Developing circular building components

Between ideal and feasible

Anne van Stijn

Developing circular building components

Between ideal and feasible

Anne van Stijn

TOC

A+BE | Architecture and the Built Environment | TU Delft BK

23#05

Design | Sirene Ontwerpers, Véro Crickx
Cover image | Anne van Stijn

ISBN 978-94-6366-674-9
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.7480/abe.2023.05

Developing circular building components

Between ideal and feasible

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Friday 21 April 2023 at 12:30 o'clock

by

Anne VAN STIJN
Master of Science in Architecture, Urbanism and Building Sciences,
Delft University of Technology, The Netherlands
born in Sittard, The Netherlands

TOC

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.dr.ir. V.H. Gruis	Delft University of Technology, promotor
Prof.dr.-ing T. Klein	Delft University of Technology, promotor
Dr.ing. G.A. van Bortel	Delft University of Technology, copromotor

Independent members:

Prof. PhD, M.Sc. M. Birkved	University of Southern Denmark, Denmark
Prof.dr.ir. C.A. Bakker	Delft University of Technology
Prof.dr.ir. J.W.F. Wamelink	Delft University of Technology
Dr.dipl.-ing. T.W.A. Schröder	Eindhoven University of Technology

This study was part of the research projects "Circular Components" (grantnumber CIR17018), "REHAB" (grantnumber CIR18006) and "Circular Kitchen (CIK)" (grantnumber 210060). As such, this research was financed by the Delft University of Technology, Amsterdam Institute for Advanced Metropolitan Solutions, EIT Climate-KIC, contractors Dura Vermeer and ERA Contour, and social housing associations Eigen Haard, Wonion and Ymere.

L’esprit délibère et le cœur conclut

Louise Dupin, Traité sur l’Amitié (Treatise on Friendship), 1726

TOC

Preface

The start of a journey

Let me start by saying that I have never considered myself as a particularly 'green' person. I had never joined a climate march or other environmental protest. I have always enjoyed the taste of meat too much to become an environmental vegetarian. I drove a gasoline car to the university rather than taking public transport. When looking for a house to live in, its energy-performance was not too high on the requirement list. To my Dutch compatriots, I could jest that my 'goat-woollen socks' must have gotten lost somewhere in the back of my closet. You may wonder how somebody like me ended up dedicating half a decade to a research about circular economy? More importantly, you may wonder if this research changed my perspective on life? Let me take you on my journey…

Making affordable, accessible, sustainable and good-quality housing

Since the beginning of my career, I have been committed to social housing. Specifically, to designing solutions which improve the quality, accessibility, affordability and sustainability of housing in the Netherlands and abroad. My passion started during my bachelors at the Faculty of Architecture and the Built Environment at the Delft University of Technology. I actively looked for classes and projects which allowed me to work on housing challenges in the Netherlands. Working in the (so-called!) 'problem neighbourhoods' of Rotterdam South, I developed a toolbox to improve the energy-efficiency and quality of dwellings in an affordable manner. During my masters in Architecture, I expanded my scope to housing challenges abroad. I worked on improving the living conditions of the informal housing in the neighbourhoods of Istanbul, Turkey and the slums of Addis Ababa, Ethiopia. By this time, I was convinced I would become an architect and, preferably, a famous one. I dreamt for my picture to be added to the hallway of 'starchitects' in my faculty for making ground-breaking designs on the improvement of existing housing.

TOC

As the years progressed my focus shifted from designing the physical plans to designing the processes needed to realize them. Fascinated by the challenge to house an urban billion, I moved to China for a year. Whilst cycling on one of the gigantic ring roads of Beijing, I passed hundreds of concrete housing slabs and towers. Colossi which seemed to be 'crumbling'. My interest peeked, so I started visiting these buildings. Like a real action-researcher, I rented a room in one of them. I soon found that these high-rises need to be adapted to current user needs and require improvements to their energy efficiency. However, the future of these high-rises affects many stakeholders; their contradictory interests resulted in a financial impasse hindering investments. I graduated from my masters by developing a rehabilitation plan for China's crumbling high-rises, including policy proposals, a business model and physical renovation plan. The idea was that a coalition of stakeholders could renovate these dwellings step-by-step using mass-producible and customisable *building components*.

Circular building components for housing renovation

Busy planning a career as a starchitect, I had not once considered doing a PhD. Until I found myself applying for my first research position. I firmly believed that making mass-producible and customisable building components could revolutionize the way we renovate. It had the potential to make renovations more attractive, affordable and less cumbersome. Until now, my ideas for building components had been theory. I really wanted to develop them further after my graduation. By sheer coincidence my big brother Niek had come home with a 'big talk'. He explained how the circular economy was going to play a BIG role in making our society more sustainable. After reading into it, I figured that he was probably right. A feat not always easy to admit to a sibling. I got convinced that the transition to a circular economy was going to be a necessity to house people now and to keep housing them in the future.

I could not believe my luck when a research post opened in the 'circular components' project. This post was under supervision of Prof.dr.ir. Vincent Gruis; it was a dual position in the department of Management in the Built Environment (MBE) of the Delft University of Technology and in the Amsterdam Institute for Advanced Metropolitan Solutions (AMS). It provided me the opportunity to kick-start the development of two circular building components: a circular kitchen and a circular central heating boiler. I started almost immediately after I completed my MSc graduation. When a few months had passed, I knew that a one-year post would not suffice. Together, Prof.dr.ir. Vincent Gruis and I looked for opportunities to continue and expand the team. We extended the stakeholder consortium and acquired funding to further the development of the circular kitchen in the (CIK) project. Ir. Bas Jansen joined our team and took over as ‘chef de cuisine’. Although I would stay closely involved in the circular kitchen development over the next four years, I was given the opportunity to head my own research project. In the REHAB project I wanted to develop multiple circular building components specifically in the context of housing renovation. I forged partnerships with housing associations and contractors who shared my enthusiasm; I was granted research funding by AMS institute which afforded me the opportunity to do my PhD research. In the REHAB project, I co-developed the circular skin, circular dwelling extension and the NZEB-light together with the stakeholders. The PhD that lies before you draws from the research I conducted in these three projects.

Learning something together every day

Many will tell you that doing a PhD is a solitary journey. Indeed, it quickly requires you to become an independent voyager, but nobody said anything about being lonely. Rather, I chose to go on a group-trip. At the peril of omitting people, I do want to name a few of the many individuals who joined me on my way.

Designing circular building components and realising them in projects and practice requires many minds and hands. Over the past years, me and my fellow researchers collaborated closely with social housing associations, manufacturers, contractors, consultants, architects, climate installation service providers, universities, universities of applied sciences and knowledge institutes. I want to express my gratitude to all who have been partners in this effort. In particular I want to thank Robert Dalenoort of Syntrus Achmea; Bob Geldermans, Joke Dufourmont, Joppe van Driel and Virpi Heybroek of the AMS institute; Jan van Os of ATAG, Serge Wouters and Ward de Groot of Barli; Bas te Brake, Dave Lageschaar, Joop Boerekamps, Piet-Hein Kraakman and Wim Diersen from Bribus Keukens; Nadia Silvestri, Natalia Alandete Lara, Sander Jahilo and Zeno Winkels of the Climate KIC; Peter van Heun of Climatic Design Consult; Ger Uitermark, Kevin Uitermark and Remco Sinnige of Dirkzwager Groep; Frank Beking, Johan Timmer and Ludwig Smits of De Variabele; Gurbe van Belle and Terry Pater of DOOR architecten; André Köster, Bram van Vliet, Claudia Oranje, Debby van Kraaij-Rasing, Edwin Blom, Henk Marsman, Henk Minnaard, Jurgen Schoenmakers, Sandra Bouwmeester and Silvia van de Kamp-Dobbe of Dura Vermeer; Aad van Meel, Bart de Jong, Fred Springintveld, Goran Pogarcic, Ilse van Andel and Peter Hildering of Eigen Haard; Do de Schepper, Jeroen Eijkelboom, Nils Vanwesenbeek, Simone Aanhaanen and Saskia van der Weerd of ERA Contour; Philippe Felleman and Ronald Pilot of Feenstra; Bert Kok, Martin Koldenhof and Maurice Duenk of Klein Poelhuis Installatietechniek; Herman Boerma en Jan Kragt of Lenferink Vastgoedonderhoud; Peter de Clerck and Tessa van den Boogaard of Linex;

