the sub-parameters in the CBC generator were either available (A), partially available (PA), or not available (NA) through the websites of the kitchen manufacturers and publications about their kitchens, and Figure 5.3 shows the relative number of sub-parameters for which data are A, PA, and NA.

TABLE 5.2 Availability of data for sub-parameters on manufacturers' websites and publications, categorized as available (A), partially available (PA), or not available (NA) per kitchen and in total.

	Blue Kitchen			Chainable Kitchen			Coulisse Kitchen			Green Kitchen			Never-Ending Kitchen			No Waste Kitchen			The Circular Kitchen			Total			
	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA	A + PA
# available	13	12	21	17	9	20	7	2	37	1	0	45	4	6	36	11	10	25	32	0	14	85	39	198	124
% available	28%	26%	46%	37%	20%	43%	15%	4%	80%	2%	0%	98%	9%	13%	78%	24%	22%	54%	70%	0%	30%	26%	12%	61%	39%
Total #	46			46			46			46			46			46			46			322			

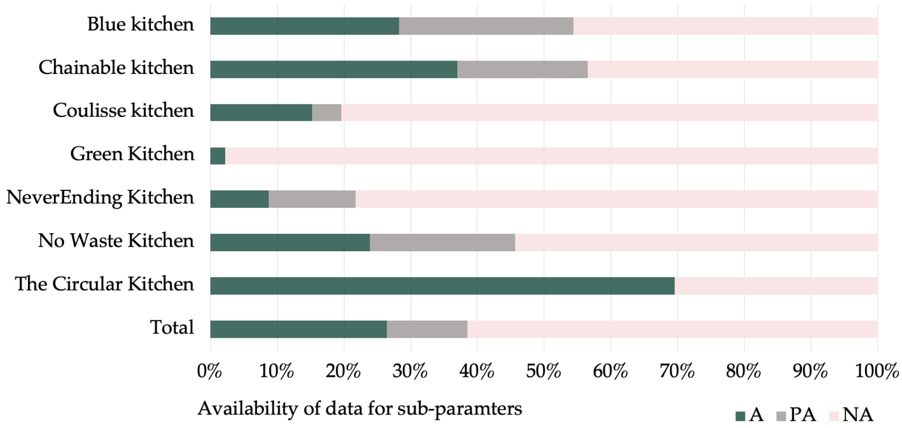

FIG. 5.3 Percentage of the data for sub-parameters that are available (A), partially available (PA), or not available (NA) per kitchen, and in total.

In total, 26% (85 out of 322) of the data were available, 12% (39 out of 322) were partially available, and 61% (198 out of 322) were unavailable. Some information was available (either A or PA) for 39% (124 out of 322) of the data. Since the CIK was developed using the CBC generator, it provided the highest amount of data: 70% of the data were either A (32 out of 46) or PA (0 out of 46). In some cases, the data for the CIK indicated that the sub-parameter was not applied. This was not counted as A or PA, therefore 100% A or PA was not reached. The website and publications regarding Chainable and Blue Kitchen also provided data for more than 50% of the sub-parameters: 57% (37% A and 20% PA) and 54% (28% A and 26% PA), respectively. On the other end, the website and publications regarding the NeverEnding Kitchen provided data for only 22% of the sub-parameters (9% A and 13% PA), and Coulisse Kitchen only provided data for 19% of the sub-parameters (15% A and 4% PA). The lowest amount of data was found for the website and publications regarding the Green Kitchen, which only provided data for 2% of the sub-parameters (2% A and 0% PA).

The difference in these numbers could be explained by the extent to which circular kitchens are the core business of a company. Some companies only produce circular kitchens, and thus their company website is dedicated to circular kitchens (Blue Kitchen and Chainable), while others either have different products (No Waste Kitchen and Coulisse) or have non-circular kitchens as their core business (DKG), and therefore only have a small section of information about their circular kitchens.

Figure 5.4 shows the relative amount of data regarding the technical, industrial, and business models that were available, partially available, or not available on the companies' websites, or from publications about their circular kitchens. The relative amount is shown as a percentage of the total number of questions in that category; for example, 41% of the data regarding the technical model were available for Blue Kitchen.

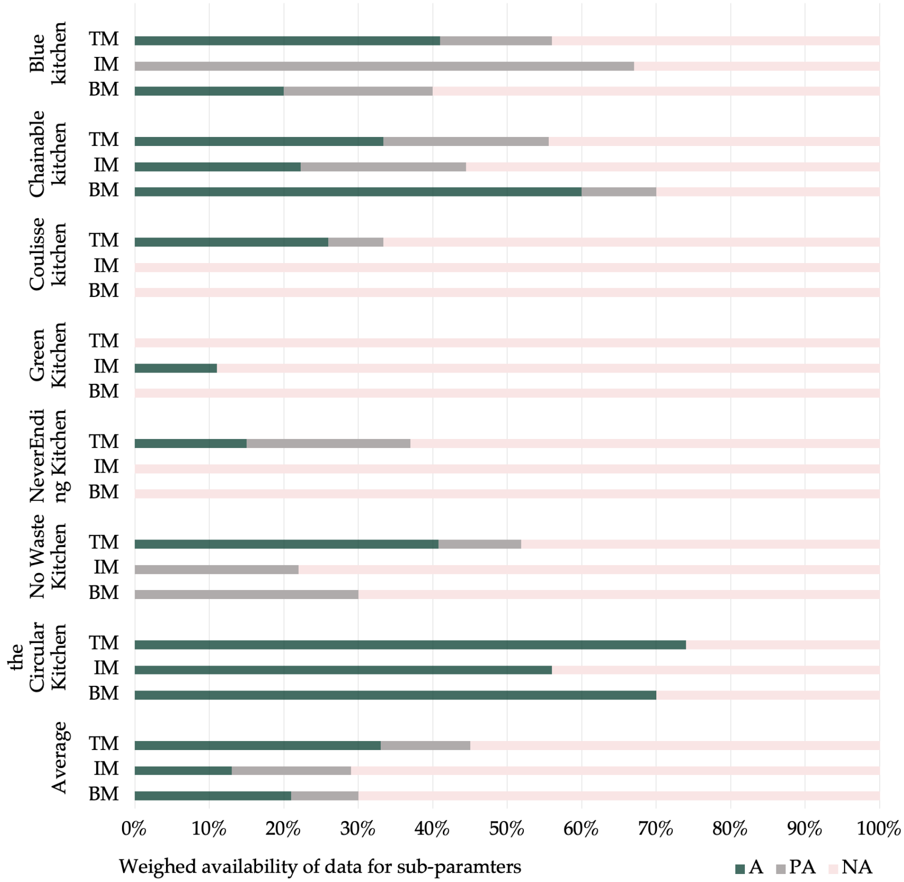

FIG. 5.4 Percentages of the data for sub-parameters that are available (A), partially available (PA), or not available (NA) per kitchen and on average per category (technical model (TM), industrial model (IM), and business model (BM)), weighed according to the number of questions in the category.

On average, the highest relative amount of data was available regarding the technical model (33%), followed by data regarding the business model (21%), and the lowest relative amount of data was available for the industrial model (13%). Moreover, 45% of the data (be it available, or partially available) were provided regarding the technical model, 30% for the business model, and 29% for the industrial model.

Figure 5.4 shows that some kitchen producers deviate from the average. First, it can be seen that Green Kitchen only provides some data regarding the industrial model. Furthermore, Chainable is the only producer that provides the highest amount of data (relatively) regarding the business model. These two outliers were selected for the interviews to check whether the sourced data were correct. The interviews are discussed in the next section. As the CIK was developed using the CBC generator, the data from the CIK research provided the most complete answers to all of the categories.

5.4.2 Interviews

In addition to gathering data from the websites and publications related to circular kitchens, interviews were conducted. Since not all manufacturers were available for interviews, two outliers were selected based on pre-existing data: Chainable (a start-up), where we interviewed one of the founders, and DKG (an established kitchen producer), where we interviewed a product manager. The participants were asked the questions as described in the interview guide (see Appendix D) to verify the pre-existing data, clarify the data that were unclear, and gather data that were partially available or unavailable.

Table 5.3 shows the availability of data as a result of the interviews. Similar to the data for the CIK, answers that suggested that a sub-parameter was not applied were not counted as A or PA. The results show that both Chainable and DKG have considered significantly more aspects related to the technical, industrial, and business models than they have published. Notably, Chainable provided an answer to 89% of the questions related to the industrial model, while their website and publications did not provide any data for the industrial model. Similarly, DKG provided an answer for 85% and 80% of the questions regarding the technical model and business model, respectively, while their websites did not provide any data.

TABLE 5.3 ercentages of the data for sub-parameters that are available (A), partially available (PA), or not available (NA) for the Chainable Kitchen and Green Kitchen from the company's website and pub-lications and the interviews, per category, weighed according to the number of questions in the category.

	Chainable Kitchen						Green Kitchen					
	Company Website, Publications			Interview			Company Website, Publications			Interview		
	A	PA	NA	A	PA	NA	A	PA	NA	A	PA	NA
Technical model	41%	15%	44%	89%	4%	7%	0%	0%	100%	85%	0%	15%
Industrial model	0%	67%	33%	89%	0%	11%	11%	0%	89%	78%	0%	22%
Business model	20%	20%	60%	90%	0%	10%	0%	0%	100%	80%	0%	20%

These additional data were used to refine the qualitative analysis of the technical, industrial, and business models of the kitchens. This was especially the case for DKG, who only mentioned the recovery of used kitchens on their website and answered most of the questions on their new concept during the interview. For the Chainable Kitchen, some data could be refined based on the interviews. For example, the expected lifespan of the kitchen's parts, where production of parts takes place, and which channels are used to sell the kitchen could be defined (see Appendix D).

5.4.3 Similarities and Differences between Circular Kitchens

Through an in-depth comparison of the results, most kitchen producers were found either not to have considered a change in their supply chain and business model from the business-as-usual model of sale without take-back or not to have mentioned it. Two manufacturers were an exception: (1) the Circular Kitchen elaborates the proposed supply chain and business model; (2) Chainable mentions take-back and also offers kitchens as a service.

As most of the kitchen producers focused on the technical model, most of the similarities and differences can be found here. Figure 5.5 shows the technical model of the Blue Kitchen. Notably, the Blue Kitchen combines a stainless-steel frame with bio-based panels. All parts are attached to the steel frame and can be disassembled and reused. Figure 5.6 shows the technical model of the Chainable Kitchen. Like the Blue Kitchen, the Chainable Kitchen uses a steel frame, to which bio-based panels are attached. The steel frame is standardized and self-contained, thus wall-mounting is not needed. The countertop is made of granite. Figure 5.7 shows the technical model for the Coulisse Kitchen. Like the Chainable Kitchen and Blue Kitchen, the Coulisse Kitchen uses a steel frame and bio-based panels, and like the

Chainable Kitchen, it is self-contained and does not need wall-mounting. The steel frame can also be disassembled; however, the Coulisse Kitchen is custom-made. Figure 5.8 shows the technical model of the Green Kitchen. The Green Kitchen is made from standardized bio-based panels but cannot be adapted after installation. The cabinets are directly mounted to the wall. Figure 5.9 shows the technical model for the NeverEnding Kitchen. It is made of bio-based panels that can be assembled and disassembled by its “plug-and-play” concept. The modular cabinets are mounted on a modular retaining wall, and all the parts can be recycled at the end of use. The NoWa Kitchen very closely resembles the NeverEnding Kitchen and is illustrated in Figure 5.10. Figure 5.11 shows the technical model of the CIK. Like the NoWa Kitchen and the NeverEnding Kitchen, it applies a plug-and-play concept, uses a retaining wall, and is made of bio-based materials (although different bio-based materials). However, instead of using a panel-based structure, the CIK uses a wooden frame, to which infill elements such as drawers and finishing panels can be attached.

The circular kitchens that were studied were bifurcated based on the choice of materials for the structure: technical (Blue Kitchen, Chainable, and Coulisse) or biological materials (Green Kitchen, NeverEnding Kitchen, NoWa Kitchen, and CIK). Furthermore, the kitchens that have a structure made of technical materials all use a frame structure, while most of the kitchens that use bio-based materials for the structure use panels (Green Kitchen, NeverEnding Kitchen, and NoWa Kitchen). Only the CIK design uses a bio-based frame structure. However, Bribus has since redeveloped the CIK to remain closer to the technical model of their current (non-circular) kitchens. Instead of a frame, this kitchen uses a panel structure as well, without a retaining wall.

Furthermore, the start-ups deviate further from the current standard kitchens for housing kitchens, which are made with bio-based (melamine-coated chipboard) panels that are glued together. This deviation is either in the material choice, by introducing more technical materials to prolong the lifespan of the kitchen, or by using a retaining wall to increase the adaptability of the kitchen. The established kitchen manufacturers develop circular kitchens that are more similar to the current standard kitchens (after redevelopment in favor of feasibility in the case of the CIK), using bio-based panels for the structure, and not using a retaining wall.

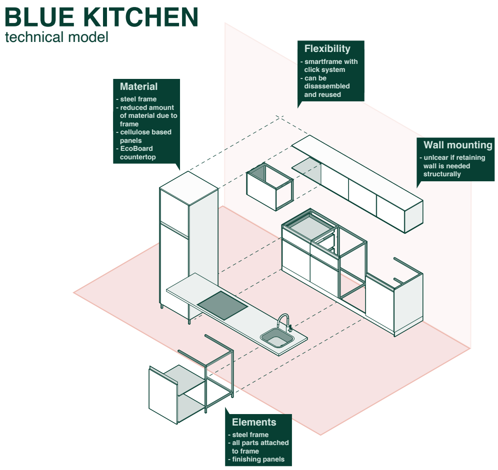

FIG. 5.5 Technical model of the Blue Kitchen

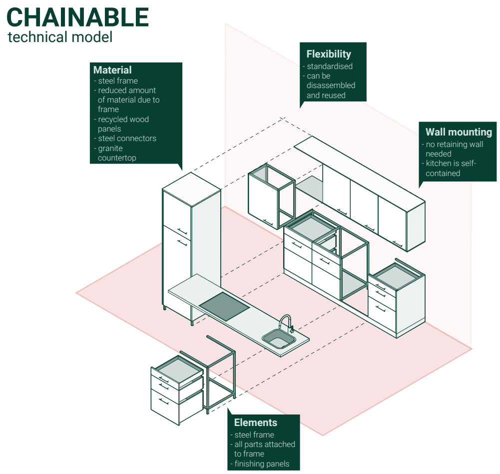

FIG. 5.6 Technical model of the Chainable Kitchen

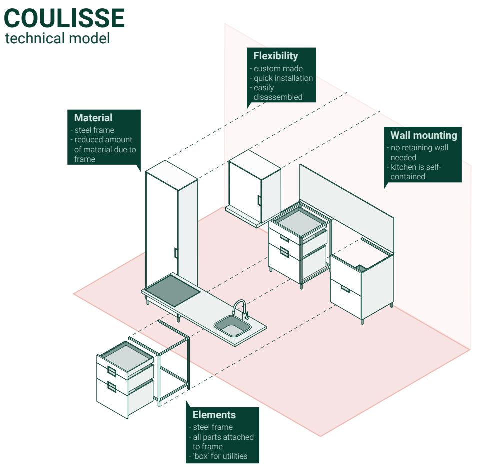

FIG. 5.7 Technical model of the Coulisse Kitchen

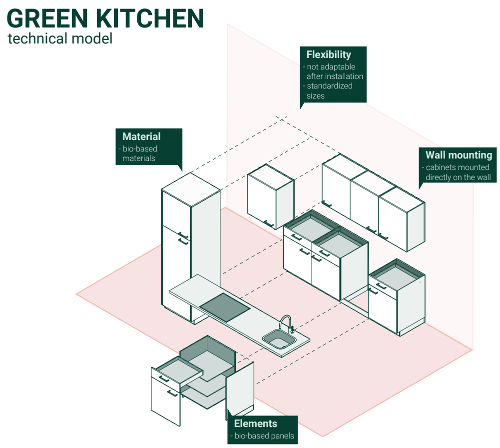

FIG. 5.8 Technical model of the Green Kitchen

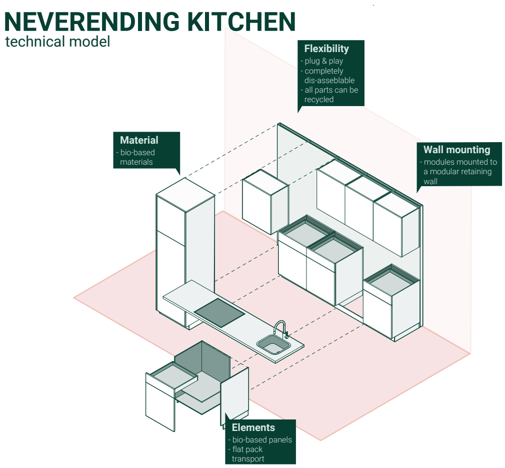

FIG. 5.9 Technical model of the NeverEnding Kitchen

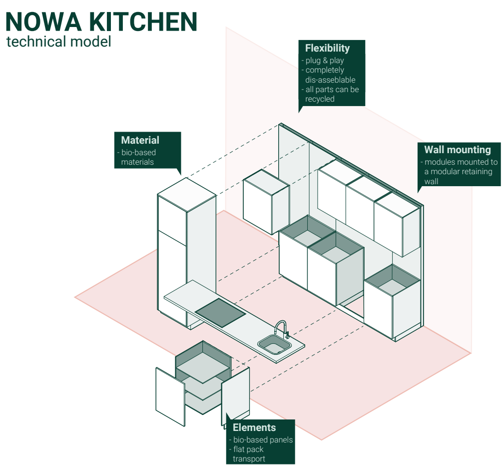

FIG. 5.10 Technical model of the NoWa Kitchen

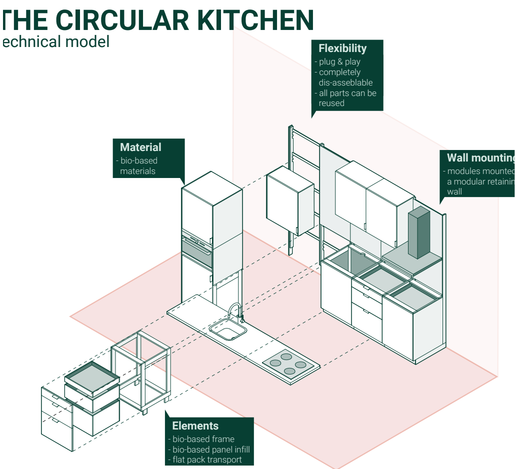

FIG. 5.11 Technical model of the CIK

Finally, all the circular kitchens have demountable parts, allowing for VRPs to take place, and prolonging the overall lifespan of the kitchen. Table 5.4 gives an overview of the circular kitchens that were studied, the materials of the structures if they use a retaining wall, and whether the parts are all demountable.

TABLE 5.4 Overview of the main types of circular kitchens. Whether a kitchen applies the design strategies is indicated with "•".

Kitchen Name	New or Established in the Kitchen Sector?	Structure Type		Retaining Wall			Demountable Parts	
		Biological Panels	Technical Frame	Yes	Optional	No	Yes	No
Blue Kitchen	New		•			•	•	
Chainable Kitchen	New		•		•		•	
Coulisse Kitchen	New		•			•	•	
Green Kitchen	established	•				•	•	
NeverEnding Kitchen	New	•		•			•	
No Waste Kitchen	New	•		•			•	
the Circular Kitchen	established	• *		• *		• *	•	

** The CIK technical model was redeveloped after the research project to be made of panels instead of a frame and not to have a retaining wall.*

5.5 Discussion

This study aimed to determine which technical, industrial, and business models for circular kitchens are feasible in practice. The circular kitchens that are currently available for the Dutch housing market were analyzed to do so, assuming that implementation adoption in practice is an indicator of feasibility. However, there was no insight into the number of sales or the financial feasibility of these kitchens. Additionally, kitchen types that have not been offered to the market cannot be excluded from being feasible, as this would assume that kitchen manufacturers have exhaustively considered all the design options based on actual feasibility in practice. Therefore, it cannot be claimed with certainty that the studied kitchens are feasible, or that these are the only feasible circular kitchens. Furthermore, the kitchen manufacturers mostly provided information regarding the technical model, and therefore did not indicate the industrial and business models' feasibility, while for a façade, examples can be found for development focusing on a business model (Azcárate-Aguerre et al., n.d.; Azcarate-Aguerre et al., 2018), as well as examples of a more holistic approach (van Stijn, 2023).