Albert Groothuizen, Jurn de Winter and Tom Petiet of Portaal; Bart van Diepen, Gert de Vos and Pieter Sonneveld of Remeha; Bas Slager and Hermen van de Minkelis of Repurpose; Arjen Karssenberg, Gerard Scheele and all the students who helped building the prototypes of the circular façade during the course "de innovatieve bouwsteen" from the Rotterdam University of Applied Sciences; Ronnie Jansen of Rudie Jansen Schilders & Totaalonderhoud; Freek Hermsen, Raymond Heister, Rob Boogaarts, Teun van Kuijk of Stichting Woonbedrijf SWS; Bram Aaldering of Te Mebel Vastgoedonderhoud BV; Dick Lodder, Hans van Erven, Herman Brans and Mark de Waard of Topline Maatwerkbladen BV, Rob van den Oudenrijn of Van den Oudenrijn, Andries Laane and Feike Laane of Villanova architecten, Derk Wassink and Rob Tanck of Wassink Installatie; Joost van den Bergh, Monique Bezemer-Voll and Wilfred Gerritse of Waterweg Wonen; Barend Wassink, Gerrolt Ooijman, Hans Bosboom, Ingrid Pierik and Marc Barenbrug of Wonion; Caroline Kroes, Hanneke van der Heijden and Gilles du Hen of Woonstad Rotterdam; Frank Boom of WSI techniek; Bas Kalshoven, Evelien van Stralen, Jan Jaap Vogel, Jeffrey Maarsman, Karel de Koning, Mariska Diks, Rob Oosterloo and Ron Onverzaagt of Ymere. Without your enthusiasm, knowledge and hard work this research would never have been possible.

Chalmers University of Technology became our research partner in the CIK project joining us in the innovation process of the circular kitchen. Their team of researchers very quickly became true 'partners in crime' and Göteborg our second base of operations. I want to thank prof. dipl.-des. Ulrike Rahe, prof.dr.ir. Paula Femenías, and my fellow PhD researchers Anita Ollár, Giliam Dokter and Sofie Hagejärd for the warm welcome we received and all your valuable insights during our years of work together.

When I started writing the research proposal for my PhD, I found myself both fascinated and utterly confused with the research methodology I wanted to apply: Research through Design. I dove into its history and theories, trying to make sense of it all. But that got me wondering: why hadn't anybody from our faculty written down how to do it, preferably in simple terms? I am grateful that I found dr.ir. Louis Lousberg somewhere along this road. Together we had many inspiring methodological discussions which resulted in three book chapters on Research through Design.

I want to express my gratitude to dr. Leonora Charlotte Malabi Eberhardt from Aalborg University. At a conference, we found ourselves having the – exact – same research interest. We both wanted to work on the environmental performance assessment of circular building components using Life Cycle Assessment (LCA). From your conference presentation I was immediately impressed with your expertise. So, naturally, my first words to you were "I think you are doing it all wrong".

Thankfully, you quickly proved me wrong and it became the start of a wonderful research collaboration. I want to thank you for guiding me on how to 'speak LCA'. I believe we were a great team and I look forward to finding new opportunities to collaborate in the years to come.

When ir. Bas Jansen joined the circular kitchen project, I did not just gain a colleague. Rather, I gained a companion on my PhD journey. Not only did we collaborate in much of our work, we also experienced many PhD milestones together. You taught me how to keep my calm during most of them. It has been a luxury to be in the same boat with you!

From theory to practice

I have had the time of my life during the years I worked on my PhD. I have loved everything, from developing research proposals, setting-up and maintaining collaborations, acquiring funding, managing research projects, lecturing, teaching, developing innovations, sharing knowledge at conferences and (even) writing this dissertation. I loved it so much that I was certain I wanted to pursue a scientific career. And, in my 'humble' opinion, prof.dr.ir van Stijn does have a ring to it. So, before my PhD even came close to finishing, I started up a follow-up research project. Spoiler alert (!): during my PhD I found that integrating circular economy principles in the built environment would require fundamentally new ways of collaborating in the supply chain. I formed a coalition with prof.dr. Paul Chan, dr. Tuuli Jylhä, and prof.dr.ir. Vincent Gruis. Together we forged new partnerships; chaired by prof.dr. Paul Chan, we developed a research proposal focussing on circular collaboration – aptly named the CirCol project. Little did I know that working on this proposal would also help me to better reflect upon my PhD research. I want to thank the entire CirCol team for the new perspectives you showed me. You have helped me enrich the work that now lies before you.

At the same time, I had spent most of my PhD at the project table; I also loved my work in and with practice. I wanted to give back everything I learned. Scientific articles in English are probably not the most suitable medium for this. So, together, Merel Stolker (C-creators) and I wrote a handbook on circular renovation for housing associations. Rather than going deep, we went broad. Sourcing from this dissertation, other publications and interviews, we linked the current knowledge on circular economy to the renovation project cycle. We aimed to provide concrete guidance to integrate circularity in the day-to-day processes occurring at housing associations. I want to thank Merel Stolker for the great collaboration, her hard work and dedication to this book. It shows in the final result. Together we launched

this book, presenting it to Zita Pels (deputy of the province of Noord-Holland) and Ferdi Licher (director of construction and energy at the Ministry of the Interior) who handed the book over to Frans van de Kerkhof (director of housing association Eigen Haard) and Jeroen Pepers (director of Aedes, the national association of Dutch social housing associations). In March 2022, I decided to join Aedes in her efforts as a sector developer. In my work, I now support, activate, and connect Dutch social housing associations in realizing their sustainability goals and search towards circularity.

Much more than a helping hand

It took a village to make this dissertation. I am very grateful to all those who supported and guided me on my journey.

I want to express my gratitude to all who provided the daily support for our research efforts. The Department of MBE could not function without its excellent secretariat. I want to thank you all for your help and your listening ears. I could not have set-up and managed research projects without the help and advice of our valorisation centre, project administration, financial controllers and contract managers. A special thanks goes to Jordi Kerkum who as MBE department manager counselled me in setting up my own research projects. His presence is enough to light up any room he entered. I also want to thank Jin-ah Duijghuisen for her hard work. As the student assistant of the CIK project, she has supported us in the organisation of the project and our research.

I would like to express my appreciation to the doctoral committee members Prof.dr.ir. C.A. Bakker, Prof. PhD, M.Sc. M. Birkved, Dr.dipl.-ing. T.W.A. Schröder, and Prof.dr.ir. J.W.F. Wamelink for all their valuable feedback.

My research has been funded through subsidies and contributions from AMS institute, Delft University of Technology, Dura Vermeer, Eigen Haard, EIT Climate KIC, ERA Contour, Wonion and Ymere. I want to thank you for believing in the importance of this research. Without you support, my PhD would never have been possible.

I want to thank prof.dr.-ing. Tillmann Klein, my second promotor. Your knowledge and on-point remarks helped me improve this dissertation. I would like to thank my daily supervisor dr.ing Gerard van Bortel for all your support. I have benefitted immensely from your knowledge of social housing and experience in research and writing. I also want to thank you for your ever-present smile, which has shone light upon my path. I want to express a special thanks to my promotor prof.dr.ir Vincent

TOC

Gruis. You did not only bring your knowledge to the table, but you took the time to teach me the tricks of the academic trade. Your trust in me has allowed me to grow, both in my work and as a person. I have always considered myself very lucky to be one of your PhDs.

I want to thank all my fellow PhDs. Not only did our discussions contribute to the progress of my work, you kept me company along my journey. You remembered me to smile everyday along the way. I want to especially mention my fellow HIP-er Rowie Huijbregts and my fellow spice girls and hobbits, Sara Brysch, Valentina Cortés Urra and Macarena Gaete Cruz. I want to thank you for being there through thick and thin.

A special word of thanks goes to all my family. Your listening ear and kind words have helped me cross the finish line. I want to especially thank my father, Mat van Stijn, who told me it was a great opportunity to do a PhD. It is your blessing and confidence that motived me to start this journey in the first place. I also want to thank my mother, Myraise van Stijn, who has meticulously proofread my work and is always there for me.

My deepest gratitude goes to my handsome husband, Vincent Hans. You were with me throughout my journey, the highs and the lows. Over the years, we have brainstormed, discussed, calculated, modelled, made equations and spelled words together. Most important, together we pressed the scary 'send button'. You have supported and motivated me along the way. I happen to think you are perfect and you will always have my unwavering love and respect.

To be or not to be… circular

So, coming back to that all important question: what did I take away from this journey? Did it change my perspective?