Consequentially, claims made by manufacturers about how "circular" or "sustainable" their circular kitchen is, are difficult to verify: a product or component cannot become circular just by having a circular technical model; a functioning industrial model is needed (if reuse is not organized in the supply chain, it cannot happen), and a business model is needed to incentivize circular behavior (if reuse takes more effort, but has no direct benefits, then it will become more unlikely). This is of special importance to the circular kitchens that rely on reuse to lower environmental impact and material use later in the life cycle.

Furthermore, whether transitioning to technical materials in an industry that uses largely biological materials serves the purpose of the CE should be questioned. These steel structures likely cause a higher environmental impact in the production stage (see for example Petersen & Solberg (2002)). Therefore, it can be argued that this transition from biological to technical materials is only beneficial if the purpose of the CE is only to reduce future waste and material use through the long-term reuse made possible by these technical materials. However, lowering human-induced emissions and preventing the depletion of raw materials are important goals of the CE as well. Previous studies have shown that applying circular strategies (especially when using metals for long-term reuse) does not always yield good environmental performance (for example, see Wouterszoon Jansen, van Stijn, & Eberhardt (2022)). However, combining circular strategies to narrow, slow and close loops has been shown to improve environmental performance (Cruz Rios et al., 2019; De Wolf, 2017; Eberhardt et al., 2021; Geldermans et al., 2019; van Stijn et al., 2022). Therefore, using biological materials where possible (narrowing the loop of finite materials, and reducing environmental impact in the production stage), and reusing all the materials (reducing material use, waste, and impact in late stages), as is achieved in the kitchens that use biological materials can be expected to have better environmental performance overall.

Notably, all the kitchens studied have applied designs for future slowing and closing strategies. Only very few have focused on (only) narrowing loops (for example, using smaller kitchens, or no kitchens at all, and using non-virgin materials). Arguably, one would expect kitchens to be designed and manufactured based on these strategies as well. However, kitchens that apply such strategies were not found by searching for "circular kitchen". This could be explained by an expectance of consumers/users not accepting smaller kitchens, users being expected to have a poor perception of non-virgin materials (users want a new product) (Akinade et al., 2020; Charef & Emmitt, 2021; Ghisellini et al., 2018; Torgautov et al., 2021), or doubts about the safety and quality of non-virgin materials (Condotta & Zatta, 2021; Cruz Rios et al., 2019; Giorgi et al., 2022). Other explanations can be that fitting non-virgin materials are not available at consistent quantities needed for kitchen production, due to a lack of reverse logistical mechanisms for the recovery of these materials (Adams et al., 2017; Akinade et al., 2020; Azcarate-Aguerre et al., 2022; Cruz Rios et al., 2021; Torgautov et al., 2021). A similar focus on adaptability is seen in Dutch proto-circular design practice, with Habraken (Habraken, 1961), IFD (Maas & Van Gassel, 2003; Van Gassel, 2003), and Lichtenberg's "Slimbouwen" (Lichtenberg, 2005).

Furthermore, the established kitchen manufacturers (eventually) have developed kitchens that are more similar to the current standard of (non-circular) kitchens. The bio-based frame structure of the prototype version of the CIK was a clear outlier compared to the circular kitchens offered in practice. Although this design performed well environmentally and economically (Eberhardt et al., 2021; van Stijn et al., 2020; Wouterszoon Jansen et al., 2020; Wouterszoon Jansen, van Stijn, & Eberhardt, 2022), it was eventually not seen as feasible in practice. If feasibility is judged by whether a kitchen is offered in practice, then this study confirmed that the CIK frame design would not have been feasible in practice. That Bribus eventually changed the design and DKG developed a circular kitchen that is more similar to their current non-circular kitchen could be explained by the significant investments that have been made in the existing manufacturing line and supply chain (such as machinery, or long-term supplier relations), incentivizing the development of new products that fit within this manufacturing line and supply chain (Wouterszoon Jansen, van Stijn, Gruis, et al., 2022).

5.6 Conclusions

To gradually achieve a more circular built environment, building components can be replaced by more circular components. One of the logical components to apply this to is the kitchen: a component with a relatively short lifespan that is produced as a standardized product, and for which producing prototypes is relatively affordable. However, knowledge of which types of technical, industrial, and business models for circular kitchens are feasible in practice remains limited. Therefore, circular kitchens were compared that are currently offered or will be offered soon in the Dutch housing sector. The CBC generator was adapted to function as an evaluative framework, data were sourced from company websites and publications, and interviews with two of the outliers took place to confirm and gather additional data.

As a result, six circular kitchens were found and the CIK was included, adding up to seven circular kitchens in total. Of these seven circular kitchens, two of their manufacturers can be described as established kitchen manufacturers, while the other five can be seen as start-ups. The established manufacturers were found to deviate less in terms of technical, industrial, and business models from the non-circular kitchens they are already offering, while the start-ups apply more radical innovations. Most of the kitchen manufacturers mainly provided information regarding the technical model, and all the manufacturers have applied strategies for slowing and closing loops in the future. However, sufficient information is currently unavailable concerning the industrial and business models, and the kitchens or their parts have not yet reached their end of life, as they were developed recently. Hence, the realization of these future loops and the actual benefits of applying circular strategies to these kitchens remains uncertain.

Furthermore, a bifurcation was found based on the choices of materials for the structure, and whether this structure is a frame (in the case of technical materials) or is based on panels (in the case of biological materials), with the CIK being a clear outlier with its bio-based frame structure. The adaptation of the CIK design by its manufacturer before it became a market-ready product confirms the lack of feasibility of a bio-based frame structure. Another clear difference between the circular kitchens was the use of a retaining wall. This wall was not exclusively applied in either frame- or panel-based structure kitchens but appeared in both. Finally, all of the kitchens that were found and compared in this study prioritized circular design options to slow and close future cycles. This strategy has been suggested to improve the environmental performance of circular building components as well (van Stijn et al., 2022)

This study is limited to circular kitchens in the context of the Dutch housing sector and relies on information that was available from kitchen manufacturers' websites, online publications, and two interviews. Therefore, the outcomes of this study might not be generalizable in other contexts. Additionally, the feasibility of certain types of circular kitchens can change over time, with currently feasible types potentially becoming unfeasible in the future while new types emerge as feasible alternatives. Furthermore, the absence of certain types in practice does not necessarily indicate their lack of feasibility.

Although this study is not exhaustive, it indicates which types of circular kitchen technical models are feasible in practice. Such knowledge, and knowledge of how circular kitchens differ could facilitate easier implementation of future circular kitchens, as conforming to types that have proven to be feasible can reduce the effort needed to develop such a kitchen, while learning from less successful cases provides useful insights as well. Furthermore, conforming to certain types of circular kitchens can be a step towards industry-wide standardization, making VRPs in a CE more likely. It should be acknowledged that this study has also demonstrated a disparity between ideal and feasible circular designs within a research project (such as the CIK) and what is feasible in practice. Hence, future researchers undertaking circular component development in a research context should prioritize incorporating market implementation as a crucial step. Finally, it is recommended that future researchers investigate the feasibility of circular kitchens in different contexts, as well as explore the feasibility of circular designs for other building components. The adapted CBC generator, utilized in this study, can serve as a valuable tool for such investigations.

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6 Conclusions

The building industry is crucial in society's pursuit to become more sustainable. Transitioning to a Circular Economy (CE) could support minimizing resource use, environmental impacts, and waste in the built environment. This transition can occur through replacing building components with more circular alternatives during new construction, renovation, and maintenance.

Circular kitchens are a promising component to focus on for achieving circularity due to several favorable factors. Kitchens are relatively simple to manufacture, have less complex supply chains compared to other components, and are used in 'controlled' indoor environments. The present standardization in kitchen design allows for modular parts, aiding value-retaining processes (VRPs), and with lower client investments needed, financial risks are reduced. Additionally, their shorter service life and frequent replacement create ongoing demand for production, encouraging investment in kitchen machinery. There are many ways to develop circular building components such as a circular kitchen. Strategies for narrowing, slowing, and closing loops can be applied separately or in combination, different types of materials can be applied, and circular variants for the technical, industrial, and business models can be developed.

In this research, the aim was to develop a feasible (or probable) Circular Kitchen (CIK) that reduces environmental impacts compared to current, non-circular kitchens (i.e. a CIK that is desirable). This was conducted within the Dutch housing sector, specifically focusing on housing associations as the primary clients for circular kitchens. Their significant presence in the Dutch housing market and their long-term investment strategy make them key drivers for the transition to a CE in the built environment. To generate knowledge for and from this process, four research goals (RGs) were defined (see Section 1.5.2). In the first study, RG1 was addressed by developing an LCC method to evaluate the economic performance of circular building components. The second study focused on RG2, where the environmental and economic performance of various circular building component variants was evaluated. The third study revolved around RG3, drawing lessons from stakeholders' choices in the CIK development to aid the future development of feasible circular building components. Lastly, the fourth study addressed RG4, researching the feasibility of various circular kitchens from outside of the CIK project and examining their similarities and differences with each other and the CIK.

This concluding chapter begins with a summary of the key findings regarding the four research goals, as discussed in Sections 2-5. Section 6.2 presents the conclusions concerning the research's design goal and reflects on the comprehensiveness and generalizability of this study. Section 6.3 offers three new insights by reflecting on the research as a whole.

6.1 Summary of conclusions per research goal

6.1.1 Conclusions RG1

RG1. Develop an LCC method that determines the economic performance of circular building components.

In this study, three main life cycle costing (LCC) approaches were outlined, including Conventional LCC (C-LCC), Environmental LCC (E-LCC), and Societal LCC (S-LCC). C-LCC has a single stakeholder perspective, often excluding the complete life cycle, particularly end-of-life scenarios. E-LCC broadens the perspective by involving multiple stakeholders, while S-LCC encompasses direct and indirect costs to society.

The Circular Economy involves various stakeholders, such as manufacturers, customers, and end-of-life actors. E-LCC, when used in conjunction with life cycle assessment (LCA) and incorporating all stakeholders, provides a foundation for Circular Economy LCC (CE-LCC). However, existing methods do not fully address the complex, multiple use cycles inherent in Circular Economy products.

To support the development of circular products, existing LCC techniques were adapted to (1) consider products as a composite of components and parts that have varying and multiple use cycles, (2) include processes that take place after the end of use, (3) provide practical and usable information to all stakeholders, and (4) allow for alignment of the functional unit and system boundaries with LCA. A new LCC method, CE-LCC (see Figure 6.1), was developed and applied to compare three CIK variants and a business-as-usual case. Out of these, the most adaptable

CIK variant demonstrated the most favorable long-term LCC outcome, considering various scenarios, including interest rates, the anticipated technical lifespan of parts, and VRP percentages. The CE- LCC model can provide decision makers with an economic assessment that is an essential part of a comprehensive circular assessment. In doing so, it can support the transition towards a more sustainable (building) industry.

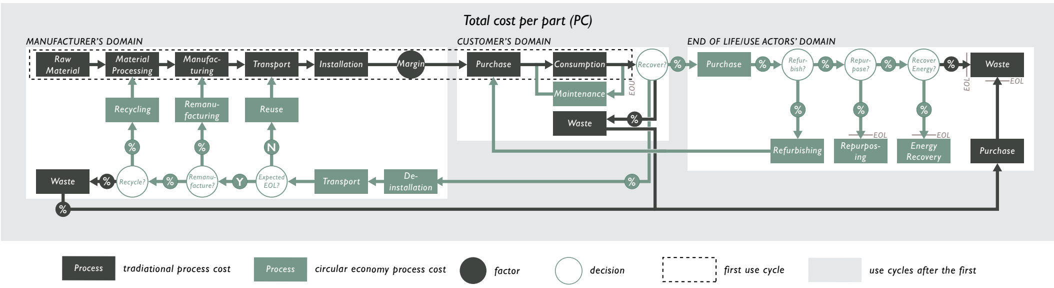

FIG. 6.1 The overall structure of use cycles of a part in the CE-LCC model.

6.1.2 Conclusions RG2

RG2. Identify which types of circular building component variants perform best environmentally and economically.

This study aimed to determine which pathway, biological (BIO) or technical (TECH), yields the best circular performance for building components, defined as a combination of environmental and economic performance. The circular performance of variants for circular kitchens and façades was assessed through circular environmental assessment (CE-LCA, expressed in shadow costs, a single, prevention-base indicator, and MFA) and circular economic performance assessment (CE-LCC, expressed in total costs (TC)).

The results, as seen in Table 1.1, indicated that biological solutions consistently excelled in shadow costs but performed second best and worst in the MFA for the kitchen and façade, respectively, while also ranking the lowest economically. In contrast, technical solutions consistently ranked highest in the MFA and could reduce environmental impacts by gradually replacing parts. However, the technical kitchen scored second best in shadow costs and best in TC, whereas the technical façade ranked lowest in shadow costs and third best in TC. The HYBRID variant of the façade demonstrated the potential for achieving better results by purposefully combining biological and technical materials.

TABLE 6.1 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

Importantly, the business-as-usual (BAU) components consistently ranked lower than circular variants on all indicators, highlighting the potential for improving the environmental and economic performance of building components through circular pathways. The study concluded that there was no one-size-fits-all approach; the key to enhancing circular performance lay in effectively applying materials and circular design principles. The recommended approach involved mitigating environmental impacts while avoiding excessive material imports and extending lifespan through the use of biological and technical materials as appropriate. Simultaneously, gradual replacements should be realized to extend the lifespan of the entire component and introduce multiple future cycles for components, parts, and materials.

This study reinforced the notion that continuing with the business-as-usual approach is never the best option. Instead, a transition to a more sustainable built environment can be achieved by implementing circular building components.

6.1.3 Conclusions RG3

RG3. Draw lessons from stakeholders' choices in the CIK development that can aid the future development of feasible circular building components.

This study focused on identifying choices that stakeholders made toward a feasible circular design and the impact of those choices, aiming to support designers, policymakers, and decision-makers in other circular design processes. A longitudinal case study of a circular building component, the CIK, was conducted. The researchers actively co-created the CIK's design, supply chain model, and business model throughout five phases, documenting all decisions made by stakeholders. Five lessons were derived by analyzing these stakeholders' decisions and reflecting on the development process.

Lesson one emphasized the importance of prioritizing feasible circular design options over more ideal circular options, as the immediate implementation of circular solutions is more beneficial to a more sustainable built environment than postponing the implementation to create a 'more circular' design. The second lesson underscored the significance of component aesthetics for broad acceptance among clients and end-users, highlighting the need for satisfying various preferences. The third lesson stressed the substantial impact of decisions made at the detail scale on a component's feasibility and circularity, recommending simultaneous design at different scales. The fourth lesson emphasized the importance of participation of stakeholders that are representative of the whole supply chain in aligning the value proposition and ensuring effective project focus. It suggested involving individuals with optimal influence, technical knowledge, and project dedication. The fifth lesson revealed the need for sufficient time and resources when considering integral redevelopment of the physical design, supply chain model, and business model.

While these lessons may not cover all contexts comprehensively, they offer insights into decision-making during circular component development, potentially aiding future component development.

6.1.4 Conclusions RG4

RG4. Identify which types of circular kitchens are feasible in practice, and examine their similarities and differences with each other and the CIK.

In this study, seven circular kitchens, including the CIK, were identified and compared to identify which types of circular kitchens are feasible in practice. These kitchens can be seen in Figure 6.2 a-g.

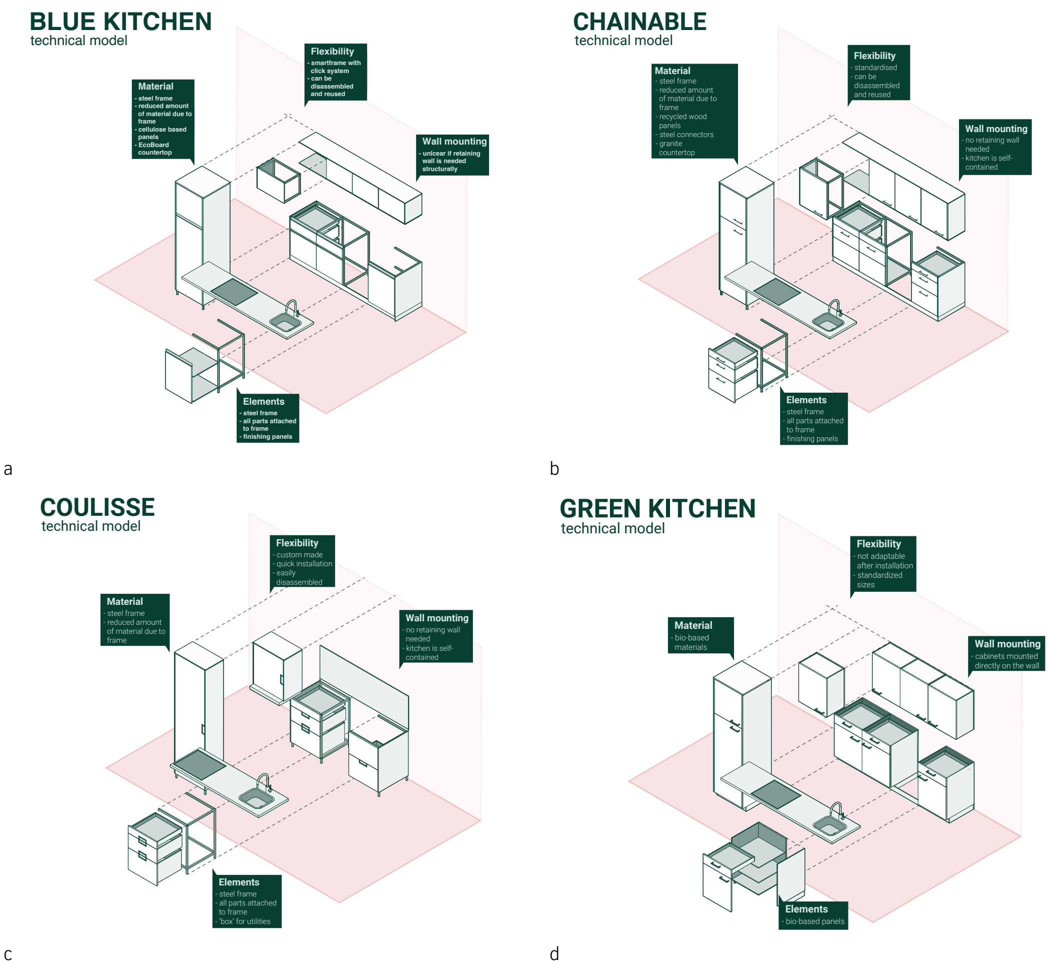

FIG. 6.2 Technical models of the (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, and (g) CIK.