Doing a PhD has taught me to look beyond myself. It showed me a glimpse of the complexity of the human system and its relation to our spaceship Earth. About half a year into my PhD, I found myself despairing. The more I discovered about the circular economy, the worse it got. I realise the opportunity of doing a PhD is a true privilege, but more knowledge will not always make for a happier life. I had just finished reading Hardin's 'the tragedy of the commons'; I doubted that humanity would ever be able to solve our ever-increasing resource use, emissions, pollution and waste generation in time. Now and again, I still find myself seeing doom scenarios approaching at rapid speed. However, then I just have to think back on all who worked with me during this PhD. They have shown me hope. Hope that together we can make the changes necessary to fulfil the needs for those who live today without depriving future generations from calling this planet their home. I hope that this thesis will make a modest contribution into showing others that same hope.

TOC

Contents

Abstract

The building sector consumes 40% of resources globally, produces 40% of global waste and 33% of all emissions. Creating a circular economy within the built environment is therefore of paramount importance to achieve a sustainable society. By replacing building components with more circular ones during new construction, maintenance and renovation, we can gradually make buildings circular. There are many different possible design variants for circular building components. Yet, knowledge on which variants are the most most circular, and which are feasible to implement is lacking. In this dissertation, we aimed to develop feasible, circular building components focussing on the context of renovation of Dutch, low-rise, post-war, social housing. Eight circular building components were designed and tested for implementation with housing associations and industry partners. Combining Action Research and Research through Design approaches, the development process was used to generate knowledge on 4 research goals.

Our first research goal was to develop a design tool for circular building components. Through systematic review of 36 existing circular design tools, we developed the Circular Building Components (CBC) Generator. The CBC-generator provides all the circular design parameters which should be considered; it provides extensive circular design options per parameter; through its canvases it supports systematic synthesis of design options to a cohesive and comprehensive circular design.

The second goal was to develop a Life Cycle Assessment (LCA) model to support environmental impact assessment of circular building components. We developed the Circular Economy Life Cycle Assessment (CE-LCA) model. This model builds on existing LCA standards applied in the building sector: EN 15804 (2012) and EN 15978 (2011). In CE-LCA, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include all cycles. Impacts can be divided between use cycles using various allocation approaches.

The third goal was to develop environmental design guidelines for circular building components. We compared 4 circular design variants and a business-as-usual design for a kitchen (short lifespan) and renovation façade (medium lifespan) through Material Flow Analysis (MFA) and CE-LCA. Analysing the assessment results, we derived 8 lessons learned. Amongst all, we found that in both components, the environmental performance improves most by combining circular design options to narrow, slow and close cycles.

Furthermore, we concluded that different building components could benefit from different combinations of circular design options: components with a short lifespan benefit more from slowing and closing future cycles; components with a medium lifespan benefit more from reducing resource use now and slowing future loops on site. We found that circular design options do not always reduce resource use, environmental impacts and waste generation: tipping-points were identified based on the number of use cycles, lifespans and the assessment methods applied.

The fourth research goal was to identify which stakeholder choices led to circular building components which were considered feasible to implement in projects and practice. We documented and analysed the stakeholder choices throughout the co-creation processes of 8 circular building components. We found that different combinations of circular design options were perceived as feasible for different building components. For product-like components, narrowing loops now could be combined with slowing and closing likely future cycles. In building-like components, narrowing loops now and slowing likely future loops on-site were found more feasible. However, the particular application and context influenced the perceived feasibility of circular design options. What was considered feasible also evolved throughout the development process. In the beginning of the development process more circular design options were considered feasible. Towards realization compromises on circular design options were needed to achieve a fit to the current business and supply-chain model.

We concluded that not all circular design options led to desirable circular building components; not all desirable circular design options were yet found feasible. To develop and realise more circular building components we recommended 4 changes in practice: (1) additional circular knowledge, skills and experience are needed in the supply chain; (2) development of circular supply-chain and business models are needed; (3) start implementing 'low-hanging fruit' first; (4) work towards a common understanding of CE and set common goals. Finally, we urged for all to look beyond circularity. Although significant reduction in resource use, environmental impacts and waste generation is possible, the development of circular building components does not provide a 100% reduction. Additional sufficiency-oriented strategies may be needed to reach our sustainability goals. This research makes scientific contributions to circular design theories, management models for the built environment, and research methodology. The examples and knowledge developed in this research can support practice to develop more feasible and more circular building components; through their potential implementation, towards creating a circular economy in the built environment.

KEYWORDS Circular Economy, building components, housing, Life Cycle Assessment (LCA), design guidelines, feasibility

Summary

1. Introduction

The building sector is said to consume 40% of resources globally, produces 40% of global waste and 33% of all human-induced emissions (Ness & Xing, 2017). Therefore, the building industry plays a crucial role in society's pursuit to become more sustainable. Transitioning from a linear to a Circular Economy (CE) could support minimizing resource depletion, environmental impacts and waste in the built environment.

The CE model builds on previously developed schools of thought and there is no commonly accepted understanding of the concept (Kirchherr, Reike, & Hekkert, 2017). We understand CE as "a regenerative system in which resource input and waste, emissions, and energy leakage are minimised by narrowing, slowing and closing material and energy loops" (adapted from Geissdoerfer, Savaget, Bocken and Hultink (2017, p. 759)). Narrowing loops is to reduce resource use or achieve resource efficiency. Slowing loops is to lengthen the use of a building, component, part or material. Closing loops is to (re)cycle materials from End-of-Life (EoL) back to production (Bocken, de Pauw, Bakker, & van der Grinten, 2016). Value Retention Processes (VRPs) – such as reuse, repair, refurbish, recycle and recover – operationalize narrowing, slowing and closing cycles (Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020).

In the built environment the main focus has been on how we can best reuse waste material or recycling. Recycling is the outer loop in the CE model as described by the Ellen MacArthur Foundation (2013). Although recycling is of vital importance to achieve a circular built environment, one of the most important principles of the CE is that we first make optimum use of the inner loops. Loops such as repair, reuse, refurbishing and remanufacturing prevent waste as much as possible. Or, to utilize the biological cycles instead (See Figure Sum.1). Various authors have provided circular design strategies which can support narrowing, slowing and closing loops (e.g., Bakker, den Hollander, van Hinte and Zijlstra (2014), van den Berg and Bakker (2015) and Moreno, De los Rios, Rowe and Charnley (2016)). Circular design options such as designing lightweight components or using non-virgin, bio-based, or low-impact materials can support narrowing loops now. Making a

TOC

modular design, standardizing sizes and applying demountable joints can slow loops through facilitating repair, reuse and adjustments in the future. Applying recyclable or biodegradable materials which can be separated at EoL, can support closing future loops.

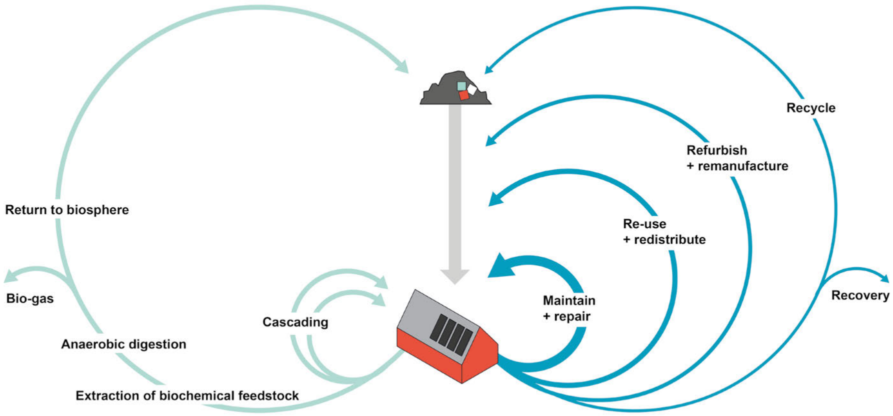


FIG. SUM.1 Using inner loops to prevent waste

Examples that apply circular design options in the building context already exist. By reviewing and categorizing these examples, we identified 17 different circular building approaches. The building approach which provided most potential to narrow, slow and close cycles, modularized the building into building components. Buildings consist of different building components, such as kitchens, façades, and roofs. Buildings can gradually be made circular by replacing linear building components with more circular ones during new construction, maintenance and renovation (see Figure Sum.2).

There are many ways imaginable to integrate circularity into building components. The gap we addressed in this research is twofold. First, there are little examples of circular building components in practice. Second, to support the development of circular building components, designers, policy makers, and other decision-makers could benefit from knowledge on how to design and realize them. However, existing research focused on circularity in consumer goods or did not provide concrete design guidance.