TOC

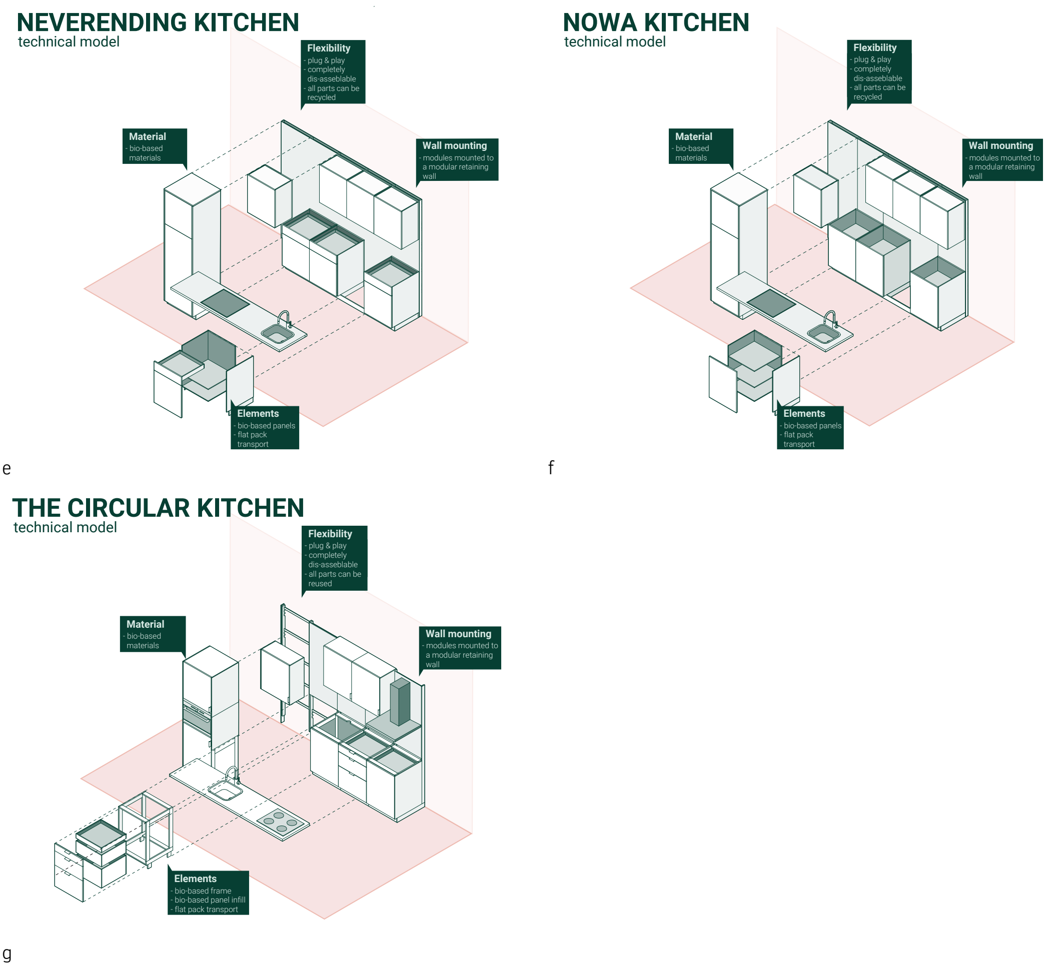

FIG. 6.2 Technical models of the (a) Blue Kitchen, (b) Chainable Kitchen, (c) Coulisse Kitchen, (d) Green Kitchen, (e) NeverEnding Kitchen, (f) NoWa Kitchen, and (g) CIK.

These kitchens were manufactured by both established companies and start-ups, revealing differences in the degree of innovation applied. The established manufacturers tended to align more closely with non-circular kitchen models, while start-ups implemented more radical innovations. Detailed information was primarily available concerning the technical model, while insights into industrial and business models were relatively scarce.

Notably, the kitchen designs displayed a bifurcation based on material choices for their structure, specifically between frame structures using technical materials (in this case steel) and panel-based structures using biological materials (different types ranging from plywood to cellulose panels). The CIK stood out with its bio-based frame structure, which was later adapted by the manufacturer, indicating its infeasibility. Notably, some designs included a retaining wall, either optional or mandatory, while others did not, but this application did not depend on the type of construction that was used in the kitchen design.

All of the examined circular kitchens prioritized circular design options to facilitate closing future loops, thereby enhancing their long-term environmental performance. However, it is crucial to acknowledge that the feasibility of circular kitchen types may change over time, and the absence of certain types in current practice does not necessarily signify their infeasibility. Additionally, since these kitchens were recently developed and none have reached their end-of-life stage, the extent to future resource loops will be closed and the actual benefits they will yield remains uncertain.

This study, while specific to the Dutch housing sector, provides valuable insights into feasible circular kitchen technical models. Such knowledge can ease the implementation of future circular kitchens, potentially streamlining industry-wide standardization and enhancing the circular transition. The study also highlights the disparity between ideal and feasible circular designs in a research context, and circular kitchens in practice, emphasizing This study, while specific to the Dutch housing sector, provides valuable insights into feasible circular kitchen technical models. Such knowledge can ease the implementation of future circular kitchens, potentially streamlining industry-wide standardization and enhancing the circular transition. The study also highlights the disparity between ideal and feasible circular designs in a research context, and circular kitchens in practice, emphasizing the importance of considering market implementation in such projects.

6.2 Conclusions on the design goal

In this section, the conclusions of the four research goals are brought together to reflect upon the design goal of this research. The main design goal was to develop a Circular Kitchen that is feasible in practice and performs better environmentally than non-circular kitchens.

If a component is feasible in practice, it would achieve Technology Readiness Level (TRL) 9: actual proof of real-world system operation. See Figure 6.3 for all the TRLs. Some authors have published articles related to the development of circular building components throughout some of the TRLs. For example, van Stijn (2023) published on the development of 8 circular building components (including the CIK) from TRL 1 (see van Stijn & Gruis (2018)) up to TRL 7 (see (van Stijn et al., 2023)). Furthermore, many publications resulted from the Circular Retrofit Lab where a cluster of student housing units transformed into a demonstrator lab. This involved implementing dynamic solutions for internal partitioning, technical services, furniture, and building facades (see, for example, Brancart et al. (2017), Cambier et al. (2021), and Rajagopalan et al. (2021)). Yet, these studies did not include the concluding TRLs, as is accomplished in this research.

By aiming to develop a Circular Kitchen that is feasible in practice, the CIK should have progressed through all the TRLs, and in doing so, would have contributed to bridging the gap between theory and practice by providing actual proof of real world application.

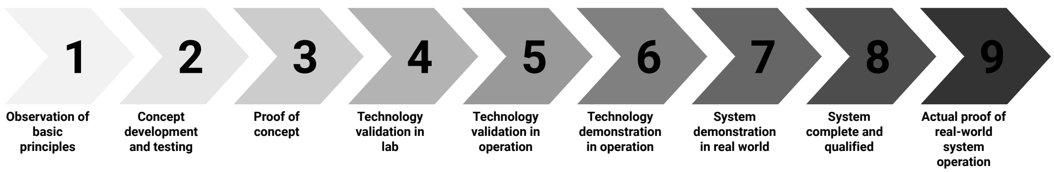

FIG. 6.3 Overview of different technology readiness levels (TRL), adapted from Hensen et al. (2015).

So, was this goal reached? Was the CIK feasible in practice, and did it perform better environmentally than current, non-circular kitchens? And if not, which strategies would be advisable to develop a better circular kitchen? The following sections aim to answer these questions.

All CIK designs evaluated outperformed the current standard non-circular kitchen. Among them, the demonstrator CIK design (TECH kitchen in Study 2) exhibited the highest performance in the MFA and the second-highest in the CE-LCA. Conversely, the BIO kitchen showcased the best performance in the CE-LCA and the second-best in the MFA. However, while the performance of the BIO design relies on a similar lifespan, replacement rate, and method as the current non-circular kitchens, implementing the CIK design based on technical pathways necessitates substantial changes in the supply chain and business model. Failure to realize these changes and a decrease in the adoption of VRPs, or alterations in financial agreements (such as including incentives for VRPs), may render other components more environmentally favorable. Biological solutions offer greater environmental performance assurance, as their impact primarily occurs at the beginning of the use cycle and does not depend on VRPs occurring in the (distant) future. Economic performance was seen as a pivotal aspect in evaluating the CIK's feasibility, with stakeholders emphasizing the importance of minimizing total costs (of ownership) and ensuring the retail price did not significantly surpass that of conventional non-circular kitchens. In study one, despite the CIK's higher initial purchase cost (50% more than non-circular kitchens), the most adaptable CIK variant proved to have the lowest total cost over periods longer than 20 years. The second study confirmed these findings, albeit with a new comparison between the TECH kitchen and a biological circular kitchen.

However, as evident from studies three and four, the CIK was not feasible beyond the research setting and did not find practical application as initially intended. There are several plausible explanations for this outcome, with some being apparent from studies three and four, and insights from the kitchen manufacturer. First, although aiming to do so in the future, housing associations still only sparingly prioritize total costs for investment decisions. Second, the mass production of the CIK design would have necessitated significant investments in production facilities for the kitchen manufacturer. Finally, the decision to make these investments coincided with unforeseen negative feedback received after placing the CIK demonstrator in several homes. In conclusion, the design goal was not reached: the CIK fell short of reaching TRL 7 and did not reach application in the real world.

Nevertheless, to advance our understanding of making circular kitchens feasible in practical terms, seven circular kitchens were analyzed in Study 4, with five operating at TRL 9. In doing so, the knowledge gap that remained because of the CIK not reaching TRL 9 was stil closed, and additional insights into why the CIK was not feasible in practice and knowledge on how circular kitchens could become feasible at TRL 9 were still generated. These insights, along with all the other knowledge gained throughout this research project is currently being applied to further develop new circular kitchens, both nationally and internationally[6].

6.3 Reflections

This research examined circular kitchens from a multitude of perspectives, encompassing all stages of development across four studies. By combining knowledge from these studies, this research can offer more than the sum of its parts. In this concluding section, three new insights are presented, derived from reflecting on the research outcomes as a whole: (1) how to possibly make better, more feasible circular kitchens, (2) how to approach designing for a circular built environment, and (3) how to apply the CE to increase its potential contribution to a more sustainable built environment. These reflections offer implications for practice, as well as directions for further research.

6.3.1 Reflections on better, more feasible circular kitchens

As can be concluded from Section 6.2, the CIK design was not feasible in the context that it was envisioned in. But how could a circular kitchen be feasible in the context of the Dutch housing sector? And how could that feasible circular kitchen still yield better environmental performance than the current standard kitchen? This section will aim to answer those questions by combining conclusions and insights from all four studies.

6 Kitchen manufacturer Bribus is currently working on the implementation of a new circular kitchen design and is collaborating with Chalmers University on an international circular kitchen research project called ‘The circular kitchen 2.0’.

Study four revealed that circular kitchens had both been developed and applied in practice by start-ups and established manufacturers. The former tended to employ radical circular innovation, while the latter focused on incremental improvements to enhance the circularity of their existing products. The manufacturer of the CIK, being an established manufacturer, also chose the path of incremental improvements following the completion of the CIK research project. As a result, when striving for large-scale implementation, it is advisable to prioritize the feasibility of the design while concurrently making incremental enhancements to its environmental performance. High feasibility can be attained by concentrating on reducing initial purchasing costs and aligning production methods, business models, and supply chains with current industry standards. Incremental improvements in environmental performance can be achieved by narrowing material loops up front through the application of lower-impact materials or materials that have a longer lifespan wherever possible at relatively low costs and with minimal adaptations, as well as slowing potential future loops through standardization, modular design, and the use of demountable joints at selected points to facilitate repairs, replacement of finishing materials, and minor adjustments.

When a manufacturer is unable or opts not to produce a new product on a large scale from the outset, they can explore more innovative circular designs that aren't constrained by existing production facilities that have already incurred substantial investment waiting for returns, or large-scale clients that still mostly focus initial costs. These radical designs can aim for optimal environmental performance by narrowing material loops up front through the substitution with lower-impact materials or materials that have a longer lifespan and slowing and closing future loops through standardization, modular design, and the use of demountable joints for repairs, adjustments, reuse, and recycling. Design decisions can be based on the feasibility of total costs, and designs can apply different production methods, business models, and supply chains from the current industry standard. Notably, it is important that production, sales, reuse, and recycling remain viable, and that ongoing efforts are directed towards making incremental enhancements in financial feasibility to expand market share, and with it, to increase total environmental benefits. These considerations and priorities are shown in Figure 6.4.

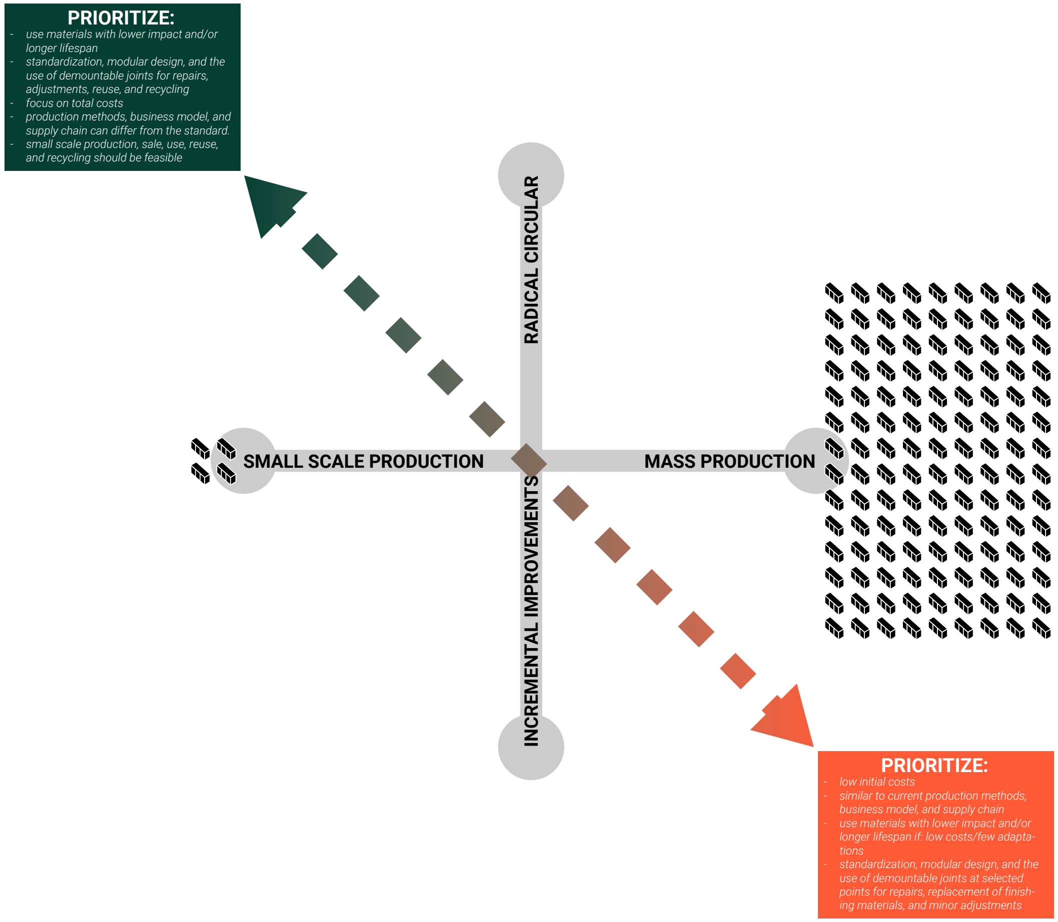

FIG. 6.4 Circular design priorities based on the intended initial scale of production

6.3.2 Reflections on designing for a circular built environment

Certain circular design strategies necessitate more extensive changes in the technical model (physical design), supply chain model, and business model of building components than other design strategies. For instance, in scenarios where materials can be replaced by renewable, biodegradable alternatives (see the biological components in Section 3), minimal alteration is required in the business and supply chain models, primarily impacting the treatment of 'waste' after the component's end-of-life. Conversely, achieving environmental benefits through re-use cycles in modular, technical circular designs demands significant adjustments in the supply chain and business models.

Although this need for alternative supply chain and business models is known, Study 3 indicates (see Section 4.5.3) that even adopting an alternative design method is essential to effectively design for re-use cycles for these modular components as well. This section elaborates on such an alternative design method for circular building components[7].

6.3.2.1 Conventional product and architectural design methods

As standardized modular building components could be produced as a product, design methodologies pertinent to product design, as well as those associated with building design, become significant. Although scholars in product design theory acknowledge that many design phases tend to overlap or occur concurrently in practice (Milton & Rodgers, 2011), they typically propose the following phases, or variations thereof: (1) product planning, (2) conceptual design, (3) embodiment design, (4) detailed design, (5) testing, and (6) production (Ginting, 2020; Roozenburg & Eekels, 1995; Ulrich & Eppinger, 2008). Designs are generally abstract (or global) in the concept phase and progressively acquire more detailed specifications as they advance through the design phases.

Conventional architectural design methods advocate a similar converging design process that progresses from a conceptual (or global) to a detailed level (Daudén, n.d.; Roozenburg & Cross, 1991). Groat & Wang (2013) delineate various phases

7 While one could argue that designing components and buildings utilizing reclaimed materials and existing reused parts might also demand an alternative design method, this research lacks sufficient insights to support such an argument. Therefore, this argument is not incorporated into this section.

in the design process: (1) program, (2) schematic design, (3) design development, (4) construction documents, (5) bid, and (6) evaluation. Comparable phases are evident in the industry terms outlined by The Association of Dutch Architects (BNA) and Trade Association of Consultancy, management and engineering firms (NLingenieurs) (BNA & NLingenieurs, 2014): (1) initiative & feasibility phase, (2) project definition, (3) schematic design, (4) preliminary design, (5) final design, and (6) technical design (7) price and contract formation (which can also take place after earlier phases), (8) execution-ready design, (9) execution management, and (10) use/exploitation. These design phases, the specificity (or level of detail) of the design, and the goals of the phases can be seen in Figure 6.5.

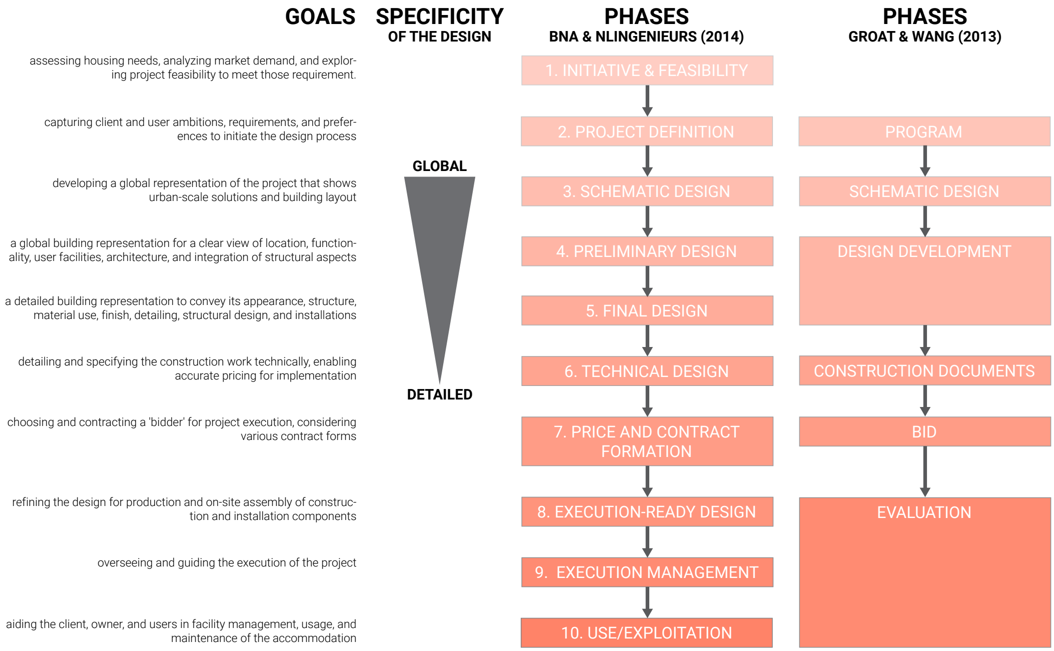

FIG. 6.5 Phases in the design process of buildings according to BNA & NLingenieurs (2014) and Groat & Wang (2013), including their goals and the specificity of the design.

6.3.2.2 Design methods for modular, circular building components and buildings

As Section 4.4.3 shows, the method by which parts are connected, the production methods, and the materials used, play pivotal roles in achieving a successful modular building component design. Consequently, the design approach employed must encompass decisions on these factors early in the design process to circumvent issues in subsequent development stages. Furthermore, conducting full-scale prototyping, either of the entire component or essential sections, becomes imperative to identify potential design limitations concerning the combination of production methods, connections, and materials, as is exemplified in the findings of Dokter et al. (2023). These findings affect design methods in the built environment on two scales: that of the building component, and that of the building.

At both scales, the level of modularity in a component's or building's design dictates the need to focus on design details early. For instance, in a custom-designed building employing standardized window frames, considering these frames' dimensions early on might influence some aspects of the building layout. However, these frames need not dictate the building envelope. Conversely, when standardized elements like structure, façade, and interior walls are utilized, they significantly impact the building envelope. Opting for a method of addition by selecting or even designing these components first might be a more feasible design approach than initially determining the envelope and then accommodating these components within it. In the case of the CIK, the method of connecting modular parts and its rigidity significantly influenced conceptual choices. For less modular designs, where disassembly is not necessary, a simple solution like gluing parts together may suffice, making the design of connections less critical in the conceptual phase. Designers should determine the desired level of modularity early on and adapt the focus within the design process accordingly. A fully standardized modular building requires a detailed design approach from the start, diverging toward a global scale. Some examples of this approach can already be seen in the Dutch social housing sector, for instance in the newly built modular homes of the Bouwstroom (Aedes & VTW, 2022), and in the 'Nul op de meter' energy renovation concepts (Rijksdienst voor Ondernemend Nederland, 2015). Notably, a fully modular building would apply modular components that need to be designed as well. The design of both al of the standardized modular components and the building that they are applied in might not fit the scope of one project, and as a consequence, the need for a catalogue of standardized modular components could arise in practice.