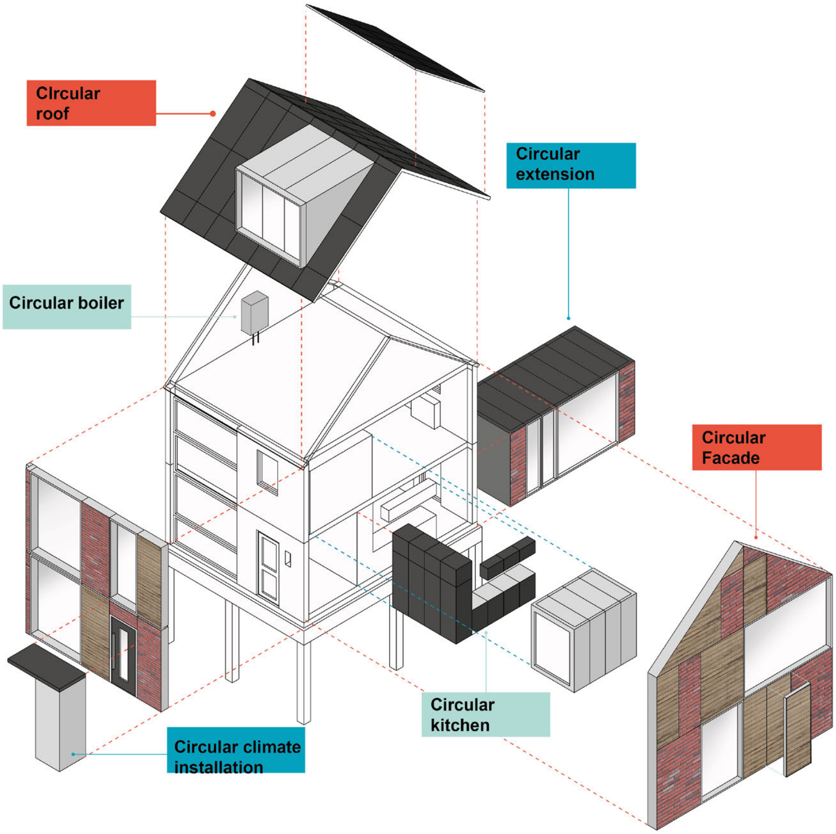


FIG. SUM.2 Using circular building components to integrate CE into new construction, maintenance and renovation

1.1 Goals

In our research, we distinguished between a design goal and research goals. The design goal focused on developing the circular building components themselves, whereas the research goals focused on generating knowledge through designing circular building components.

1.1.1 Design goal

On the one hand, we aimed at designing the most ideal – or desirable – circular building components. We understood ideal as the component which reduces resource use, environmental impacts and waste generation the most. On the other hand, we need components which are feasible – or likely – to be implemented within current projects and practice. Hence, **our design goal was to develop 'ideal' and 'feasible' circular building components.** The circular components were developed focusing on renovation of low-rise, post-war, social housing in the Netherlands. We (co)developed and tested 8 example circular building components: (1) a circular kitchen, 'circular skin' including (2) renovation roof and (3) -façade components, (4) a 'circular dwelling extension', 'circular Net-Zero-Energy-Building (NZEB) renovation light' including (5) renovation roof, (6) -façade, and (7) central heating component, and (8) a central heating boiler.

1.1.2 Research goals

We identified 4 key questions in the design(ing) of circular building components which underpin our research goals.

To develop a circular building component we first needed to know 'how' to integrate circularity in the design of building components. We systematically reviewed 36 existing circular design frameworks. We found that they remained fragmented and did not focus on building components. So, **our first research goal was to develop a design tool for circular building components.**

After synthesizing different possible designs for circular building components, we needed to select the most circular building component – the ideal. Two methods are often identified to support environmental performance assessment in a CE context: Material Flow Analysis (MFA) and Life Cycle Assessment (LCA). In standard LCAs, environmental impacts are assessed over a single use cycle of a building (component) (Hauschild, Rosenbaum, & Olsen, 2018; Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020; Suhariyanto, Wahab, & Rahman, 2017). Such LCAs do not fully capture the burdens and benefits of a CE (see Allacker, Mathieux, Pennington and Pant (2017); De Wolf, Hoxha and Fivet (2020); Malabi Eberhardt et al. (2020)). Therefore, **our second research goal was to develop a CE-LCA model for building components.**

Designers, policymakers, and other decision-makers could benefit from environmental design guidelines based on LCA and MFA assessments to support them in designing the most circular building components – 'the ideal'. We found that existing environmental design guidelines for circular building components were based on assessments of singular building components, singular circular design options, applied different assessment methods and provided conflicting guidelines.

Therefore, **our third research goal was to develop environmental design guidelines for circular building components through comparing the environmental performance of multiple circular design options for different building components using MFA and CE-LCA.**

Finally, practice needs to be able to develop designs which are feasible to implement in projects and practice. Existing feasibility studies focused on building or construction-industry level and did not compare multiple building components and/or include multiple circular design options. Furthermore, they were based on interviews, studies of completed cases or literature review rather than observation. They listed barriers, yet, they did not identify their relative importance throughout the development process. Therefore, **the fourth research goal was to identify which specific stakeholder choices throughout the development process led to circular building components which are considered feasible to implement in projects and practice, comparing multiple circular design options and different building components.**

1.2 Approach and methods

We used a combination of Research through Design and Action Research approaches. By designing and realising circular building components together with housing associations and industry partners, we learned how we should synthesize and assess them; we generated knowledge on which circular design options result in ideal and feasible circular building components.

We applied a 'designerly-pragmatist' paradigm. To generate knowledge from design(ing), we used the following steps: (1) identify and motivate problems, (2) define research goals and planning, (3) develop design, (4) simulate design, (5) evaluate, and (6) communicate findings (based on Peffers et al. (2006) and van Aken and Romme (2009)). We combined the models of Geraedts and Wamelink (2009), NEN 2634, Roozenburg and Eekels (1995) with Technology Readiness Levels to understand and steer the design activities. We selected the most suitable research methods to extract knowledge per step; we used multiple methods in parallel (i.e., methodological triangulation). In all studies the Action-Research cycle of 'design, propose, observe, reflect' (adapted from Carr & Kemmis, (1986)) was used to harness the knowledge of stakeholders. The applied methods are further described in the results section.

2 Results

2.1 Results circular design tool

Through systematic analysis of 36 existing, circular design frameworks, we identified the circular design choices – or design parameters – which need to be considered when developing a circular design. Furthermore, we identified which circular design options were proposed per design parameter. Through combining and specifying the identified design parameters and options, we constructed a design tool for circular building components: the Circular Building Components (CBC) generator. The CBC-generator consists of a technical, industrial and business model generator. Each generator includes a matrix containing the relevant circular design parameters (see Table Sum.1) and circular design options. Each matrix is complemented with a design table and design canvas. Different variants for circular building components can be synthesized by filling the canvasses whilst systematically "mixing and matching" design options. To illustrate and test the CBC-generator, the tool was applied in the development of an example building component 'the circular kitchen' and tested in a student workshop.

TABLE SUM.1 Circular design parameters included in the CBC-generator

Technical model parameters	Industrial model parameters	Business model parameters
Materials	Key partners	Key partners
Energy	Key activities	Customer segments
System architecture	Key resources	Supply chain relations
Amount	Transport	Cost structure
Time(s)	Process energy	Revenue streams
Lifecycle stage		Value propositions
Circular design strategy		Key resources
		Channels
		Take back systems
		Adoption factors

Whilst existing tools and frameworks are not comprehensive, nor specifically developed for designing circular building components, the CBC-generator provides all the circular design parameters which should be considered; second, it provides extensive circular design options per parameter; and third, through its canvases it supports systematic synthesis of design options to a cohesive and comprehensive circular design. As such, the CBC-generator makes an important step towards supporting industry in developing circular building components. However, the CBC-generator only provides support in the synthesis and not yet in the assessment of the most circular design. For example, if it is more "circular" to upgrade or recycle

TOC

a building component, does not become evident in the tool. Furthermore, the developed tool does not show which are logical combinations of design options.

In collaboration with the researchers from the Circular Kitchen project (from Chalmers University of Technology and Delft University of Technology), the CBC-generator was further developed to a card-based game: ‘Cards for Circularity’ (Dokter, van Stijn, Thuvander, & Rahe, 2020). The card-game was tested in multiple workshops with students and practice to investigate how circular knowledge is adopted in design practice (see Figure Sum.3).