Conversely, a fully custom building can follow the traditional converging design approach. Designs that neither follow a standardized modular approach, nor a completely custom approach fully, might require both the global and the detailed level as a starting point of the design process. Figure 6.6 shows this proposal for such selection of design method based on the degree of standardized modularity. As is the case for conventional design phases, design iterations can go back and forth between phases – a design process is rarely a linear one – and this figure indicates one or multiple starting points for the design process, and a priority and general direction. Figure 6.6 should be seen as a conceptual model, and the extreme ends of the spectrum could never take place in reality. Even the most modular standardized design is made within a context, and even the most custom design incorporates builds on pre-existing knowledge, methods, and designs in some way.

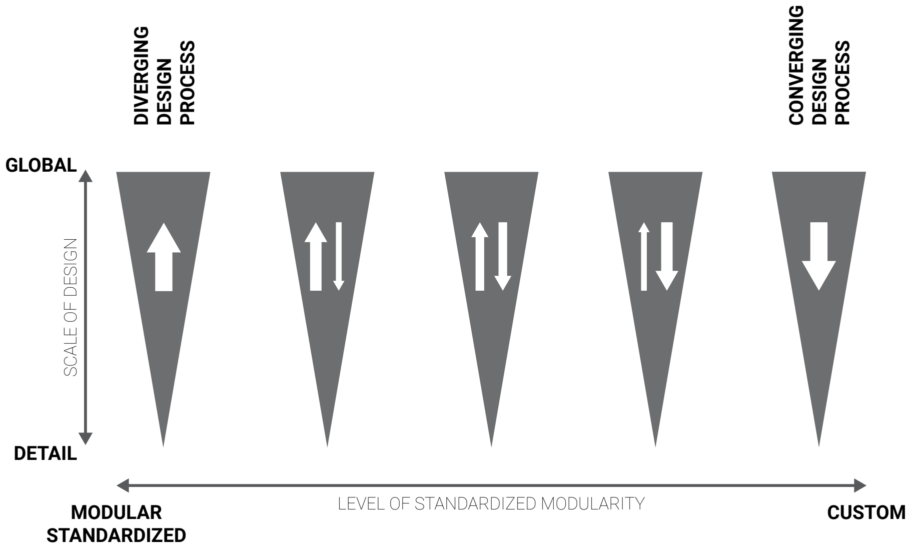

FIG. 6.6 Implications of the degree to which standardized, modular design strategies are applied to the design process, in which white arrows imply the direction of the design process. The right side of the diagram represents the current traditional practice, and the left represents a process optimized for modularity.

6.3.3 Reflections on slowing and closing loops

The CE could help address the core societal problem of reducing resource use, environmental impacts, and waste generation in the built environment. However, this research has shown that a blind pursuit of circularity may inadvertently worsen environmental challenges. This brings forth the question: how should circularity be pursued – if it should be pursued at all? Building on the findings of this research, a distinction can be drawn between circular strategies that can be more or less effective in fostering sustainability within the built environment through circular components.

Study 2 (see Section 3) has shown that not all circular design options improve the environmental performance of building components; even well-intentioned circular designs can increase resource use, environmental impacts, and waste generation. Additionally, Study 2 has shown that circular components generally require higher investments up front, which in some cases could be earned back over time.

Furthermore, Study 3 has shown numerous challenges and risks associated with developing components for future VRPs. Realizing environmental and economic benefits through these VRPs necessitates alterations in the components' business models, supply chain models, and even design methodologies (see Section 6.3.2). While significant changes, as illustrated in Figure 6.4 are feasible, they tend to occur mainly within the realm of small-scale production, contributing only marginally (if these components contribute at all).

Designing for slowing and closing loops introduces uncertainty. VRPs typically occur far into the future and thus require system continuity and long-term stakeholder collaboration to be realized. Additionally, components that rely on future VRPs typically require multiple loops to achieve superior overall environmental performance compared to designs focusing on immediate reductions in environmental impacts (see also, for example, Cruz Rios et al. (2019)), adding to the uncertainty of environmental benefits.

Similar skepticism arises from developments in practice. For instance, the recent inclusion of Chainable's kitchen in the Dutch Environmental database (NMD)[8] and the prior inclusion of Bribus's Eco kitchen (their non-circular kitchen) allows for a comparison of their environmental performance.

8 The Dutch Environmental Database (NMD) houses product cards with essential product details and environmental information obtained through a Life Cycle Assessment (LCA), adhering to defined Assessment Method guidelines.

Table 6.2 illustrates that when considering only one lifespan, the Chainable kitchen causes 115% more shadow costs (MKI), and has 137% more global warming potential from production and construction (GWP_a), along with a 195% higher global warming potential throughout their entire lifespan compared to the Bribus Eco kitchen. When evaluating a predefined timeframe based on the total lifespan of one Chainable kitchen (60 years), the Chainable kitchen outperforms its counterpart over this period due to its extended lifespan. Nonetheless, these advantages are marginal, with 28% fewer shadow costs and a 1,6% reduction in GWP, which only manifest after multiple decades.

TABLE 6.2 Environmental performance data for the Bribus Eco kitchen (their non-circular kitchen) and the Chainable kitchen, according to NMD, expressed in milieukostenindicator (MKI) – a single score indicator expressing environmental burdens by shadow-costs in Euro's – and global warming potential (GWP) – expressed both as only the emissions originating from production and construction (GWPa), and the total emissions (GWPtot).

Kitchen name	Lifespan	MKI (1 use cycle)	GWP_a (1 use cycle)	GWPtot (1 use cycle)	MKI (60 years)	GWP_{tot} (60years)
Bribus Eco kitchen	20	€ 18,97	112,9	112,4	€ 56,92	337,2
Chainable kitchen	60	€ 40,88	267,2	331,9	€ 40,88	331,9

Consequently, this research shows that, given the risks and challenges associated with achieving long-term benefits through building components designed for future VRPs, prioritizing strategies that have immediate environmental benefits is essential to consistently achieve a more sustainable built environment. Such strategies are Refuse, Rethink, and Reduce (Potting et al., 2017), or narrowing loops (Bocken et al., 2016). Additionally, high-impact finite materials should be substituted with low-impact, renewable materials: this can also be seen as part of the Reduce approach. Similarly, the slowing and closing of existing material loops can be integrated into this strategy. For example, reusing components that already exist prevents the production of new ones, and can therefore be seen as Refuse. Although this is in line with what many authors such as Potting et al. (2017) and Ness (2020) suggest, practitioners often prioritize design for future reuse, remanufacturing, and repair as the main strategy for their circular designs.

In conclusion, this study has shown that not all circular approaches are beneficial to environmental goals (possibly both long and short-term), either because they do not perform better environmentally, or because they are not feasible.

Appendices

APPENDIX A

Sensitivity Analysis Section 3

Introduction

This supplementary material is part of the research article titled ‘The technical or biological loop? Economic and environmental performance of circular building components’. In this research, 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 to determine which pathway is the most circular. 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) were used. In this supplementary material, the CE-LCC model is explained, data that was used as input for the model is provided, and a sensitivity analysis in conducted for the CE-LCC.

Sensitivity Analysis

Assumptions were made on numerous parameters in the CE-LCC. To test the impact of these assumptions and therefore the robustness of the outcomes, two sensitivity analyses were conducted; (1) interest rate was varied, and (2) the frequency of lifecycles was varied. Table App.A.1 and Table App.A.2 show the sensitivity analysis scenarios and the altered parameters. In this section, the method used in the sensitivity analysis and the results are explained.

Sensitivity analysis 1: method

TABLE APP.A.1 Parameters for interest-based sensitivity analysis scenarios

Scenario	Component	Inflation	Manufacturer interest rate	Customer interest rate
Interest 1 (baseline)	Circular Skin	2%	4%	4,5%
	Circular Kitchen	2%	3%	4,5%
Interest 2	Circular Skin	2%	2%	2%
	Circular Kitchen	2%	2%	2%
Interest 3	Circular Skin	2%	-0,5%	-0,5%
	Circular Kitchen	2%	-0,5%	-0,5%

When analyzing costs over a longer period of time, the time-value relationship of money has to be considered. However, variables that determine the discount value, such as the interest rate and inflation, might change over the 90 or 80-year period. Interest rates have a profound impact on the investments companies make, and while the Social Housing Guarantee Fund (WSW) is expecting the interest on Dutch 10-year bonds to rise to 4.5% within 20 years (Autoriteit Woningcorporaties, 2018), the recent rise in negative yield bonds (Ainger, 2019) has led others to believe that low, or even negative yields, might remain (Harding, 2019). Since interest rates have a profound influence on the investments companies make, three scenarios for comparison were compared: (I1) 4.5%, (I2) 2% and (I3) -0.5% (based on Dutch 10-year state bonds in September 2019 (IEX, 2020)) nominal interest, all with an inflation rate of 2% (based on data from Centraal Bureau voor de Statistiek (CBS, 2020)). The discount rate for the scenarios was calculated as follows:

$$i = \frac{1 + nominal\ interest}{1 + inflation} - 1 \qquad \text{EQ. APP.A.1}$$

The variation in interest for the different scenarios will be applied consistently for all variants. For this sensitivity analysis, the variants are directly compared in the similar scenarios, since showing the impact of interest scenarios per variant separately will merely show the workings of Equation App.A.1. By comparing the variants, the difference in economic performance of the variants relative to each other can be seen directly.

Sensitivity analysis 1: results

The results of sensitivity analysis 1 can be seen in Figure App.A.1 – Figure App.A.6. The figures show that the effect of altering the interest for the façade variants does not change which variant has the lowest TC: this remains the HYBRID façade. However, since initial investment becomes a smaller part of the total costs in lower-interest scenarios, variants with a higher investment cost perform better overall in relative terms. The TECH façade therefore has a lower TC after the first use cycle of 30 years than the BIO variant. A similar change can be seen for the kitchen variants: the impact of initial investment on the TC becomes lower in relative terms. However, for the kitchen, economic performance for the variants relative to each other is not altered significantly by a change in interest rates.

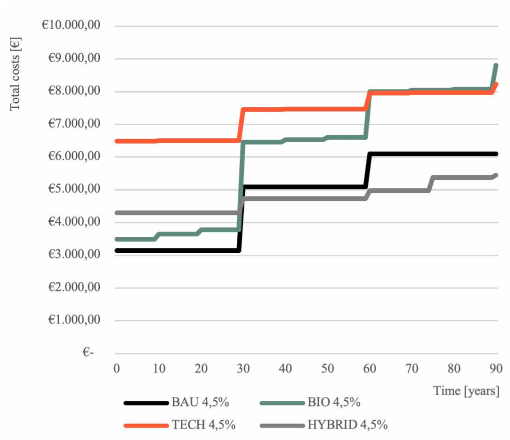

FIG. APP.A.1 LCC Sensitivity analysis on the influence of interest rate when comparing façade variants (baseline, scenario 1)

FIG. APP.A.2 LCC Sensitivity analysis on the influence of interest rate when comparing façade variants (scenario 2)

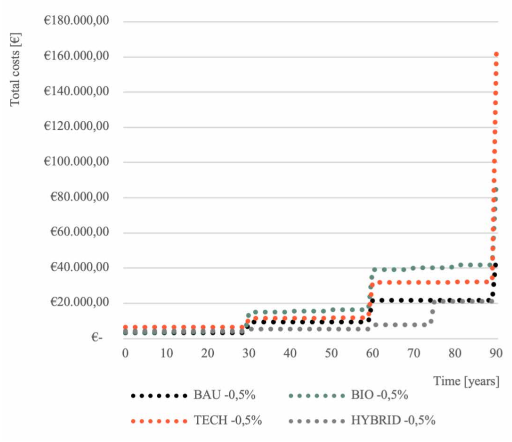

FIG. APP.A.3 LCC Sensitivity analysis on the influence of interest rate when comparing façade variants (scenario 3)

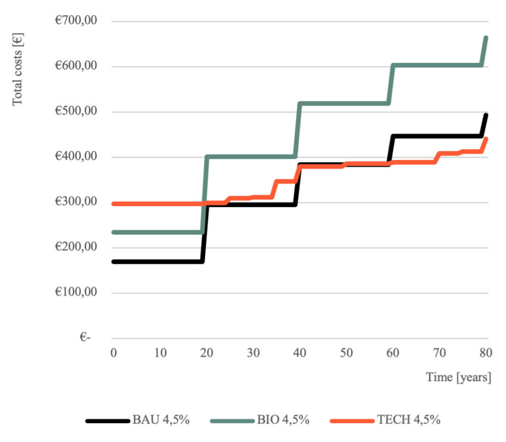

FIG. APP.A.4 LCC Sensitivity analysis on the influence of interest rate when comparing kitchen variants (baseline, scenario 1)

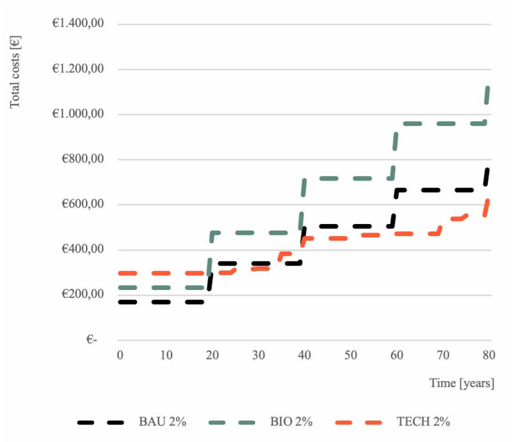

FIG. APP.A.5 LCC Sensitivity analysis on the influence of interest rate when comparing kitchen variants (scenario 2)

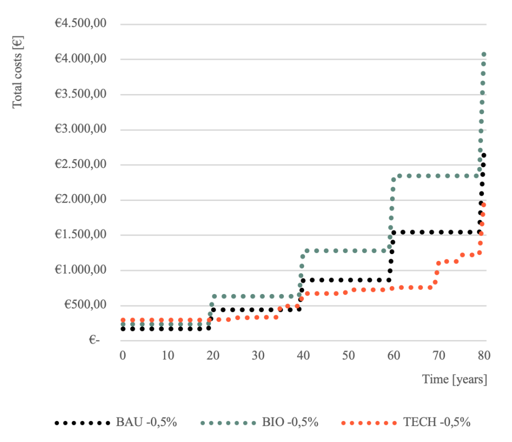

FIG. APP.A.6 LCC Sensitivity analysis on the influence of interest rate when comparing kitchen variants (scenario 3)

Sensitivity analysis 2: method

The second sensitivity analysis for the LCC outcomes is aligned as far as possible with the second sensitivity analysis for the LCA and MFA and is focused on the frequency of cycles.

TABLE APP.A.2 Parameters for interest-based sensitivity analysis scenarios in which Lf is functional lifespan and Lt is technical lifespan. For the TECH kitchen, the lifespans are defined for the construction, infill and finishing respectively.

	Variant	Scenario 1	Scenario 2	Baseline	Scenario 3	Scenario 4	Scenario 5
Circular Skin	**BAU**	L_f=Lt =15	-	L_f=Lt =30	L_f=Lt =45	L_f=Lt =90	-
	BIO	L_f=Lt =15	-	L_f=Lt =30	L_f=Lt =45	L_f=Lt =90	-
	TECH	Lf=15, Lt=*0,5	-	Lt=30, Lt=*1	Lt=45, Lt=*1,5	Lt=90, Lt=*3	-
	HYBRID	Lf=15, Lt=*0,5	-	Lt=30, Lt=*1	Lt=45, Lt=*1,5	Lt=90, Lt=*3	-
Circular Kitchen	**BAU**	Lt=7, Lf=7	-	Lt=20, Lf=20	Lt=40, Lf=40	Lt=80, Lf=80	-
	BIO	Lt=7, Lf=7	Lt=10, Lf=10	Lt=20, Lf=20	Lt=40, Lf=40	Lt=80, Lf=80	-
	TECH	Lt=7-7-7-7, Lf=7-7-3,5-7 (every mutation replaced)	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-40-40-40 Lf=80-40-20-40	Lt=80-80-80-80, Lf=80-80-40-80	Lt=80-40-40-40 Lf=80-40-7-40 (Finishing parts)	Lt=80-40-40-40, Lf=80-40-40-40 (Finishing parts)

The second sensitivity analysis for the LCC model resembles the second LCA/MFA analysis. In this analysis, the frequency of cycles is altered; assumptions were made on the functional and technical lifespan of the material, part, subcomponent and component that determine how often production, use, VRPs and disposal take place. Scenarios were compared in which these technical and functional lifespans were varied. First, varying both the technical and functional lifespans for the CIK and Circular Skin variants in parallel was tested. Second, the finishing parts of the TECH kitchen can easily be replaced to increase the lifespan of the whole kitchen, which may cause users to change these parts more frequently. Therefore, a lower and higher functional lifespan of the finishing parts for this variant was tested. Table App.A.2 shows an overview of all the scenario parameters tested in this comparison.

Sensitivity analysis 2: Results

Figure App.A.7-Figure App.A.20 show the results for sensitivity analysis 2. For the façade, changing the lifespans has a significant impact on the total costs of all variants, as well as on the performance of the different variants relative to each other. Scenario 1 shows the BIO façade to have the highest, the TECH the second highest, the BAU third highest, and the HYBRID the lowest TC. However, scenario 3 shows that the TECH has the highest TC and the BAU the lowest. Furthermore, scenario 4 shows that with a lifespan that outlasts the period of 80 years that was studied, only costs for maintenance (occurring for the TECH and the BIO) are added to the initial purchase costs before a final replacement at year 90. A similar effect can be seen for the kitchen variants: in scenario 1, where the lifespans are shorter than in the baseline scenario, the TECH kitchen remains the variant with the highest TC throughout the period studied, while in the baseline scenario its TC either resembles or is lower than that of the BAU kitchen after the first use cycle of 20 years. However, the reduction in lifespans for the TECH kitchen from the baseline to scenario 1 is significantly higher (from 80 years to 7 years for some parts), than it is for the BIO and BAU (from 20 to 7 years for all parts). Furthermore, the BIO kitchen consequently has a higher TC than the BAU kitchen. Finally, the results show that altering the functional lifespan of the finishing parts for the TECH has very little influence on the TC outcome.

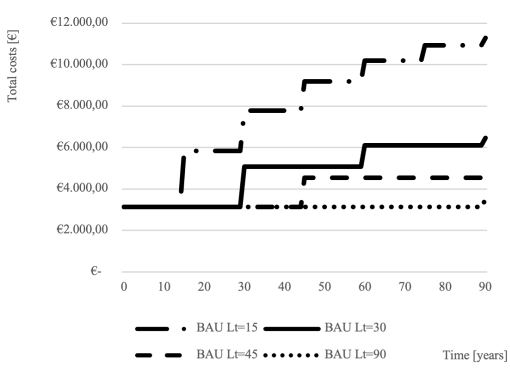

FIG. APP.A.7 Sensitivity analysis on the Ltechnical and Lfunctional for the BAU façade.Table 9.2

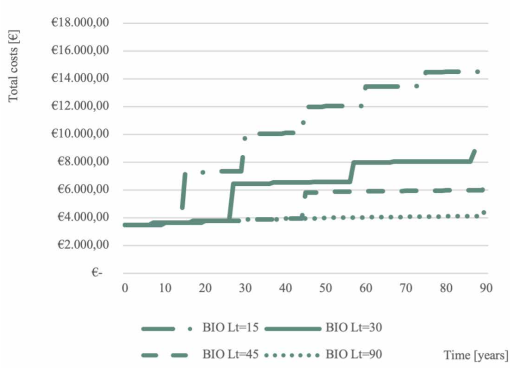

FIG. APP.A.8 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the BIO façade.

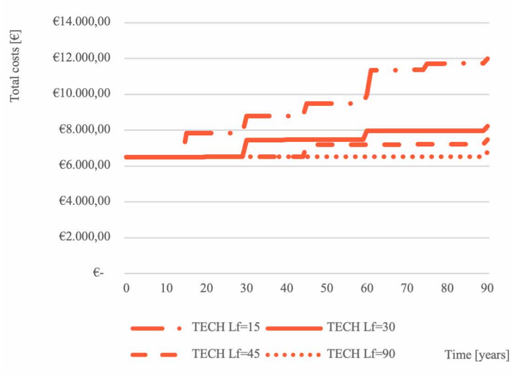

FIG. APP.A.9 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the TECH façade.