FIG. SUM.3 Cards for circularity used during the design of a circular supply-chain model for a circular dwelling extension

2.2 Results Circular Economy Life Cycle Assessment model

We elaborated on key principles of CE in building components and analysed how existing LCA standards deal with these; we identified gaps and defined requirements for LCA of circular building components. Following, we developed the Circular Economy Life Cycle Assessment (CE-LCA) model for building components. This model builds on existing LCA standards applied in the building sector: EN 15804 (2012) and EN 15978 (2011). In CE-LCA, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include all cycles (see Figure Sum.4). Impacts can be divided between use cycles using various allocation approaches. For short-cycling parts and materials, when reuse and recycling avoids primary production of the same ‘thing’, applying the same processes, an equal distribution of impacts between all cycles could be reasonable (and simple). The Circular Economy Linearly Degressive (CE LD) allocation approach of Malabi Eberhardt et al. (2020) is suitable when the use and value of materials is not the same in each cycle. The

CE LD approach allocates the largest share of impacts from initial production and construction to the first use cycle and the share of impacts allocated to following cycles decreases linearly. For disposal most impacts are allocated to the last cycle. Impacts of VRPs are distributed equally between all use cycles. The CE-LCA model has been tested in the case of the circular kitchen and evaluated with 44 experts.

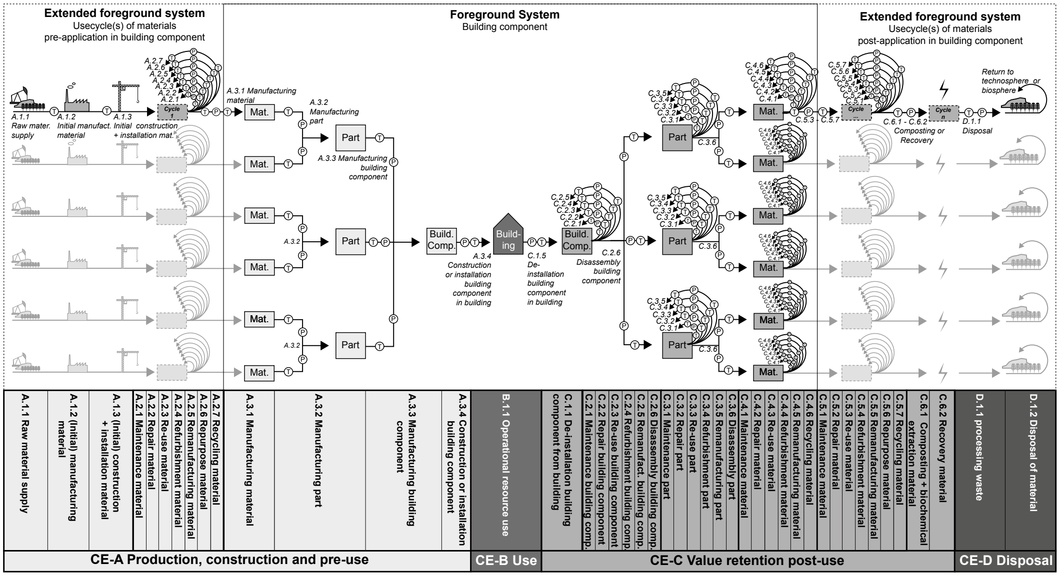
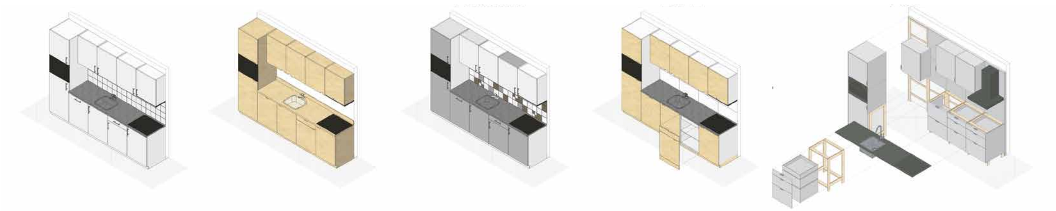


FIG. SUM.4 Circular Economy Life Cycle Inventory model (for a larger image, see Figure 5.3)

We found the CE-LCA approach suitable in ex-ante assessments in which scenarios are explored to identify which circular building components have the best environmental performance. The scientific contribution of this study lay in the development of a model to apply LCA on circular building components with multiple cycles and in our discussion of the methodological questions which arose. Similarly to Allacker et al. (2017), De Wolf et al. (2020) and Malabi Eberhardt et al. (2020) we found that all cycles of the building component system are difficult to determine in a practice setting; this increased uncertainty, makes the approach sensitive to mis-use and could hinder reducing environmental impacts both in the short and long term. However, we suggested that applying CE-LCA, or equivalent multi-cycling LCA, is still necessary to transition to a 'truly' circular built environment. Without including all cycles in the assessment, we cannot get an accurate overview of the burdens and benefits of circularity. At the same time, the CE-LCA model could be developed further to reduce uncertainty, improve accuracy, usability and fair-use. Additionally, users should exercise awareness of the value and limitations of CE-LCA and use the model appropriately.

2.3 Results environmental design guidelines for circular building components

We developed environmental design guidelines by comparing the environmental performance of 4 circular design variants and a business-as-usual design for two building components: a kitchen (as an example of a component with a relatively short lifespan) and renovation façade (medium lifespan). See Figure Sum.5 for the design variants and the applied circular design options per variant.



Variant 1
Business as Usual
Linear design

Variant 2
BIO
Bio-based, biodegradable materials, short lifespan

Variant 3
Reclaim!
Non-virgin materials, short lifespan

Variant 4
LIFE+
Optimising lifespans, long-life materials, bio-based, biodegradable materials

Variant 5
Plug-and-play
Adjustable modular design, optimising lifespans, durable materials, facilitating repair, adjustments, reuse and recycling

Variant 6
Business as Usual
Linear design

Variant 7
BIO
Bio-based, biodegradable materials, short lifespan

Variant 8
Reclaim!
Non-virgin materials, easy to disassemble

Variant 9
Product-2-product
Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts

Variant 10
Plug-and-play
Adjustable modular design, standard sizes, optimising lifespans, durable materials, facilitating repair, adjustments, reuse and recycling

FIG. SUM.5 Design variants for the circular kitchen and renovation façade

We compared their environmental performance through MFA and CE-LCA including extensive sensitivity analysis. From the analysis of 78 CE-LCAs and MFAs, we derived 8 lessons learned. Amongst these, we found that in both components, the environmental performance improves most by combining circular design options to narrow, slow and close cycles. Furthermore, we concluded that different building components could benefit from different combinations of circular design options: components with shorter lifespans benefit more from slowing and closing future cycles; components with a medium lifespan benefit more from reducing resource use now and slowing future loops on site. We validated the guidelines with 49 experts and by comparing our guidelines to existing environmental design guidelines.

We do not claim that our guidelines are entirely novel: the circular design options have been proposed before and parts of our guidelines overlapped with existing guidelines. Our contribution lay in having compared the environmental performance of multiple circular design options for different building components. As such we provided a preliminary answer to what *specific* circular design option(s) would result in the most environmental savings, for different *specific* circular building components. Applying our guidelines can support designers, policy makers and other decision makers to develop more circular building components. Yet, we stress that our guidelines should be understood as 'preliminary' as applying circular design options does not always result in a better environmental performance. Tipping-points were identified based on the number of use cycles, lifespans and the assessment methods applied. Further development and testing of the presented guidelines in practice could improve their generalizability and validate their usability in practice.

In collaboration with researchers from the Circular Kitchen project (from Delft University of Technology), the MFA and CE-LCA results of this study were compared to outcomes of an economic performance assessment using a Circular Economy Life Cycle Costing model. We found that a purposeful combination of both biological and technical materials, which can be separated after use, yielded the best economic and environmental performance (Wouterszoon Jansen, van Stijn, Malabi Eberhardt, Gruis, & van Bortel, 2022). Together with researchers from Aalborg university, we developed additional environmental design guidelines for a circular building structure (as an example of a component with a long lifespan). This research has been published in Malabi Eberhardt, van Stijn, Kristensen Stranddorf, Birkved and Birgisdottir (2021) and their findings are in line with the guidelines presented in our study. They found that building components with long lifespans benefit – even stronger – from reducing resource use now and slowing future loops on site.

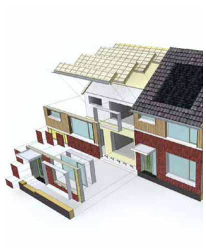
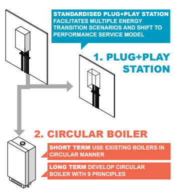
2.4 Results key stakeholder choices in the development of feasible circular building components

We presented a longitudinal study on the stakeholder choices in 5 development processes of 8 circular building components. The researchers actively co-created with stakeholders from initiative to market implementation and documented stakeholder choices. See Table Sum.2 for the developed circular building components. Through iterative process reflection and analysis, we identified the choices which influenced the perceived feasibility of different circular design options within different building components throughout their development. We validated our findings with the stakeholders involved in the development process.