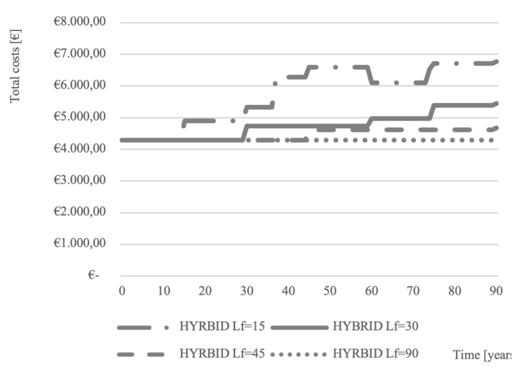

FIG. APP.A.10 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the HYBRID façade.

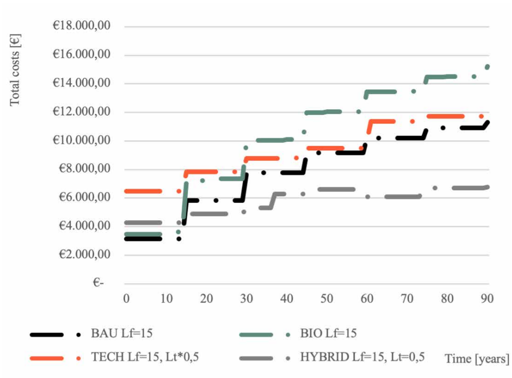

FIG. APP.A.11 Comparison of LCC Sensitivity analysis scenario 1 for the Ltechnical and Lfunctional for the façade variants.

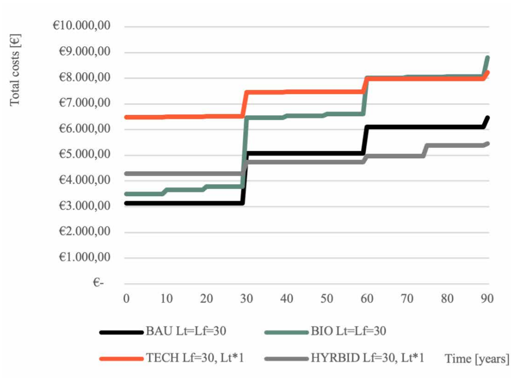

FIG. APP.A.12 Comparison of LCC Sensitivity analysis baseline scenarios for the Ltechnical and Lfunctional for the façade variants.

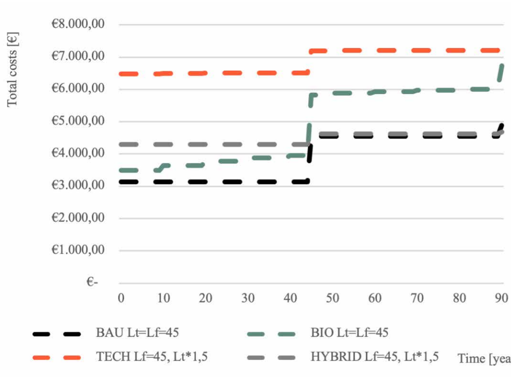

FIG. APP.A.13 Comparison of LCC Sensitivity analysis scenario 3 for the Ltechnical and Lfunctional for the façade variants.

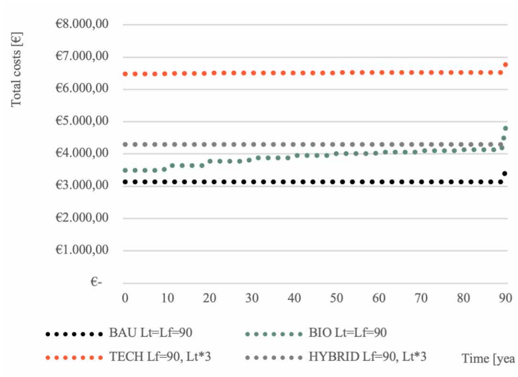

FIG. APP.A.14 Comparison of LCC Sensitivity analysis scenario 4 for the Ltechnical and Lfunctional for the façade variants.

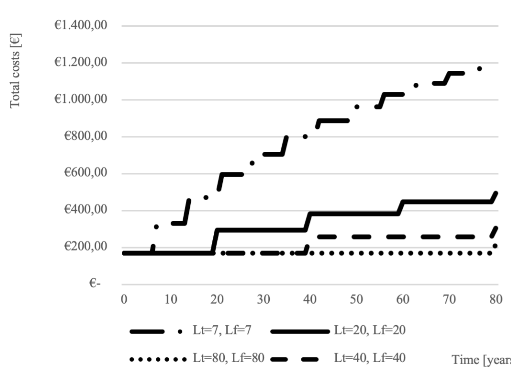

FIG. APP.A.15 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the BAU kitchen.

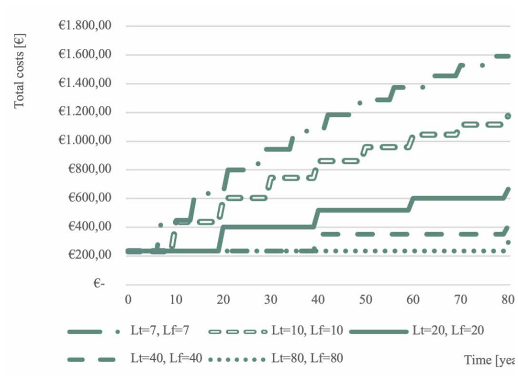

FIG. APP.A.16 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the BIO kitchen.

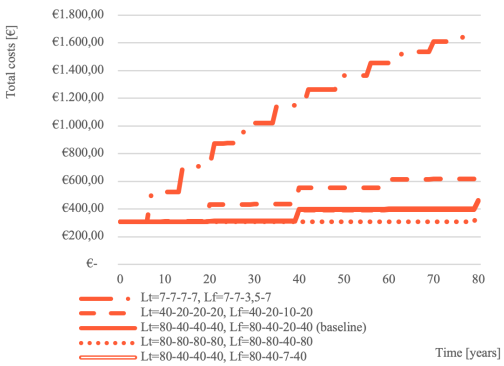

FIG. APP.A.17 LCC Sensitivity analysis on the Ltechnical and Lfunctional for the TECH kitchen.

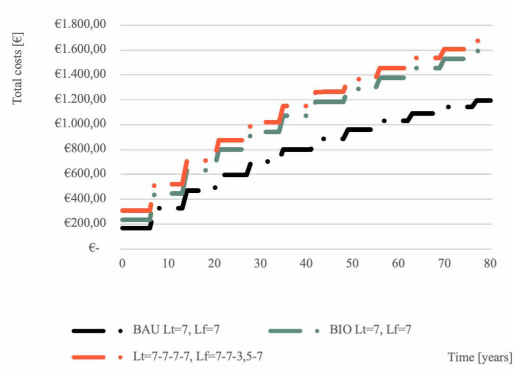

FIG. APP.A.18 Comparison of LCC Sensitivity analysis scenario 1 for the Ltechnical and Lfunctional for the kitchen variants.

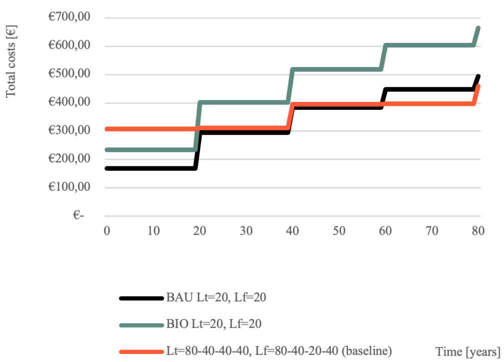

FIG. APP.A.19 Comparison of LCC Sensitivity analysis baseline scenario for the Ltechnical and Lfunctional for the kitchen variants.

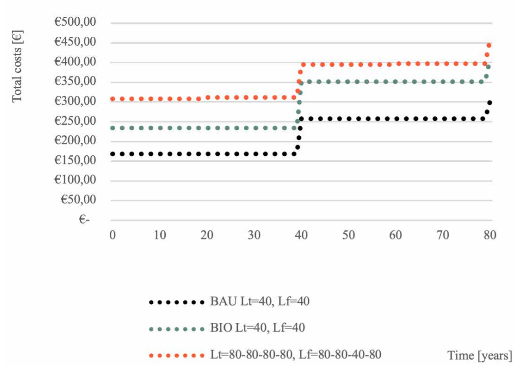

FIG. APP.A.20 Comparison of LCC Sensitivity analysis scenario 3 for the Ltechnical and Lfunctional for the kitchen variants.

Interpretation of the results

In high-interest scenarios, costs made in the future have a lower impact on the TC than in low-interest (or even negative-interest) scenarios. Due to the high reuse rate of the TECH façade, costs made after the initial purchase are relatively low. Therefore, a shift takes place, and the TECH façade has a lower TC in interest scenarios 2 and 3 than the BIO façade. However, both still result in higher TC outcomes than the BAU and HYBRID façade. Of the circular façade variants, the HYBRID façade is consistently the one with the lowest TC. Similar changes in outcomes can be seen for the kitchen; however, the TECH kitchen remains the circular variant with the lowest TC, which closely resembles or is lower than the TC for the BAU kitchen after 20 years in all interest scenarios.

Varying the lifespans of both components has shown to significantly influence the outcomes of the analysis: the variant with the lowest TC changes from scenario to scenario. Therefore, it is of utmost importance to base the input for functional and technical lifespan on sources that are as reliable as possible. However, the results show that a change of functional lifespan for some parts does not necessarily result in a significant change in TC.

APPENDIX B

Calculation and Paramaters Section 3

Nomenclature

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

CE-LCC calculation & parameters

To compare the economic performance of circular building components, the CE-LCC method was applied. Figure App.B.1 illustrates the working of the CE-LCC model. Specific formulae can be found in Wouterszoon et al. (2020), in which the CE-LCC model is detailed. To ensure maximal reproducibility and transparency, as many parameters as possible are specified in this Appendix.

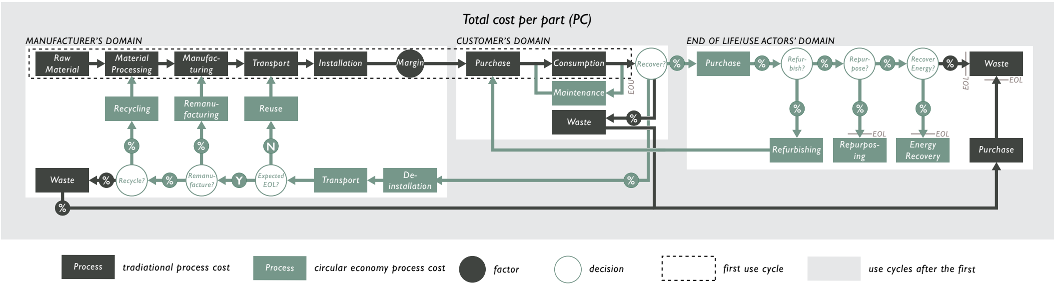

FIG. APP.B.1 The overall structure of use cycles of a part in the CE-LCC model

Table App.B.1 shows the parameters used for the analysis per building component. The interest and inflation rates for the baseline scenario are shown, and the materials used are displayed according to their mass. The end of use (EOU) - determined by the functional lifespan and the end of life (EOL) – determined by the technical lifespan are displayed per material (and where this material is applied in some cases. R2 (reuse) is not specified, as it is determined by the parameters for EOU and EOL in the model. R0 (recovery) is specified for both the manufacturer (MAN) and the end of use actor. R99 (waste) is determined by all the R-values. The cost-related parameters, and the manufacturers' profit margin cannot be published for reasons of confidentiality.

CE-LCA and MFA calculation & parameters

For the environmental performance, van Stijn et al. (2022) have applied CE-LCA and MFA. Specific parameters and calculation can be found in appendix A and B of their research.

TABLE APP.B.1 Parameters used in the baseline CE-LCC

		Inflation	Manufacturer interest rate	Customer interest rate	Material	Mass [kg]	Relative mass	Material characterization	EOU (functional lifespan) [years]	EOL (technical lifespan) [years]	R0 (MAN)	R0 (EOU actors)	R4	R5	R6	R7	R8	R99
CIRCULAR KITCHEN	BAU	2%	3%	4,5%	Particle board with HPL coating	30.09	91%	tech	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Pine	0.52	2%	tech	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					PE	0.40	1%	tech	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Stainless steel	1.83	6%	tech	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					PVAC	0.10	0%	tech	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Total	**32.94**	**100% tech**											
	BIO	2%	3%	4,5%	Bio board	24.92	95%	bio	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Pine	0.52	2%	bio	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Bio polymer	0.85	3%	bio	20	20	0%	0%	0%	0%	0%	0%	0%	100%
					Total	**26.29**	**100% bio**											
	TECH	2%	3%	4,5%	Plywood	7.86	20%	tech	50	80	90%	0%	0%	0%	0%	100%	0%	10%
					Stainless steel	0.13	0%	tech	50	100	90%	0%	0%	0%	0%	0%	0%	100%
					3mm Birch triplex coated with HPL	3.21	8%	tech	20	20	90%	0%	0%	0%	0%	80%	0%	28%
					18 mm Birch plywood coated with HPL	7.03	18%	tech	40	40	90%	0%	0%	30%	0%	50%	0%	42%
					12 mm Birch plywood coated with HPL	4.76	12%	tech	40	40	90%	0%	0%	50%	0%	50%	0%	33%
					18 mm Birch plywood coated with HPL	7.96	20%	tech	20	40	90%	0%	0%	50%	0%	50%	0%	33%
					12 mm Birch plywood coated with HPL	6.17	16%	tech	20	40	90%	0%	0%	50%	0%	50%	0%	33%
					Stainless steel	0.02	0%	tech	50	100	90%	0%	0%	0%	0%	0%	0%	100%
					Nickel steel	0.24	1%	tech	50	30	90%	0%	0%	0%	0%	0%	0%	100%
					PE	0.06	0%	tech	50	35	90%	0%	0%	0%	0%	0%	0%	100%
					Galvanized steel	1.57	4%	tech	50	25	90%	0%	0%	0%	0%	0%	0%	100%
					Total	**39.02**	**100% tech**											

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TABLE APP.B.1 Parameters used in the baseline CE-LCC

		Inflation	Manufacturer interest rate	Customer interest rate	Material	Mass [kg]	Relative mass	Material characterization	EOU (functional lifespan) [years]	EOL (technical lifespan) [years]	R0 (MAN)	R0 (EOU actors)	R4	R5	R6	R7	R8	R99
CIRCULAR SKIN	BAU	2%	4%	4,5%	PU-Glue	2.20	1%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					EPS	43.66	16%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Non-cementitious, organic reinforcement grout	89.96	34%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Glass fiber	1.46	1%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Non-cementitious, organic glue	39.69	15%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Mineral stone-strip	89.96	34%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Total	**266.93**	**100% tech**											
	BIO	2%	4%	4,5%	Bio polymer	22.90	5%	tech	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Spruce	179.61	38%	bio	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Hempflax	136.65	29%	bio	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Clay plaster base coat	98.78	21%	bio	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Glass fiber mesh	1.46	0%	bio	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Clay plaster finish	28.22	6%	bio	30	30	0%	0%	0%	0%	0%	0%	0%	100%
					Total	**467.63**	**100% bio**											
	HYBRID	2%	4%	4,5%	Stainless steel (docking station)	17.07	2%	tech	75	120	100%	0%	0%	0%	0%	0%	0%	100%
					Spruce wood (docking station)	22.67	2%	bio	75	120	100%	0%	0%	0%	0%	0%	0%	100%
					Plywood	82.62	9%	tech	30	75	100%	0%	0%	0%	0%	0%	0%	100%
					Spruce wood (insulation modules)	181.85	20%	bio	30	75	100%	0%	0%	0%	0%	0%	0%	100%
					Recycled cotton	211.85	23%	tech	30	75	100%	0%	0%	0%	0%	100%	0%	0%
					Recycled wood fiber board	107.33	12%	tech	30	75	100%	0%	0%	0%	0%	100%	0%	0%
					Stainless steel (insulation modules)	8.81	1%	tech	30	75	100%	0%	0%	0%	0%	0%	0%	100%
					Recycled PE	1.58	0%	tech	30	75	100%	0%	0%	0%	0%	100%	0%	0%
					Aluminum (insulation modules)	4.75	1%	tech	30	75	100%	0%	0%	0%	0%	100%	0%	0%
					Aluminum (style package)	4.47	0%	tech	30	120	100%	0%	0%	0%	0%	0%	0%	100%
					Rockwool	11.85	1%	tech	30	120	100%	0%	0%	0%	0%	0%	0%	100%
					Cement	45.56	5%	tech	30	120	100%	0%	0%	0%	0%	0%	0%	100%
					Brick	220.22	24%	tech	30	120	100%	0%	0%	0%	0%	100%	0%	0%
					Total	**920.62**	**22% bio, 78% tech**											

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TOC

TABLE APP.B.1 Parameters used in the baseline CE-LCC

		Inflation	Manufacturer interest rate	Customer interest rate	Material	Mass [kg]	Relative mass	Material characterization	EOU (functional lifespan) [years]	EOL (technical lifespan) [years]	R0 (MAN)	R0 (EOU actors)	R4	R5	R6	R7	R8	R99
CIRCULAR SKIN	TECH	2%	4%	4,5%	Polyurethane	2.95	1%	tech	30	122	100%	0%	0%	0%	0%	0%	0%	100%
					Aluminum	43.66	13%	tech	30	122	100%	0%	0%	0%	0%	0%	0%	100%
					Stainless steel	5.85	2%	tech	30	122	100%	0%	0%	0%	0%	100%	0%	0%
					EPS	43.66	13%	tech	30	122	100%	0%	0%	0%	0%	0%	0%	100%
					Ceramic tiles	232.84	71%	tech	30	122	90%	0%	0%	0%	0%	0%	0%	100%
					Total	**328.95**	**100% tech**											

APPENDIX C

Appendix Section 4

This supplementary material is part of the research article Cooking up a circular kitchen: a longitudinal study of stake-holder choices in the development of a circular building component. this article presents a longitudinal case study of an exemplary circular building component: the Circular Kitchen (CIK). The researchers actively engaged in a co-creation with industry partners to develop the Circular Kitchen's design, supply chain model, and business model. All the choices made from initiative to market implementation were documented. Five lessons were drawn from an analysis of the stakeholder choices that can aid future development of feasible circular building com-ponents: about ambition, aesthetics, design scale, participation and focus.

This supplementary material document includes a (1) literature review that forms the theoretical background for the research article, (2) an overview of the meetings that took place, and (3) an extensive description of the development of the CIK.

Review existing studies on the feasibility of circular (design) options in the built environment

TABLE APP.C.1 Review existing studies on feasibility of circular (design) options in the built environment

Author & Year	Goal of study	Method
(Adams et al., 2017)	Analyze the circular economy awareness, challenges and enablers in the construction industry	Survey and 1 workshop
(Akinade et al., 2020)	Identify barriers and improvement strategies for DFD in UK construction industry	Literature review + 6 focus groups with different industry stakeholders
(Azcarate-Aguerre et al., 2022)	Analyze technical implementation challenges for facade industry to adopt performance-based contracts and propose a multi-stakeholder systematic model for development and application of facade technology capable of overcoming the barriers for performance-based contracts for integrated facades	Targeted literature review, and research through design by reflection on pilot with stakeholder involvement
(Azcarate-Aguerre et al., 2018)	Outline the main drivers and barriers to the commercial application of the Facade-as-a-Service concept in the Dutch public, non-residential real estate sector from different stakeholder perspectives	Pilot, series of interviews, working sessions, and public presentations, in which the research team actively engaged experts across the most relevant stakeholders
(Chang & Hsieh, 2019)	Identify status quo, barriers and enablers of CE in building industries and BIM applications in Taiwan	1 in depth interview and 1 case study analysis
(Charef, Ganjian & Emmitt, 2021)	Explore the socio-economic and environmental barriers for implementation of CE in asset lifecycle	Pattern matching: literature study and 20 interviews multiple stakeholders
(Condotta & Zatta, 2021)	Identify vacuum and inconsistencies in legal framework for reuse processes in architectural field	Literature review and interviews with multiple stakeholders
(Cruz Rios et al., 2021)	Identifying barriers and enablers for circular building design in US	13 interviews with architects
(Galle et al., 2021)	Investigate how we can exploit the opportunities of the circular economy in construction to make the housing market more accessible?	Longitudinal case study of singular pilot
(Ghisellini et al., 2018)	Evaluate if the adoption of the CE framework is environ-mentally and economically sustainable, given that the recovery of waste materials requires investments of resources.	Literature review
(Giorgi et al., (2022)	Analyze level of application of circular strategies in building industry across 5 EU countries, identifying barriers and enablers	Interviews with different stakeholders in 5 countries

	Results	Level	Context	Focal topics
	Awareness, barriers and enablers	Construction industry	UK	
	Barriers	Construction industry	UK	Design for Disassembly
	Barriers, model	Facade	NL	Focus on facade servitisation
	Barriers and drivers	Facade	NL	Focus on facade servitisation
	Barriers and enablers	Construction industry	Taiwan	Circular design options and BIM; Technical, functional and organizational
	Barriers	Construction sector, asset lifecycle in a BIM environment; Sustainable EoL stage;	EU (FR, BE, UK, I, SP)	socio-economic and environmental perspective (no technical or regulatory)
	Barriers	Construction industry	EU	Regulation and legislation
	Barriers and enablers	Building design	US	N/A
	3 lessons learned	Building	Flanders (BE)	Scale and scalability, values, knowledge
	Barriers, solutions and success factors	Construction industry	World	C&DW
	Level of application, barriers and enablers	Building	BE, NL, UK, DK, IT	Resource & waste management, design for reversible building, business strategies & stakeholder networking; consider circular options spanning whole lifecycle of building

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TABLE APP.C.1 Review existing studies on feasibility of circular (design) options in the built environment

Author & Year	Goal of study	Method
(Guerra & Leite, 2021)	Investigate U.S. architectural, engineering, and construction (AEC) industry stakeholders' awareness of CE. The investigation also covers major barriers for the implementation of strategies aligned to the CE model, and enabling factors for a transition from a linear economic model to a CE model in the construction industry in the U.S.	Mixed-methods approach: online survey and interviews with multiple stakeholders
(Hjaltadóttir & Hild, 2021)	Answer how the building industry responds to recent CE policies by developing CE practices in daily activities?	2 cases and interviews of multiple stakeholders
(Huang et al., 2018)	Analyze CD&W management by using the 3R principle.	Semi-structured interviews (40)
(Kanters, 2020)	Identify the barriers and drivers of the transformation towards a circular building sector.	Semi-structured interviews with architects and consultants that have engaged in circular building design (12 in total)
(Selman & Gade, 2020)	Investigate potential of using CE in building design to provide consultants, architects, contractors insight into the challenges [barriers] when adopting circular design strategies	Mixed methods: Literature review of existing barriers; 4 semi-structured interviews with architect, contractor and consultants
(Torgautov et al. 2021)	Identify the construction trends and perform a barrier and opportunity analysis to develop circular economy principles in the construction sector.	PEST study and stakeholders-interviews using semi-structured surveys

Results	Level	Context	Focal topics
Awareness, challenges and enablers	Construction industry	US (multiple regions)	N/A
Industry-wide practices and firm activities	Construction industry	LU, SE	EU policies and local practices
Barriers and proposals to improve current situation	Building industry	CN	Construction & demolition waste; Legislation
Barriers and drivers	Comments on all levels	NL, UK, DK, BE	N/A
Barriers and enablers	Construction industry	DK	N/A
Awareness, barriers and opportunities	Construction industry	KZ	N/A

TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
	###			
Environmental	**5**		Potential environmental benefits of reuse are not certain	
			Building components are commonly downcycled	
			Not all materials can be effectively recycled	
			Circular design options have trade-offs between each other	
			Increased transport for VRPs can increase environmental burden	
Economic & Financial	**55**	Initial costs & profit	Circular design options and materials require higher initial investment	
			Additional time, labour and cost to design and construct circular design options	
			Fragmented supply chain lead to misalignment incentives	
			Lack of financial incentive to design for slowing and closing loops	
			High availability and low virgin material prices	
			Additional time and costs of non-virgin materials testing or recertification (due to lack of CE marking or certification)	
			Innovative circular design requires technical certification which takes long and is costly	
			Contract set-up and management costs	
			R&D investment for circular design options	
			Lower up-front profit for leased components	
			Costs of complying to legal frameworks of reuse and recycle	
			Cost of material storage	
			Initial costs are conditional above other aspects	
			Low landfill fees	
			Increased costs of circular tools	
			Increased cost for storage and transportation	
			Costs of careful disassembly are not outweighed by savings from reusing or reselling reclaimed material	
			Linear processes like demolition, downcycling and disposal are less costly than demounting and circular VRPs	
			Increased cost and time in disassembly process due to lack of information on materials in existing stock	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
		8	28	4	11	3	68	29	63	11	16	61	4	3	8	7	28	10
	1								x									
	1								x									
	1								x									
	1								x									
	1						x											
	5						x			x	x		x					x
	7		x				x		x			x	x			x		x
	4	x					x		x								x	
	1	x																
	4						x		x		x	x						
	4		x				x	x				x						
	1						x											
	1				x													
	2				x		x											
	1				x													
	1										x							
	1						x											
	1						x											
	1						x											
	1						x											
	1						x											
	1											x						
	3						x					x			x			
	1							x										

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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Economic & Financial	55	Life cycle costs	Low or uncertain end value of products and materials	
			Increased operational costs for CE service	
			Constructing with non-standard techniques increases insurance costs	
			Increased cost for new roles/activities in process	
			Long lifespan of building pushes circular business models beyond the scope of current supply chain (lease is impossible)	
			Lease premiums might be too high in the beginning (as risks are overestimated)	
			Lease business model accessible only to clients with high cashflow	
			Stakeholders favour short-term profit	
		Risk & market	Lack of scale and scaling potential	
			Risk, doubts on safety and quality when applying non-virgin material	
			Lacking certification or low performance guarantee for non-virgin materials	
			Modular buildings, DfD could compromise building resilience, durability and safety	
			Risk or unwillingness to pay for long term financial benefits of CE that may not occur whilst up-front investment is needed	
			Lease business model leads to fragmented ownership of real-estate (is risky investment for banks)	
			High competitiveness of market inhibits circular innovations	
			Difficult to enter reclaimed materials into established markets dominated by industrial products	
			Underdeveloped market salvaged components and reclaimed materials	
			Increased risk in process due to uncertainty in estimating time for disassembly and VRPs, causing scheduling issues	
			Less choice in manufacturers, contractors and suppliers (not everyone offers CE solutions)	
			Lack of alternative circular components and materials available on the market (e.g., bio-based materials)	
			Financing model sensitive to global material commodities market trends	
			Difficult to identify market for salvaged components and reclaimed materials	
			Market for prefabrication heavily dependant on import	
			Lack of application circular business models in practice (there are no examples)	
			Only examples of lease for short-life building components (e.g., furniture and heating)	
			Only examples of take-back schemes for valuable materials	
			Virgin resource-rich countries have less urgency to transition to CE	
			Lack of alignment between demand and supply (of non-virgin materials)	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
	3	x					x										x	
	1									x								
	1						x											
	1						x											
	1											x						
	1				x													
	1				x													
	3						x		x								x	
	1									x								
	6		x				x	x	x		x	x						
	5		x					x				x			x		x	
	3		x				x		x									
	4		x				x			x							x	
	2				x							x						
	1						x											
	1						x											
	3						x		x								x	
	1						x											
	1						x											
	3								x			x				x		
	1				x													
	1											x						
	1								x									
	1											x						
	1											x						
	1											x						
	1											x						
	4						x			x					x	x		

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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Economic & Financial	55	Value proposition	Stakeholders financially favour narrowing resource and energy use over slowing and closing future cycles	
			Unclear or unviable financial and/or business case	
			(Ultimately) unwillingness to pay for circular design options	
			Wait and see response of stakeholders who do not face an immediate need for a circular alternative or do not value its advantages	
			Lack of client demand for circular design options	
			Recycled or reclaimed materials are not (significantly) cheaper than virgin materials	
			Difficulty to quantify the benefits of CE hinders sales	
			Lack of marketing plan or poor marketing for reclaimed materials	
Societal & Cultural	14		Lack of interest in CE and circular design options	
			Poor perception of non virgin materials and preference for virgin materials	
			Rigid financial and corporate structure	
			Competitive fragmented supply chain	
			Conservative construction industry resistant to risk and change	
			Lack of CE leadership by designers	
			Uncertainty about future spatial needs	
			Modern consumerism culture (waste is considered as inevitable)	
			Users value authenticity and exclusivity hinders which CE	
			Customs of users and supply chain partners	
			Building sector is linked to many different other sectors and practices inhibiting change	
			Focus of EoL solutions rather than preventive solutions (nobody wants to consume less)	
			Difficulty changing take-make-use industry (entire system and mindset needs to be changed)	
			Construction industry associates sustainability with durability	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Behavioural	**10**		Lack of trust in reclaimed material suppliers	
			Scepsis on future benefits of circular design options (e.g., reusing materials in future)	
			Habits of users and supply chain partners and resistance to change	
			Luck of trust in quality, properties and durability of reclaimed materials	
			Pressure to get the project done	
			Trust of conventional construction materials	
			Lack of trust in innovative and non-conventional materials and designs	
			Lack of trust in accuracy of existing data on building	
			Lack of trust in the builders intentions (e.g., when using a circular material)	
			Lack of separate collection process for reclaimed materials negatively influences end-user perception	
Governmental & regulatory	**37**		Lack of or ambiguous legislation and regulation for CE and circular design options	
			Limited subsidies or tax levies for circular building	
			Lack of taxes on virgin material (e.g., environmental costs tax)	
			Policies ignore and/or do not discourage resource extraction and demand	
			Building and product construction and safety regulations could impair applying circular design options	
			Building and design codes favour virgin materials	
			Assessment methods do not credit circular design options sufficiently	
			Environmental performance assessment and certification is not commonly promoted in legislation and applied	
			Lack of standardisation, grading systems and certification to establish quality, performance and technical characteristics of non-virgin materials	
			Insurance constraints and legal warranties of non-virgin materials	
			Industry standards need to change for circular building	
			New contracts are needed CE business models	
			Data security and privacy issues in material passports	
			Policy focussed on recycling leads to downcycling	
			Anti-trust legislation impedes collaboration needed for circularity	
			Current policies favour linear economy models	
			Existing legislation favours ownership	
			Environmental costs and environmental value are not considered in policy	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
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TOC

TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers
Governmental & regulatory	**37**		Difficult to hold stakeholders responsible over the long term
			Lack of specific use requirements makes that reclaimed materials do not fulfil terms in End of Waste law, hindering reuse
			Reclaimed materials not mentioned in the assessment procedures to obtain CE-marking
			Unclear if reclaimed materials need to comply to legislation (e.g., CE marking or other certification processes)
			Lack of CE marking inhibits reuse by increasing risk, costs and doubt on quality and safety
			Construction Product Regulation legally prevents reclaimed material reuse in other function than original one
			Regulatory inconsistencies increase construction time, process costs, performance assessment issues and negative end-user perception
			Reusable components and materials are 'first' considered as waste in legislation, then requiring proof that they are not
			End of Waste hinders reuse of material flows which do not yet have a developed market
			Predemolition audits are not mandatory by law
			Legislation focusses on avoiding landfilling
			Lack of EU coordination in CE legislation
			Ambiguous and lack of common definition of waste in legislation
			Lack of detailed waste qualification codes inhibits separation of waste flows
			Requirements to waste can be fulfilled by focussing on inert waste (lighter waste does not need to be considered to comply)
			Legislation does not promote use of material passports or provide common framework and definitions
			Difficult to obtain a permit for a modular and demountable building
			BIM is only mandatory in public building processes
			Fiscal barriers for buildings which have fragmented ownership (due to leasing components)

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Technical	**21**		Complexity of buildings	
			Damage to materials during disassembly	
			Construction methods need to change	
			High complexity product requires technological integration which hinders circular design	
			Current buildings were not designed for disassembly, and composites hinder reuse	
			Non-virgin materials might contain hazardous or be contaminated	
			Uncertainty about lifespan and EoL	
			Industrialisation of bio-based materials hinders biodegradability	
			Over dimensioning is needed when using non-virgin materials	
			Lack of standardisation of building components	
			Lack of transportability of building components	
			Changing requirements inhibit reuse of components in future	
			Interface design between virgin and non-virgin materials and products differ	
			Large scale retail lowers costs, but leads to poor technical quality	
			Lack of sorting and processing technology for non-virgin materials	
			Fast-paced technology adds uncertainty of future reuse	
			Non-virgin and bio-based materials have less applications due to lower technical properties	
			Recycling often requires additional virgin materials due to loss of material mass or quality (immature recycling technology)	
			New equipment or factories are needed to manufacture circular design	
			Limited site access and dimensions hinder disassembly and/or reuse	
			In existing components, the finishing has a short lifespan and cannot be easily separated causing premature obsolescence	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Functional & aesthetic value	**2**		Perceived lack of aesthetics of non-virgin materials	
			Modular buildings, DfD compromises aesthetics	
Supply chain	**11**		Lack of reverse logistical mechanisms for recovery and VRPs	
			Storage capacity needed for reuse of materials	
			Transport needed for VRPs	
			Development of new roles and processes required in supply chain	
			Lack of technology to assess non-virgin materials	
			Lack of processing plants & factories for VRPs	
			More collaboration needed between supply chain partners	
			A designated employee (per stakeholder) required which safeguards circularity throughout the process	
			Need for material passport specialist along the process	
			Circular supply chain models not applied in practice	
			Temporary, project-wise building processes hinder finding synergies between supply chain partners	
Knowledge, skills & educational	**33**		Lack of awareness, consideration or concern of CE amongst stakeholders	
			Lack of circular economy knowledge	
			Lack of concrete knowledge and proof of performance and benefits of circular design options	
			Lack of information about recoverable materials / material flows are not mapped	
			Lack of disassembly information and cost-effective materials separation methods	
			Lack of information exchange for non-virgin materials (e.g., cross-stakeholder material platforms)	
			Lack of information in design stage	
			Lack of CE assessment methods or CE consideration in existing tools	
			Existing CE tools are not BIM compliant	
			Data collection issues	
			Lack of knowledge about which information needs to be stored and shared on circular components	
			Confusion between reuse and recycling	
			Lack of clear and common definitions on CE and circular design options	
			Lack of CE experience and skills by stakeholders	
			Lack of empirical knowledge on CE barriers	
			Lack of CE education in school curricula	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
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	5	x				x	x		x									x
	3	x							x		x							
	5						x		x		x	x	x					
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	3		x			x			x									
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	5						x		x			x		x			x	
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TABLE APP.C.2 Barriers for the implementation of CE (design) options identified in literature

Feasibility category	#		Barriers	
Knowledge, skills & educational			Lack of lifecycle and long-term thinking	
			Lack of information about availability and quality of non-virgin materials	
			Lack of tools to identify and classify salvageable materials (e.g., during predemolition audit)	
			Lack of information on materials during refurbishment and demolition	
			Limited visualisation capability for CE strategy	
			Need to trace material over lifecycle and update information in material passport over time	
			Handling huge amount of data of materials passports	
			Harmonised, material passport technology needs to be developed	
			Use of BIM is not widespread	
			Lack of understanding of circular design options	
			Lack of holistic and systemic thinking	
			Lack of understanding of link between materials and health of indoor space (air quality)	
			Design approach needs to include circular design options and materials in the starting points	
			Lack of local, site specific design and building approaches	
			Lack of structural information sharing between stakeholders over lifecycle (e.g., on available reclaimed materials)	
			Lack of urban planning skills leads to premature obsolescence of buildings	
			Material platforms and passports only consider material quantity and location not environmental impacts	

	mentioned by # of sources	Adams et al. (2017)	Akinade et al. (2020)	Azcarate-Aguerre et al. (2022)	Azcarate-Aguerre et al. (2018)	Chang & Hsieh (2019)	Charef et al. (2021)	Condotta and Zatta (2021)	Cruz Rios et al. (2021)	Galle et al. (2021)	Gisilini et al (2018)	Giorgi et al. (2022)	Guerra & Leite (2021)	Hjaltadóttir & Hild (2021)	Huang et al. (2018)	Kanters (2020)	Selman & Gade (2020)	Torgautov et al. (2021)
	3						x		x			x						
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Overview of meetings during the CIK development process

This section will give an overview of all the formal moments of contact between stakeholders in the consortium. Table App.C.3 gives the complete overview of meetings, workshops, and events.

TABLE APP.C.3 Overview of all the meetings related to the CIK development process

date	phase	Meeting	Meeting type	# parties present
24-01-2017	Proof of principle	Introduction meeting and interview	introduction meeting	2
31-01-2017	Proof of principle	Introduction meeting, interview, factory visit	introduction meeting	2
06-02-2017	Proof of principle	Introduction meeting and interview	introduction meeting	2
14-02-2017	Proof of principle	Introduction meeting and interview	introduction meeting	2
22-02-2017	Proof of principle	Introduction meeting and interview	introduction meeting	2
08-03-2017	Proof of principle	Introduction meeting, interview, factory visit	introduction meeting	2
28-03-2017	Proof of principle	Workshop 1 – variants	workshop	7
04-05-2017	Proof of principle	Meeting housing association	meeting	2
07-06-2017	Proof of principle	Introduction meeting and interview	introduction meeting	2
15-06-2017	Proof of principle	Workshop 2 – Preliminary concept	workshop	7
23-06-2017	Proof of principle	Meeting housing association	meeting	2
23-08-2017	Proof of principle	Meeting kitchen manufacturer – Follow up project	meeting	2
24-08-2017	Proof of principle	Meeting housing association – Follow up project	meeting	2
29-08-2017	Proof of principle	Meeting housing association – Follow up project	meeting	1
31-08-2017	Proof of principle	Focus group tenants	focus group	2
12-09-2017	Proof of principle	Meeting housing association follow up	meeting	2
12-09-2017	Proof of principle	Workshop 3 – proof of principle	workshop	1
31-10-2017	Proof of concept	kitchen manufacturer IP meeting	meeting	2
17-11-2017	Proof of concept	Meeting housing association – Follow up project	meeting	2
22-11-2017	Proof of concept	Introduction appliances manufacturer	introduction meeting	2
15-01-2018	Proof of concept	First project team meeting (project set-up)	meeting	2
26-01-2018	Proof of concept	Presentation of CIK proof of principle	presentation	2
01-02-2018	Proof of concept	Meeting housing association – Follow up project	meeting	2
15-03-2018	Proof of concept	CIK Kickoff workshop (Dutch)	workshop	7
05-04-2018	Proof of concept	Startup meeting CIK	meeting	1
04-05-2018	Proof of concept	Work session	work session	1
08-05-2018	Proof of concept	Work session	work session	2
31-05-2018	Proof of concept	PhD meet up	meeting	3
01-06-2018	Proof of concept	Cik partner workshop NL	workshop	10
06-06-2018	Proof of concept	Work session	work session	2
14-06-2018	Proof of concept	Work session	work session	0

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TABLE APP.C.3 Overview of all the meetings related to the CIK development process

date	phase	Meeting	Meeting type	# parties present
20-06-2018	Proof of concept	Further steps kitchen development	meeting	2
27-06-2018	Proof of concept	Work session	work session	2
28-06-2018	Proof of concept	Life cycle costing and appliances meeting	meeting	3
03-07-2018	Proof of concept	Work session	work session	2
18-07-2018	Proof of concept	Functional requirements meeting	work session	3
21-08-2018	Proof of concept	Work session	work session	2
03-09-2018	Proof of concept	Work session	work session	2
11-09-2018	Proof of concept	Work session	work session	2
21-09-2018	Proof of concept	CIK partner workshop Sweden	workshop	5
12-10-2018	Proof of concept	Work session	work session	2
17-10-2018	Proof of concept	Building mockups for CIK prototype	prototyping	1
19-10-2018	Proof of concept	Work session	work session	2
24-10-2018	Proof of concept	CIK partner workshop NL	workshop	8
31-10-2018	Prototype	Co-creation appliances & kitchen manufacturer	meeting	3
31-10-2018	Prototype	Work session	work session	2
16-11-2018	Prototype	Work session	work session	2
29-11-2018	Prototype	Work session	work session	2
10-12-2018	Prototype	Building prototype 1.0	prototyping	2
11-12-2018	Prototype	Building prototype 1.0	prototyping	2
08-01-2019	Prototype	Checking prototype 1.0	prototyping	2
10-01-2019	Prototype	New year's drinks	meeting	9
17-01-2019	Prototype	CIK-prototype event	event	9
14-02-2019	Prototype	CIK reflection and planning	meeting	2
18-02-2019	Prototype	Conversation on IP and other kitchen projects	meeting	2
28-02-2019	Prototype	Workshop appliances manufacturer	workshop	2
23-04-2019	Prototype	Workshop appliances manufacturer	workshop	2
30-04-2019	Prototype	Work session	work session	2
25-04-2019	Prototype	Exploring standardization of circular kitchens	meeting	2
03-05-2019	Prototype	CIK partner workshop NL	workshop	9
07-06-2019	Prototype	Work session	work session	2
17-06-2019	Prototype	CIK International partner workshop	workshop	10
18-06-2019	Prototype	Workshop appliances manufacturer	workshop	3
06-09-2019	Prototype	CIK partner workshop NL	workshop	4
08-10-2019	Prototype	CIK partner workshop Sweden	workshop	5
08-11-2019	Prototype	Meeting drawings external party	introduction meeting	2
08-11-2019	Prototype	Meeting drawings external party	introduction meeting	2
18-11-2019	Prototype	Meeting connector manufacturer	introduction meeting	2