We found that different combinations of circular design options were perceived as more feasible for different circular building components. For components with product-like characteristics, narrowing loops now can be combined with slowing and closing likely future cycles. Prioritizing narrowing loops now and slowing likely future loops on-site was found more feasible in building-like components. However, the particular application and context influenced the perceived feasibility of circular design options. We identified numerous trade-offs and synergies between circular design options and their perceived feasibility depending on the application(context). Furthermore, what is perceived as feasible changed throughout the development process (see Table Sum.2): more ambitious combinations of circular design options were perceived as feasible initially. Throughout the process, compromises on circular design options were made to achieve a fit with the current business and supply-chain model. Finally, the perceived feasibility of circular design options was also dependent on the development process, the stakeholders and individuals involved and by choices not related to circular design options.

We do not claim that all our findings are novel. Many of the barriers we found during our literature review can be recognized throughout this study. However, we identified what specific choices, by which stakeholder, at what moment in the development and for what reason, influenced the perceived feasibility of different circular design options in different building components. We presented four 'key' reasons which significantly influenced the feasibility of circular design options in our study: (1) fit of the technical model to the supply-chain and business model, (2) priority given to circularity, (3) high-complexity and (4) previous experience of stakeholders. Future research and innovation can help overcome the related barriers to make more circular building components feasible. However, we are careful to claim the generalizability of our findings. Our findings remain based on situational knowledge and might not be true for all, for always, everywhere. However, the concrete knowledge presented here can already support industry stakeholders in developing more feasible circular building components.

TABLE SUM.2 Overview of developed circular building components and reasoning behind the change in applied circular options throughout the development process

Case name	Intended circular design options during design	Realised circular design options	Most important reason for change between intended and realised	Representative image developed component
1 Circular kitchen	Modular design: long-life frames to which infill and finishing parts could be attached facilitating repair and adjustments; kitchen as a service model	Kitchen constructed with demountable panels facilitating repair	1. Frame of the kitchen not manufacturable on current machine park 2. Repairability is more important to the client than (future) adjustability	
2 Circular skin	NZEB renovation concept with modular façade and roof facilitating likely adjustments and reuse; reclaimed and biobased materials are applied	Modular renovation concept focusing initially on a modular roof facilitating likely adjustments; applying reclaimed materials where possible	1. Challenges processing reclaimed materials on machines & no technical performance guarantee 2. High initial costs façade 3. More demand for roof renovations 4. Step-by-step renovation supports client to realise energy transition	
3 Circular dwelling extension	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	N/A	
4 Circular NZEB-light	NZEB with exterior façade and roof insulation applying more circular materials and more demountable connections	(Re)placing less components to achieve NZEB-level energy performance; applying more circular materials	1. Component development not role of contractors leading to focus on narrowing and closing loops now 2. Initial costs too high for NZEB with exterior skin renovation 3. Less building components are (re)placed saving costs and new material use	
5 Circular central heating boiler	Modular climate system adjustable to future heating scenarios; modular boiler facilitating future repair, adjustments and reuse of the boiler and parts	Development of circular boiler was halted after proof-of-principle phase	1. Miss-alignment incentives: costs for applying circular design options lie with manufacturer and benefits with service provider 2. Uncertainty of future use natural gas for heating	

TOC

3. Conclusions

Transitioning to a CE in the built environment plays a crucial role in society's pursuit to become more sustainable. Buildings can be made circular by replacing building components with more circular ones during new construction, renovation and maintenance. There are many different possible design variants for circular building components. Examples in practice and scientific knowledge on the design and realization of circular building components were lacking. Therefore, in this dissertation, we aimed to develop the most ideal – or desirable – circular building components which are feasible – or likely – to be implemented within current projects and practice; through their development we generated knowledge on 4 research goals. (1) We developed a tool to support the design of circular building components. (2) To support the assessment of environmental impacts of circular building components, we developed the Circular Economy Life Cycle Assessment (CE-LCA) model. (3) We developed environmental design guidelines based on CE-LCA and MFA comparing multiple circular design options for two components. Finally, (4) we identified the stakeholder choices which influenced the perceived feasibility of different circular design options within 8 building components throughout their development.

So, which circular building components were the most ideal and feasible to implement? To identify those components that reduce the resource use, environmental impacts and waste generation the most, we looked to the findings of our third study. From the findings of our fourth study, we drew conclusions on which circular building components are most likely to be implemented in projects and practice.

3.1 Between ideal and feasible

We compared the findings of our third and fourth study. Figure Sum.6 shows which circular design options led to a better environmental performance and those perceived as more feasible to implement. We found both similarities and differences.

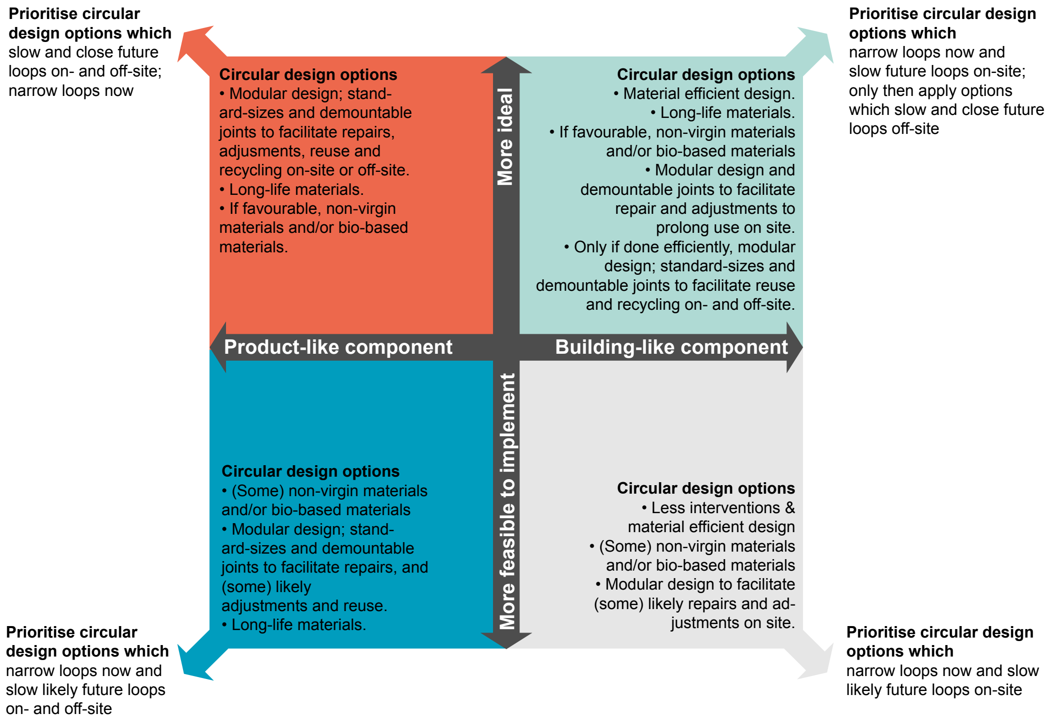


FIG. SUM.6 Circular design options which were found more ideal and feasible to implement for different types of building components

First, similar combinations of circular design options had a better environmental performance and were perceived as feasible to implement. For components with product-like characteristics – including a shorter service life – combinations of circular design options which slow and close future cycles and narrow loops now were both found desirable and feasible. Circular design options which narrow loops now and slow future loops on-site were both desirable and more feasible in components with characteristics of buildings – including a longer service life. Second, more circular design options were desirable than perceived as feasible for implementation. In particular for circular design options which slow and close loops that occur further into the future and off site. The gap between 'more circular' and 'feasible to implement' is influenced by the extent to which the supply chain and business model needs to be adapted to accommodate the circular design options. Finally, our findings did not yet indicate a circular building component design which is 'ideally circular'. Some circular design options worsened their environmental performance; the better-performing variants did not nullify resource use, environmental impacts and waste generation. Nor did we find circular component designs which were feasible in absolute. Rather we can speak of more or less circular building components – which are more or less feasible to implement – depending on how circular design options are applied in their application contexts. As such, we conclude that more circular building components can be developed and implemented in projects and practice today. However not every circular design option is desirable and not everything which is desirable is yet feasible.

3.2 Scientific contribution and practice implications

The scientific contribution of this research as a whole is as follows. First, our research brought circular design theory from the context of consumer products to the built environment and, second, to the renovation context. Third, by focussing on the building component level, this research bridged the gap between circularity on building and material level. Expanding upon theories of Habraken (1961), Duffy and Brand (1994) and Kapteins (1989, p. 11), we substantiated the importance that the building is considered as a composite of building components, parts and materials during all building management phases in order to keep resources cycling at highest utility and value (see Figure Sum.7). Fourth, this study contributed to shifting the understanding of sustainability in building management: we considered the sustainability of the building's whole life cycle rather than focusing on carbon emissions from operational energy use. We found trade-offs and synergies between both sustainability perspectives; we recommend future research on how to integrally weigh both during design. Fifth, our research showed the importance of optimizing multiple cycles to keep building components, parts and materials cycling at highest utility and value; our management models – on each level – should foster a multi-cycle scope. New models for collaboration need to be developed centered around continuous VRPs in a wide network of stakeholders. Sixth, most studies on desirability or implementability of circular design options focused on singular options and/or look at singular building components. By comparing multiple options and components, our research added a comparative perspective to the current body of knowledge. Finally, by developing the 'Action Research through Design' approach applied in this research, our work also contributed to knowledge on *how* to do research. Particularly, for research which aims to find solutions for complex societal challenges.

The practice implications of this research are as follows. First, our research may directly support practice in developing feasible circular building components through the presented design tools, design guidelines and the replicable circular building components. Our research also directly contributed to increasing circular design experience in practice. To help stakeholders in developing more circular and more feasible building components in the future, we recommend the following changes in practice. First, additional, circular knowledge, skills and experience are needed in the supply chain. Second, development of circular supply-chain and business models are needed to implement more circular designs. The supply chains should foster collaborations with a multi-cycle perspective in a wide network of stakeholders. Either this requires circularity to be integrated into each step of the project process. Or, rather than working from project to project, it requires the development of replicable circular solutions. To make the business model circular, we recommend that the value of a building, its components, parts and materials are considered over their lifecycle. Maintenance should not be considered as a cost but rather as a way to reduce the need for future investments (See Figure Sum.8). Third, practice can implement more circular building components in the short term by implementing 'low-hanging fruit' first. For example, by simplifying the design, working with local partners, focusing on low-cost options and prioritizing circularity now and in the near future. Finally, we recommend practice to work towards a common understanding of CE and set common goals. We urge for all to look beyond circularity. To sufficiently reduce resource use, environmental impacts and waste generation in the built environment, additional sufficiency-oriented strategies may be needed.

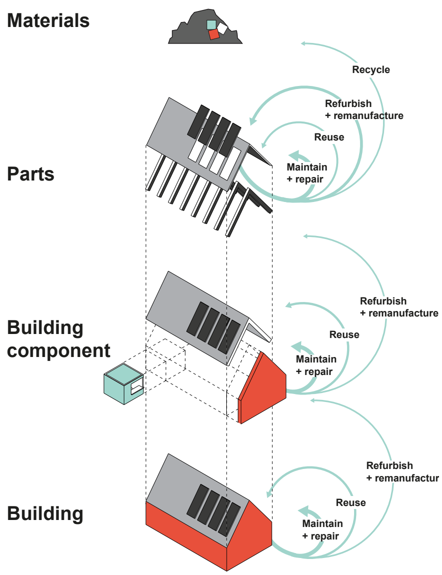


FIG. SUM.7 Cycling at highest utility and value by considering the building component, its parts and materials in relation to the building

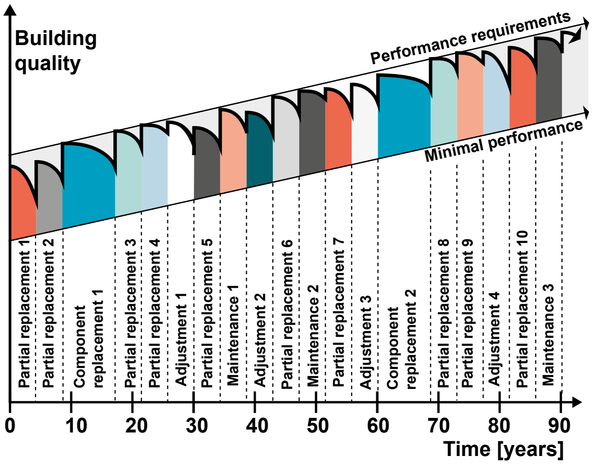


FIG. SUM.8 Upkeep of buildings through continuous partial replacements and adjustments of parts and materials within a building component

TOC

References

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment, 22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society, 61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

EN 15804. (2012). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019

EN 15978. (2011). *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. Retrieved from European Committee for Standardization (CEN) website: https://infostore.saiglobal.com/preview/is/en/2011/i.s.en15978-2011-lc-2011-11.pdf?sku=1500481

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Heesen, R., Bright, L. K., & Zucker, A. (2019). Vindicating methodological triangulation. *Synthese, 196*(8), 3067–3081. https://doi.org/10.1007/s11229-016-1294-7

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings, 66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability, 13*(10), 5621. https://doi.org/10.3390/su13105621

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability, 12*(22), 9579. https://doi.org/10.3390/su12229579

Ness, D. A., & Xing, K. (2017). Toward a resource-efficient built environment: A literature review and conceptual model. *Journal of Industrial Ecology, 21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Peffers, K., Tuunanen, T., Gengler, C. E., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2006). The design science research process: A model for producing and presenting information systems research. *DESRIST International Conference on Design Science Research in Information Systems and Technology,* 83–106. Claremont, CA.

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling, 135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production, 229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019

van Aken, J. E., & Romme, G. (2009). Reinventing the future: Adding design science to the repertoire of organization and management studies. *Organisation Management Journal, 6*(1), 5–12. https://doi.org/10.1057/omj.2009.1

TOC

van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling, 174*(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105683
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling, 161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

Samenvatting

1. Introductie

De bouwsector wordt verantwoordelijk gehouden voor 40% van het wereldwijde grondstoffen verbruik, 40% van de wereldwijde afvalproductie en voor 33% van alle door de mens veroorzaakte emissies (Ness & Xing, 2017). Daarom speelt de bouwindustrie een cruciale rol in het duurzamer maken van de samenleving. De transitie van een lineaire- naar een Circulaire Economie (CE) kan helpen om uitputting van grondstoffen, milieuvervuiling, emissies en afval in de gebouwde omgeving te minimaliseren.

Het CE model is gebaseerd op verschillende bestaande denkrichtingen en er is geen algemeen aanvaarde definitie (Kirchherr, Reike, & Hekkert, 2017). Wij definiëren CE als "een regeneratief systeem waarin grondstofverbruik, afval, emissies en energieverbruik worden geminimaliseerd door materiaal- en energielussen te vernauwen, te vertragen en te sluiten" (gebaseerd op Geissdoerfer, Savaget, Bocken en Hultink (2017, p. 759)). Lussen kunnen worden vernauwd door minder grondstoffen te gebruiken ofwel deze efficiënter te gebruiken. Lussen kunnen worden vertraagd door de levensduur van een gebouw, de gebouwcomponenten, de toegepaste onderdelen of materialen te verlengen. Lussen kunnen worden gesloten door materialen aan het eind van de levensduur weer terug te recycleren naar het begin van de productieketen (Bocken, de Pauw, Bakker, & van der Grinten, 2016). Waardebehoudsprocessen zoals hergebruik, reparatie, opknappen, recyclen en energieterugwinning operationaliseren het vernauwen, vertragen en sluiten van lussen. (Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020).

In de gebouwde omgeving ligt de focus tot nu toe vooral op hoe we afvalmateriaal het beste kunnen hergebruiken. Recyclen is de buitenste lus in het CE model, zoals beschreven door de Ellen MacArthur Foundation (2013). Recyclen is van groot belang om tot een circulaire gebouwde omgeving te komen, maar één van de belangrijkste uitgangspunten van de CE is dat we eerst optimaal gebruik maken van de binnenste lussen. Lussen zoals reparatie, hergebruik, opknappen en reviseren helpen om afval zoveel mogelijk te voorkomen. Óf, de biologische lussen kunnen worden gebruikt in plaats van de technische lussen (zie Figuur Sam.1). Verschillende auteurs beschrijven circulaire ontwerpstrategieën en -opties die het vernauwen, vertragen en sluiten van lussen kunnen ondersteunen (bijv. Bakker, den Hollander, van Hinte en Zijlstra (2014), van den Berg en Bakker (2015) en Moreno, De los Rios, Rowe en Charnley (2016)). Het ontwerpen van lichtgewicht componenten of de toepassing van hergebruikte materialen, bio-based materialen en materialen met een lage milieu impact kunnen lussen nu al vernauwen. Een modulair ontwerp, het standaardiseren van maten en het toepassen van demontabele verbindingen faciliteert reparatie, hergebruik en aanpassingen in de toekomst waardoor lussen kunnen vertragen. Het toepassen van recycleerbare of biologisch afbreekbare materialen, die aan het einde van de levensduur kunnen worden gescheiden van elkaar, kan het sluiten van lussen in de toekomst mogelijk maken.