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TOC

TABLE APP.C.3 Overview of all the meetings related to the CIK development process

date	phase	Meeting	Meeting type	# parties present
06-12-2019	Prototype	Discussion about surveys for real world prototypes	meeting	2
19-12-2019	Prototype	Work session	work session	2
07-01-2020	Prototype	Work session	work session	2
13-01-2020	Prototype	Website kick-off	introduction meeting	1
16-01-2020	Prototype	Connector manufacturer visit	introduction meeting	2
22-01-2020	Prototype	Website CIK	meeting	1
23-01-2020	Prototype	Website CIK	meeting	1
30-01-2020	Prototype	Website CIK	meeting	1
12-02-2020	Prototype	Work session	work session	2
20-02-2020	Prototype	Assembly mock-ups	prototyping	2
23-04-2020	Prototype	Workshop appliances manufacturer	online workshop	3
12-05-2020	Demonstrator	Prototype 2.0 building	prototyping	2
18-05-2020	Demonstrator	Prototype 2.0 meeting	online meeting	2
20-05-2020	Demonstrator	CIK partner workshop NL	online workshop	4
15-06-2020	Demonstrator	CIK workshop international	online workshop	6
15-06-2020	Demonstrator	CIK consortium meeting	online meeting	3
17-06-2020	Demonstrator	Website CIK	online meeting	1
24-06-2020	Demonstrator	Website CIK	online meeting	1
20-07-2020	Demonstrator	Website CIK	online meeting	1
01-09-2020	Demonstrator	Website CIK	online meeting	1
02-09-2020	Demonstrator	Website CIK presentation	online meeting	1
09-09-2020	Demonstrator	Website CIK	online meeting	1
18-09-2020	Demonstrator	CIK event planning	online meeting	2
25-09-2020	Demonstrator	Recording interviews CIK	meeting	1
29-09-2020	Demonstrator	CIK online partner workshop NL	online workshop	7
14-10-2020	Demonstrator	Recording interviews and Prototype CIK	meeting	2
15-10-2020	Demonstrator	Website CIK	online meeting	1
28-10-2020	Demonstrator	Website CIK	online meeting	1
29-10-2020	Demonstrator	Website CIK	online meeting	1
04-11-2020	Demonstrator	Website CIK	online meeting	1
04-11-2020	Demonstrator	CIK event planning	online meeting	2
23-02-2021	Demonstrator	CIK prototype 2.0 evaluation	online meeting	3
04-03-2021	Demonstrator	Webinar CIK	event	6
01-03-2021	Demonstrator	Meeting other circular kitchen manufacturer	introduction meeting	1
17-06-2021	Demonstrator	Catching up	online meeting	2
13-07-2021	Demonstrator	Climate CIK meeting	online meeting	3
15-09-2021	Demonstrator	Business Model Canvas meeting	online workshop	5

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TABLE APP.C.3 Overview of all the meetings related to the CIK development process

date	phase	Meeting	Meeting type	# parties present
04-10-2021	Demonstrator	Interview other circular kitchen manufacturer	meeting	1
24-11-2021	Demonstrator	Evaluation choices kitchen manufacturer	meeting	2
02-12-2021	Demonstrator	CIK Workshop process analysis	online workshop	5

Description of the development of the CIK

In social housing, the kitchen consists of cabinets from melamine-coated chipboard panels which are glued together. The kitchen entire kitchen is replaced, on average, every 20 years. As the initial cost price is low, kitchens are seldom repaired, refurbished, or reused. This causes unnecessary resource use, impacts, and waste generation. To improve on these kitchens, the CIK project was initiated, and a circular kitchen was developed as described in the next sections.

Initial project goal & start up

In the project initiation phase, researchers tested the interest of stakeholders in the social housing kitchen supply chain by posing questions related to the business model of kitchens, and the possibility to transition to a lease kitchen. This has led to the forming of a consortium that would explore the possibilities of a lease kitchen – that would become more circular. This consortium then agreed to start a one-year project to create a proof of principle for a circular kitchen (the CIK).

Proof of principle phase

In the proof of principle phase, the goal for the CIK was redefined as 'developing an exemplary circular component: The Circular Kitchen', initially for adoption by Dutch housing associations (HAs). A technical (design), industrial (supply chain), and business model were developed and tested for feasibility in co-creation with the supply chain partners.

The development of the proof of principle for the CIK was done in three main parts. In the first part, the focus was on understanding the current practice in the kitchen industry using interviews, micro internships, and factory visits. This allowed the identification of supply chain interests, opportunities, and barriers to implementing circular principles. Gaining this understanding was necessary to develop potentially feasible proposals.

In the second part, five potentially feasible variants of the Circular Kitchen were designed. To develop these variants the different choices to be made – parameters – for the technical, industrial, and business models were listed using brainstorms, literature, and precedent cases (seevan Stijn & Gruis (2019)). Consequently, several variants for the Circular Kitchen were developed by 'mixing and matching' these options, employing them as building blocks: (1) the 'green kitchen', where chipboard is replaced by biodegradable material, (2) the basic+ kitchen, which aims to conservatively adapt the current kitchen to become circular, (3) the plug-and-play kitchen, which facilitates the loops repair, re-use, refurbishment, remanufacturing and recycling, and accommodates for current and future needs, by separating the kitchen into parts based on expected lifespan, (4) the 'all-CE kitchen', which addresses the circularity of the kitchen in the use phase, by including appliances that reduce energy usage and waste, and (5) the '3D kitchen', which makes use of the recycling loop by using renewable energy and (infinitely) recyclable plastic to 3D print a kitchen which is tailored to the wishes of an individual tenant. These variants can be seen in Figure App.C.1.

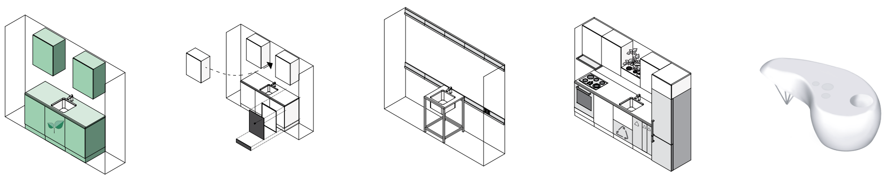

FIG. APP.C.1 The five variants developed for the CIK in the proof of principle phase. From left to right: the 'green kitchen', the 'basic+ kitchen', the 'plug-and-play' kitchen, the 'all CE-kitchen', and the '3D kitchen'.

In the third part, the proof-of-principle of the Circular Kitchen was developed further and tested for feasibility in an iterative co-creation process with TU Delft, AMS, HAs, and parties from the industry. The kitchen group selected variant 3: the plug-and-play model. According to the group, this model allowed not only to re-loop kitchen modules but also offered the most opportunities for a more service-oriented business model. Moreover, the fact that this model offers freedom of choice for tenants was seen as an added value as well. However, the group also concluded that variant 4: The All-CE kitchen needed to be combined with the plug-and-play model in an ideal long-term perspective.

The final proof of principle CIK, therefore, applies the combined all-CE and plug-and-play concept and can be seen in Figure App.C.2. The kitchen consists of a docking station in which modules can be plugged in and out. The kitchen modules themselves are also divided into a long-life frame to which function modules (kitchen appliances, closet interiors) and style packages (e.g. front, countertop, handles) can be easily attached, using dry, click-on connections. For the business model, no clear preference was identified yet. For the industrial model, which can be seen in Figure App.C.3 variant with a return street, in which the producer would re-distribute and lightly refurbish, was considered a feasible option.

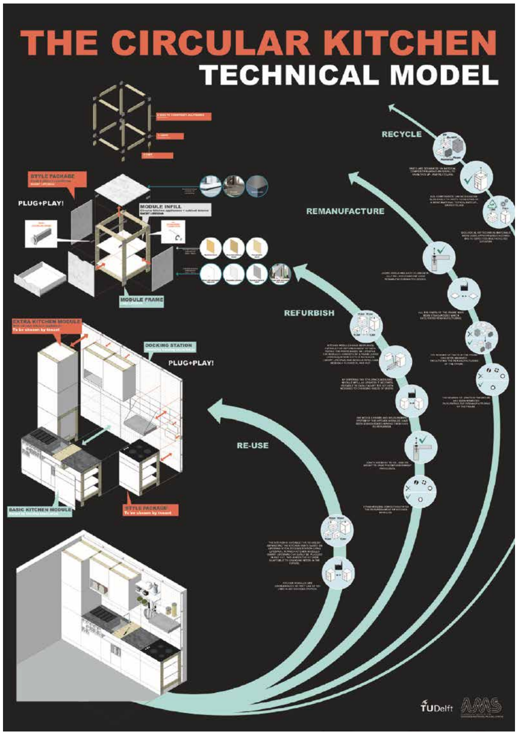

FIG. APP.C.2 The technical model of the proof of principle CIK

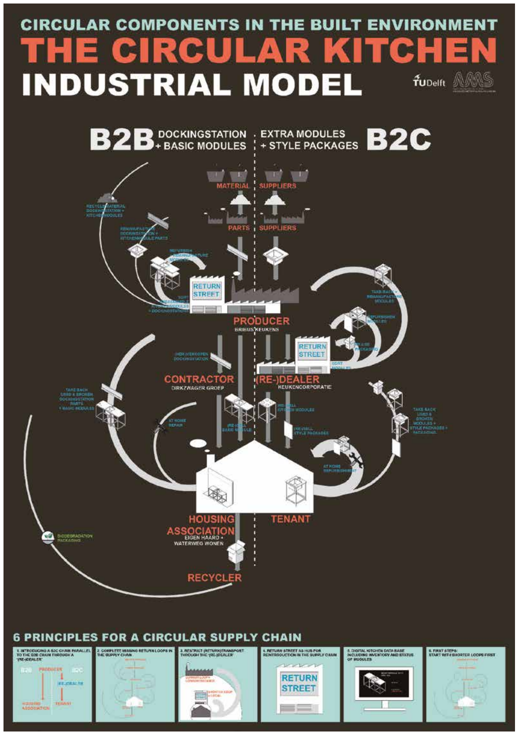

FIG. APP.C.3 The industrial model of the proof of principle CIK

Proof of concept phase

At the start of the proof of concept phase, new team members were introduced (a manager product and process development from the kitchen producer, and a researcher from the knowledge institute). These new team members formed a small team and would develop the proof of principle further to a proof of concept through work sessions, in which they developed ideas that would then be discussed and improved in workshops with the larger project groups.

In their work sessions, the small team defined what the kitchen should be assessed by: functional requirements, circular performance, and economic performance. The functional requirements were determined by a HA and the kitchen manufacturer (KM), the circular performance would be determined by life cycle analysis (LCA), and the economic performance by the total cost of ownership (TC). These criteria for assessment would later form the new goal for the CIK: ‘a kitchen that has a lower environmental impact than current kitchens while functioning at least as well, and not costing more throughout time’. This goal was then reflected on and approved by the larger group. A number of focus areas were identified as well, such as (1) the materials used should be available in the long term as well to avoid future incompatibility of the design and available material, (2) the lifespan of the material should be considered more important than the amount used (at initial production), since requiring less material in subsequent use cycles would likely offset the initial amount used, (3) the kitchen should look like a ‘standard kitchen’ because it is more likely to be accepted by the end-user.

The proof of principle kitchen was reconsidered and a number of key decisions were made. First, the choice between panels and a frame for the construction of cabinets was discussed. The less traditional frame was considered to give maximal flexibility for repairs and minimal material use and was therefore selected. Second, the small team decided that for the time being, two tracks should be considered: (1) a frame-based ‘standing’ kitchen, which would be a further developed version of the proof of principle, and (2) a hanging kitchen, which would hang from the docking station. However, towards the first pro-totype, the frame-based standing kitchen was deemed to be more feasible, since the hanging version had too many technical difficulties and risks. Therefore, the frame-based kitchen was selected for further development into a prototype. However, hanging frame-based wall cabinets were foreseen to raise too many issues, and these were therefore constructed of solid panels. Third, the style package was selected to be posi-tioned outside of the frame – covering the frame – over a style package that would be placed inside the frame, since the covered frame would ‘look more recognizable to the general public’, it would offer more space, and it has a ‘cleaner’ expression. Fourth, the base cabinets should have drawers where possible, since drawers take away the need to have side and bottom panels on the inside of the cabinet and increase ergonomics through time, which makes it more future-proof. It would cause a higher material use up front, but this was expected to be offset after multiple use cycles. Finally, the docking station was further refined and the group decided that the docking station should cover the whole wall and that it should be the structure to which the cabinets (both upper and lower) are attached. Making the docking station the central structure that connects all the modules would increase the clarity of the way the system works. Furthermore, no tiles are needed anymore, and space is created for piping and electricity.

Thus, at the end of the proof of concept phase, the plug-and-play concept was further developed and defined. It still consists of a docking station in which modules can be plugged in and out. The kitchen modules themselves are also divided into a long-life frame to which function modules (kitchen appliances, closet interiors) and style packages (e.g. front, countertop, handles) can be easily attached, using dry, click-on connections. The materials were selected to match the requirements defined by the HA's and the KM: sustainable plywood or bamboo panels with a detachable high-pressure laminate (HPL) finishing.

Prototypes

The prototype phase consisted of two sub-phases. In the first sub-phase, smaller parts of the design were tested by using mock-ups. These mock-ups served to test combinations of the design, connectors, and materials. For example, multiple connectors were tested in different materials, as can be seen in Figure App.C.4 and Figure App.C.5. We found that since chipboard is generally used in the kitchen, most of the connectors offered by the standard suppliers were less suited for other materials than chipboard, such as plywood and bamboo. Therefore, a less conventional connector was needed, and we decided to apply a tool-free connector produced by a third party that was not a current supplier of the KM. This tool-free connector was then further tested in a mock-up of a 60cm wide section of the kitchen, to test its strength in combination with bamboo panels and the ease of assembly. We then found that the depth of the hole in which the connector is placed is crucial for its functioning, and that a tenth of a millimeter difference can determine whether the connector functions or not (see Figure App.C.6 and Figure App.C.7). Machines would have to be selected specifically to achieve this accuracy. Furthermore, bamboo turned out to be too difficult to machine, as several router bits were needed for a small mock-up. Machining bamboo on a large scale would then lead to excessive consumption of router bits. Therefore, sustainable plywood was seen as the best option.

FIG. APP.C.4 Multiple mock-ups of types of connections for the CIK frame

FIG. APP.C.5 a mock-up for the connector used in CIK prototype 1

FIG. APP.C.6 Measuring depth in a mock-up for the tool-free click-on connector in bamboo

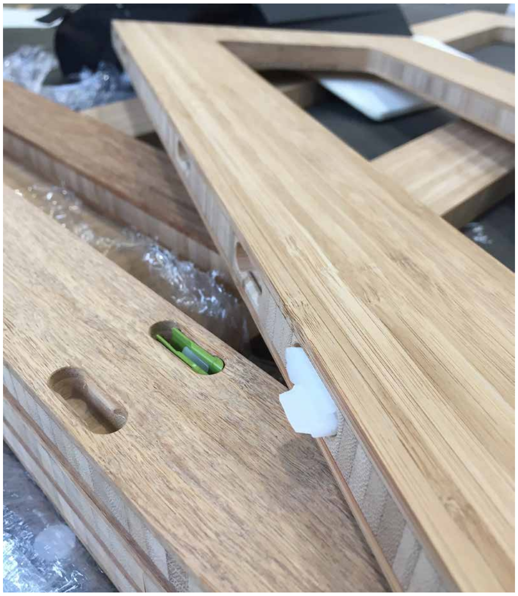

FIG. APP.C.7 Mock-up with a tool free connector applied

In the second sub-phase, production of the first prototype was prepared and the first prototype was manufactured. The first CIK prototype consists of 4 lower cabinets and wall cabinets and 1 high cabinet, based on the proof of concept. This larger setup was chosen over the more conventional, smaller, 3-cabinet-setup commonly applied by HAs, since offering tenants more energy-efficient appliances (possible through a lease construction) was seen as the way forward. Two style packages were produced in different colors, to demonstrate the ease of changing the look of the kitchen. The prototype was a one-off production, and could therefore not be manufactured at the KM's own facilities, which are equipped for mass production only. The production of the prototype was therefore out-sourced to a third party. Figure App.C.8 and Figure App.C.9 show the assembly of the prototype.

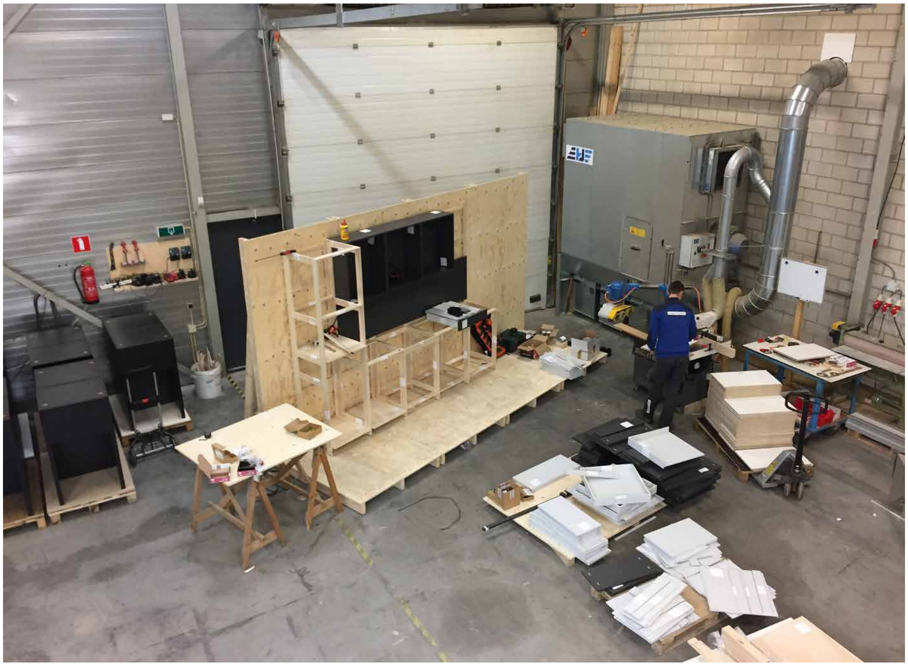

FIG. APP.C.8 CIK prototype 1 being assembled with a black style package

FIG. APP.C.9 CIK prototype 1 being assembled with a grey style package

In January 2019, the first full-scale prototype of the CIK was presented and discussed with (future) customers and end-users (see Figure App.C.10 and Figure App.C.11). The goal of this event was to give customers, end-users, and the kitchen producer the possibility to critically test the first prototype and provide feedback for further improvement. The participants noted that the prototype exceeded expectations. They stressed the fact that the prototype is sustainable and has the look and feel of a traditional kitchen. In accordance with the feedback, this combination increases the acceptance by end-users. While discussing the business model, participants agreed that end-users are willing to pay more for a sustainable kitchen than for an unsustainable one. However, the price of the first prototype was marked too high.

FIG. APP.C.10 The prototype as exhibited at the CIK presentation in 2019

FIG. APP.C.11 Attendees of the CIK presentation examining the prototype

The lessons learned from the assembly and disassembly test done with prototype 1, as well as the responses of potential customers were used to evaluate prototype 1. From this evaluation, further steps were formulated and planned in several co-creation workshops. Table App.C.4 shows these workshops during the next phase.

TABLE APP.C.4 Workshops planned for the demonstrator phase.

Workshop date	Workshop type and location	Workshop topics
10-01-2019	New years drink NL, Delft	Evaluation of prototype 1 Development plan towards prototype 2
03-05-2019	National, Delft	Update on development Variant for prototype 2 Prototype 2 real world tests
17-06-2019	International, Delft	Products as a service Contract variants Kitchen ID Comparison of CIK NL variants based on LCA.LCC and functionality
06-09-2019	National, Delft	Placement of prototype 2 kitchens Prototype 2 real world tests
08-10-2019	International, Gothenburg	Development updates End-user feedback surveys & interviews

During the new year's gathering on the 10^{th} of January 2019, the Dutch CIK project partners gathered to evaluate the prototype. A document with points to re-evaluate was presented and steps were formulated to work towards prototype 2. This included re-evaluating several design choices made for prototype 1 that will be elaborated on in the next section.

Demonstrator

After prototype 1, several design decisions were evaluated. Most notably, the docking station had to be adapted to be able to house plumbing and electricity cables, and to make the attachment of the style package easier. Furthermore, whether the cabinets should be a frame or panel-type construction would have to be reconsidered. Last, the connectors used would have to be reconsidered.

In the second workshop, on the 3^{rd} of May 2019, the Dutch project partners gathered to discuss the development of the CIK demonstrator. Here, several variants for the de-monstrator were presented as seen in Figure App.C.12. Variant 1 consists of a frame construction (including the wall cabinets), while variants 2 and 3 consists of more traditional panel construction. Furthermore, in variants 1 and 2, the construction and finishing parts are separated into two layers, while variant 3 has panels that function both as construction and finishing.

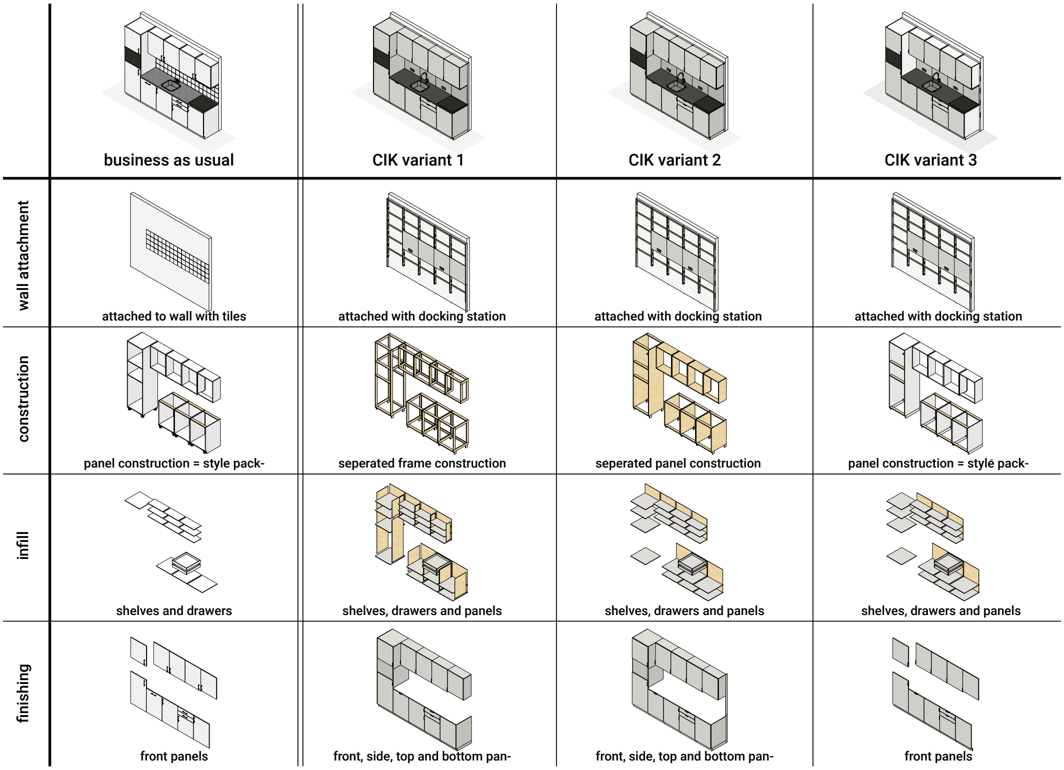

FIG. APP.C.12 Variants for the CIK demonstrator as presented during the workshop on the 3rd of May 2019

The project group was asked to rank 4 kitchens from 1st choice to 4th choice based if the kitchens were in production now and offered to them. These kitchens were presented including the functionality, purchase price, TCO, and environmental impact (measured in savings compared to the current kitchen on both eco costs and CO2eq emissions). Table App.C.5 shows the results of the votes including the remarks. The number of votes from the HA's is shown in between parenthesis and the HA remarks are marked with '(HA)'. The group showed a significant preference for Variant 1.

As a result of this workshop, the consortium decided to continue to develop variant 1, the improved version of prototype 1. Therefore, the business and industrial model was not altered compared to prototype 1.

TABLE APP.C.5 Results of the votes for CIK demonstrator variants, including remarks

	1st choice	2nd choice	3rd choice	4th choice	Total
Current Kitchen	0 (0)	2 (1)	2 (1)	12 (4)	16 (6)
remarks				- High CO2 footprint (HA) - No option for a sustainable future (HA) - CO2 taxes will raise the TCO (HA) - Most material used - Most wasteful	
Variant 3	1 (1)	4 (2)	8 (2)	2 (1)	15 (6)
remarks	+ No edges in cabinet (HA)		- Least flexible circular variant (HA) - lowest Environmental impact savings (HA) - Costs per CO2 saved (HA) - High price (HA) - More material changes		
Variant 2	1 (1)	8 (2)	4 (2)	2 (1)	15 (6)
remarks		+/- Costs per CO2 saved (HA) + Flexibility - Connections in sight (HA) - More material			
Variant 1	18 (8)	1 (1)	1 (1)	0 (0)	20 (10)
remarks	+ Most innovative (HA) + Hidden detachable connections (HA) + TCO (HA) + Environmental Impact (HA) + high flexibility (HA) + Costs per CO2 saved (HA) + lowest difference purchase price & TCO + most durable outer layer - frame seems fragile (HA) - Edges in cabinets collect dirt and make placement of kitchen items harder (HA)				
Total	20 (10)	15 (6)	15 (6)	16 (6)	

During the last national workshop of 2019, plans for the placement of ±40 demonstrators were further elaborated. Of these demonstrators, 38 would be placed in real-world homes owned by the CIK partners, where they would be put to full use. During several workshops, CIK partners divided these kitchens among the HAs. The remaining de-monstrators would be placed in showrooms and at events. Furthermore, there have been numerous requests from outside of the consortium to purchase CIK kitchens. To test the acceptance of the CIK demonstrator, end-users would be asked to fill in surveys and take part in interviews. At these moments, kitchens will also be inspected for wear.

An event to present the first version of prototype 2.0, placed in the showroom at one of the HAs, was planned for April 2020. However, due to the global COVID-19 pandemic, this kitchen could not be placed, and the event could not take place in person. Instead, plans were made to postpone the event, and set up a digital alternative. However, originally planned for Autumn 2020, the prototype could still not be placed at the HA due to the strict regulations that were in place. Furthermore, all meetings and workshops from this point on have been online, and attendance decreased. At this same time, several people involved in the project long-term became less involved and others took over their roles.

Despite the regulations, the KM did manage to agree with a HA to place 7 kitchens in a slightly adapted setup, allowing for some additional tests with the adaptability of the kitchen; these 7 kitchens are placed against a half wall, meaning the docking station had to be adapted to fit. The KM was able to adapt these prototypes and has placed the kitchens successfully. This first placement provided some valuable input, for example, the adaptability of the feet and plinth for leveling the kitchen needs to be improved. The second-generation prototypes have therefore proven to be adaptable enough to be placed, whilst still providing some valuable input for improvement.

In 2021 a demonstrator was placed in a house provided by a HA. This kitchen had a 4-cabinet-setup, including an oven, induction hob, and extraction hood, and can be seen in Figure App.C.13.

FIG. APP.C.13 CIK demonstrator as placed in a house provided by a HA.

This placement provided useful feedback needed to further develop the prototype into a market-ready circular kitchen. Several key issues were identified: (1) the kitchen did not allow for plenty of space behind the docking station for plumbing in practice (see Figure App.C.14), (2) the adjustment of the feet did not suffice, (3) users were expected to not accept the unfinished panels on the inside of the cabinets (see Figure App.C.15).

FIG. APP.C.14 Existing plumbing ‘colliding’ with parts of the CIK demonstrator kitchen

FIG. APP.C.15 CIK Demonstrator upper cabinet without a door, showing the cabinet’s interior

Towards market implementation

The KM has since been redeveloping the circular kitchen to remain closer to the current production process and business model. Instead of a frame, the kitchen cabinet is constructed from demountable panels. Through this design, they aim to facilitate the repair of parts in local shops. Instead of plywood, a more circular variant of the current chipboard is used.

APPENDIX D

Appendix Section 5

Interview guide

The following material is part of the research article “Comparing circular kitchens: a study of the Dutch housing sector”.

As part of this research semi-structured interviews were conducted.
Table App.D.1 shows the interview sample questions, and how they were based in CBC-generator parameter options. CBC sub-parameters that could not be transformed into a relevant question for circular kitchens are shown with a ‘-‘.

TABLE APP.D.1 Overview of the CBC parameters and sub-parameters, and the kitchen-specific question that was iteratively derived from the parameters.

	CBC Parameter	CBC Sub parameter	Kitchen specific interview question	#
TECHNICAL MODEL	Materials/ resources	technological materials	What materials are used for the kitchen? (biological vs. technical materials)	1
		biological materials	Are there any plans to change these materials in the future? If yes which one?	2
	Energy	Type of energy	Can the kitchen be adapted to electric cooking at a later date? If so, how?	3
	System architecture	System elements	What elements is the kitchen made up of?	4
			Is the kitchen wall-mounted, and if so, how?	5
			Does your kitchen need a retaining wall and how much space does it take up?	6
			When using a retaining wall, how should it be attached to a (intermediate) wall?	7
			Is equipment supplied with the kitchen? If so, which one and is it also circular? (in the case of not yet electric cooking)	8
	Amount	Number of elements or resources	-	
	Time(s)	Number of lifecycles	-	
		Expected lifespan	What is/are the expected technical lifespan(s) of the entire kitchen and its elements?	9
			What is/are the expected functional lifespan(s) of the entire kitchen and its elements?	10
	Lifecycle stage	Lifecycle stage of building component, part, material	-	
	Circular design strategies	Design for material reduction	Have strategies been used to ensure that less material is used? If yes which one?	11
		Design for energy reduction	Have strategies been applied to ensure that less energy is used? If yes which one?	12
		Design for attachment	In which colors is the kitchen available as standard?	13
			Have strategies been applied in the kitchen to increase the bond/ attachment between the kitchen and the user? If yes which one?	14
		Design for reliability and durability	Have strategies been applied to increase the lifespan/ sustainability of the kitchen? If yes which one?	15
		Design for standardization and compatibility	Have strategies been applied to standardize the kitchen and the elements from which it is constructed? If yes which one?	16
		Design for ease of maintenance and repair	Has ease of maintenance and repairs been considered in the design of the kitchen? If so, how?	17
			Are tools needed to assemble the kitchen? And if so, which one?	18
		Design for upgrades and adjustments	To what extent is the kitchen adaptable after initial installation? Does the kitchen design allow for upgrades and customizations? If so, how?	19

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TABLE APP.D.1 Overview of the CBC parameters and sub-parameters, and the kitchen-specific question that was iteratively derived from the parameters.

	CBC Parameter	CBC Sub parameter	Kitchen specific interview question	#
TECHNICAL MODEL			Is the kitchen height adjustable? And if so, how?	20
			To what extent can plumbing be made flexibly and changed during their service life?	21
		Design for disassembly	To what extent can the kitchen be disassembled and reassembled and how does that work?	22
		Design for recycling	Has recycling of the parts/elements/entire kitchen been considered in the design of the kitchen? If so, how?	23
	-		Describe your circular kitchen?	24
			Do you have environmental impact results? If yes, how were these results calculated/which method is appropriate to calculate these results?	25
			Does the kitchen have any certificate related to sustainability?	26
INDUSTRIAL MODEL	Key partners	Partners in supply chain or value network	Which partners do you work with?	27[1]
			Who are the material suppliers? And what do they deliver?	28
	Key activities	Activities	What activities do the partners carry out?	29
		Re-loop activities	What agreements have been made about take-back with the suppliers?	30
		(re-) Production process per activity	-	
	Key resources	Facilities for activities	In which facilities are these activities performed? (Shops, factories, sorting points, etc.)	31
		System elements	Which partners are responsible for which elements of the kitchen?	32
	Transport/logistics	Mode of transport	How does delivery take place from the supplier to you?	33
			Has thought been given to the transport from the kitchen to the customer/user?	34
		Distance	Are parts made outside the Netherlands?	35
	Process energy	Type of energy	What kind of energy is used to produce the kitchen?	36
BUSINESS MODEL	Key partners	Partners in supply chain or value network	Which partners do you work with?	27[1]
	Customer segments	Owner	Who owns the kitchen when using the kitchen?	37
		Customer	Do you only deliver business to business or also business to customer?	38
			Do you deliver to a specific type of customer?	39
	Supply chain relations	Primary contact customer	-	
		Kind of customer relationship	-	
		Primary supply chain contact	-	

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TABLE APP.D.1 Overview of the CBC parameters and sub-parameters, and the kitchen-specific question that was iteratively derived from the parameters.

	CBC Parameter	CBC Sub parameter	Kitchen specific interview question	#
BUSINESS MODEL		Kind of collaboration	-	
	Cost structure	Cost proposition	-	
	Revenue streams	Financial arrangement	Under what conditions is the kitchen delivered: lease terms, warranty, conditions for take-back/purchase, etc.?	40
		Income division	-	
	Value proposition	Product/service proposition	What else is included in addition to the kitchen furniture? (Kitchen appliances, taps, etc.) And under what conditions?	41
			What agreements have been made about the maintenance of the kitchen?	42
		Value delivery	-	
		Value capturing	-	
	Key resources	Key resources per supply chain partner	-	
	Channels	Sale and (re)loop channels	Through which channels do you sell the kitchen? (webshop, telephone, shops, etc.)	43
			Through which channels do you arrange returns?	44
	Take back systems	Facilities for take-back	What agreements have been made with suppliers of parts (and possibly equipment) of the kitchen about taking back?	45
	Adoption factors	Circular business model's adoption factors	-	
			What happens if the kitchen is damaged?	46

1 This question is deducted from two CBC sub-parameters.

Research Data

The research data file as published originally is available for download online through https://www.mdpi.com/2075-5309/13/7/1698.

Curriculum vitae

Bas Jansen

About the author

With a Master's in Architecture, Building, and Planning from the Technical University of Eindhoven, I specialized in Architectural Urban Design and Engineering, eventually focusing on building with natural materials. I founded Atelier Wouterszoon to design and execute small-scale projects with minimal environmental impact. My interest in sustainable materials, like cross-laminated and other types of wood, grew through hands-on experience, including a ‘Nationale Houtbouwprijs’-winning project in 2021. To make a more meaningful impact on the sustainability of the built environment, I transitioned to developing circular building components, focussing on housing associations— the core subject of this dissertation. This shift has enabled me to tackle sustainability challenges both practically and systemically through close collaboration with multiple stakeholders.

Working with housing associations has shown me that they often lead in sustainability, driven by a commitment to providing affordable, high-quality, and sustainable living for all. This understanding led me to join Rochdale, where I focused on integrating circular construction practices. Over the past two years, I have guided the organization in adopting circular approaches and developing construction, renovation, and maintenance strategies that prioritize resource efficiency and minimize environmental impacts.

Relevant professional experience

2011-2014 **Assistant Designer, CASA Vertigo, Eindhoven**
Co-designing and realizing exhibitions at the Faculty of Architecture, Technical University of Eindhoven.

2012-2016 **Bicycle Courier, Tour de Ville Fietskoeriers, Eindhoven**
Contributing to the sustainability of the transport sector while improving my fitness.

2014 **Intern, Innauer Matt Architekten, Bezau, Austria**
Co-designing homes in Austria's Bregenzerwald, where biobased construction and private commissioning are cultural norms.

2016-now **Founder, Atelier Wouterszoon, Amsterdam**
Working on sustainable, affordable architectural projects, ranging from furniture to home renovations.

2016 **Manager, Tour de Ville Fietskoerier, Amsterdam**
Established a franchise of Tour de Ville Fietskoeriers in Amsterdam.

2016-2017 **Junior Architect, MAATworks, Amsterdam**
Designed several cross-laminated timber homes, involved in all construction phases.

2018-2022 **PhD Researcher, TU Delft, Faculty of Architecture, Management in the Built Environment**
Conducted international, multi-stakeholder research on the development of circular building components with a holistic approach, examining their design, supply chain, and business models. Also expanded practical and knowledge networks, organized co-creation workshops, spoke at conferences, and taught various courses.

2022-now **Strategic Sustainability Advisor, Woningstichting Rochdale, Amsterdam**
Developing strategies for circular construction and maintenance. Providing concrete advice at all organizational levels based on accumulated knowledge and experience. Representing external stakeholders to promote plans and gain support for collaboration.

List of publications

Journal publications (peer reviewed)

- Wouterszoon Jansen, B., Duijghuisen, J.A., van Bortel, G. A., & Gruis, V. (2023). Comparing Circular Kitchens: A Study of the Dutch Housing Sector. Buildings 2023, 13(7), 1698; https://doi.org/10.3390/buildings13071698

- van Stijn, A., Wouterszoon Jansen, B., Gruis, V, & van Bortel, G. A. (2023). Towards implementation of circular building components: a longitudinal study on the stakeholder choices in the development of 8 circular building components. Journal of Cleaner Production, 420, 138287. https://doi.org/10.1016/j.jclepro.2023.138287

- Dokter, G., Boks, C., Rahe, U., Wouterszoon Jansen, B., Hagejärd, S. & Thuvander, L. (2023). The role of prototyping and co-creation in circular economy-oriented innovation: A longitudinal case study in the kitchen industry. Sustainable Production and Consumption, 39, 230-243. https://doi.org/10.1016/j.spc.2023.05.012

- Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. A. (2022). Cooking up a circular kitchen: a longitudinal study of stake-holder choices in the development of a circular building component. Sustainability, 14, 15761. https://doi.org/10.3390/su142315761

- Wouterszoon Jansen, B., van Stijn, A., Malabi Eberhardt, L. C., Gruis, V., & van Bortel, G. A. (2022). The technical or biological loop? Economic and environmental performance of circular building components. Sustainable Production and Consumption, 34(1), 476-489. https://doi.org/10.1016/j.spc.2022.10.008

- van Stijn, A., Malabi Eberhardt, L. C., Wouterszoon Jansen, B., & Meijer, A. (2022). Environmental design guidelines for circular building components based on LCA and MFA: Lessons from the circular kitchen and renovation façade. Journal of Cleaner Production, 357, 131375. https://doi.org/10.1016/j.jclepro.2022.131375

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Resources, Conservation and Recycling, 174(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105683

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24#14

The Circular Kitchen

Perspectives for Design and Implementation

Bas Jansen

Global warming's impacts on ecosystems and economies underscore the urgent need for sustainability in the built environment, particularly in the housing sector, which significantly contributes to greenhouse gas emissions and material consumption. The Circular Economy (CE) presents a promising solution by minimizing resource use, environmental impact, and waste through strategies like slowing, narrowing, and closing material loops. This research focuses on developing a Circular Kitchen (CIK) as a model for circular building components. It targets Dutch Housing Associations for their market influence and long-term investments and involves other kitchen supply chain stakeholders.

The study identifies four key research goals: developing a life cycle costing (LCC) method for evaluating circular components, assessing the environmental and economic performance of circular building components, deriving lessons from stakeholder choices, and examining the feasibility of circular kitchens beyond the CIK project. The findings suggest that while the CIK designs outperform standard kitchens environmentally and economically, real-world application remains challenging. Although the CIK did not reach mass implementation, the insights gained inform the development of more feasible circular building components. This research advances the understanding of CE in the built environment, providing strategies to improve the feasibility and environmental performance of circular building components.

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