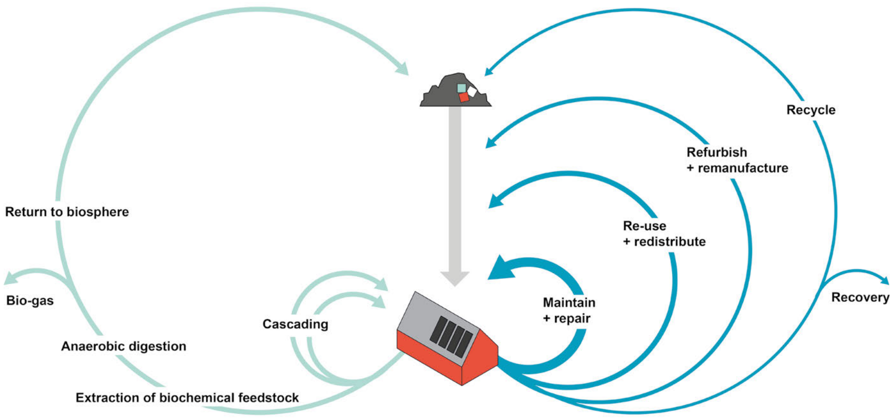


FIG. SAM.1 Binnenste lussen gebruiken om afval te voorkomen

Er zijn al verschillende voorbeelden in de bouw die circulaire ontwerpopties toepassen. Door deze voorbeelden te analyseren en te categoriseren, identificeerden we 17 verschillende circulaire bouwbenaderingen. De benadering met het meeste potentieel om lussen te vernauwen, te vertragen en te sluiten, splitste het gebouw op in afzonderlijke gebouwcomponenten. Gebouwen bestaan uit verschillende gebouwcomponenten, zoals keukens, gevels en daken. Door lineaire gebouwcomponenten te vervangen door meer circulaire componenten tijdens nieuwbouw, onderhoud en renovatie kunnen gebouwen geleidelijk aan circulair worden gemaakt (zie Figuur Sam.2).

Er zijn veel manieren denkbaar om circulariteit te integreren in gebouwcomponenten. Het kennishiaat dat we in dit onderzoek proberen te vullen is tweeledig. Ten eerste zijn er in de praktijk weinig voorbeelden van circulaire gebouwcomponenten. Ten tweede, meer kennis over het ontwerpen en realiseren van circulaire gebouwcomponenten kan ontwerpers, beleidsmakers en andere besluitvormers ondersteunen bij de ontwikkeling van dergelijke componenten. Bestaand onderzoek richtte zich vooral nog op circulariteit in consumptiegoederen of gaf geen concrete ontwerprichtlijnen.

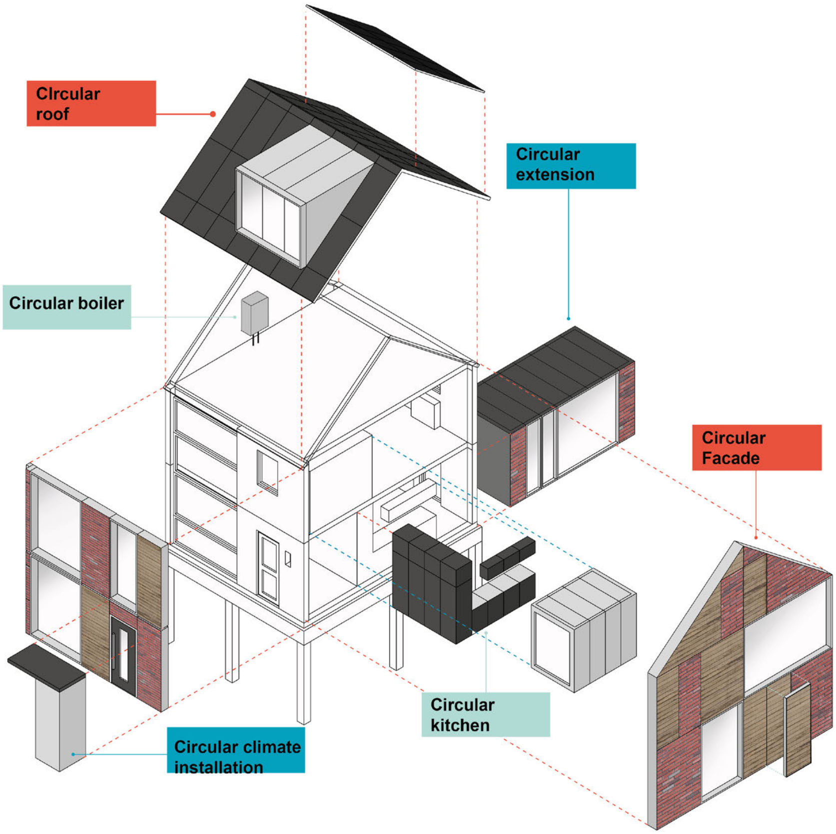


FIG. SAM.2 Circulaire gebouwcomponenten gebruiken om CE te integreren bij nieuwbouw, onderhoud en renovatie

1.1 Doelen

In ons onderzoek maakten we onderscheid tussen een ontwerpdoel en onderzoeksdoelen. Het ontwerpdoel was gericht op het ontwikkelen van de circulaire gebouwcomponenten zelf, terwijl de onderzoeksdoelen gericht waren op het genereren van kennis door middel van het ontwerpen van de circulaire gebouwcomponenten.

1.1.1 Ontwerp doel

Enerzijds was ons doel om de meest ideale – of wenselijke – circulaire gebouwcomponenten te ontwerpen. We zochten naar gebouwcomponenten die het gebruik van grondstoffen, milieu impact en afvalproductie het meest reduceerden. Anderzijds hebben we gebouwcomponenten nodig die haalbaar – of waarschijnlijk – zijn om te realiseren binnen de huidige projecten en bouwpraktijk. **Ons ontwerpdoel was dan ook om 'ideale' en 'haalbare' circulaire gebouwcomponenten te ontwikkelen.** Deze werden ontwikkeld in de context van renovatie van sociale, naoorlogse laagbouwwoningen in Nederland. We (co)ontwikkelden en testten 8 circulaire gebouwcomponenten: (1) een circulaire keuken, een circulaire schil inclusief (2) renovatie-dak en (3) -gevel, (4) een 'circulaire aanbouw', een 'circulair Nul Op de Meter (NOM)-light concept' inclusief (5) renovatie-dak, (6) -gevel, en (7) klimaat installatie, en (8) een circulaire cv-ketel.

1.1.2 Onderzoeksdoelen

We identificeerden 4 vragen binnen het ontwerpproces van de circulaire gebouwcomponenten die de basis vormden voor onze onderzoeksdoelen.

Om een circulair gebouwcomponent te ontwikkelen moesten we eerst weten 'hoe' we circulariteit meenemen in het ontwerp van gebouwcomponenten. Daartoe hebben we 36 bestaande circulaire ontwerptools systematisch geanalyseerd. We ontdekten dat deze gefragmenteerd bleven en zich niet specifiek richtten op het ontwerpen van gebouwcomponenten. **Ons eerste onderzoeksdoel was daarom om een ontwerptool te ontwikkelen voor circulaire gebouwcomponenten.**

Nadat we verschillende 'mogelijke' ontwerpen voor circulaire gebouwcomponenten hadden gemaakt, moesten we het meest circulaire gebouwcomponent – 'het ideaal' – kunnen selecteren. Er worden vaak twee methoden toegepast voor de beoordeling van milieuprestaties in een CE-context: Materiaal Stroom Analyse (MSA) en Levens Cyclus Analyse (LCA). In standaard LCA's worden milieueffecten tijdens een enkele gebruikscyclus van een gebouw(deel) beoordeeld (Hauschild, Rosenbaum, & Olsen, 2018; Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020; Suhariyanto, Wahab, & Rahman, 2017). Dergelijke LCA's geven echter de lusten en lasten van een CE niet volledig weer (zie Allacker, Mathieux, Pennington en Pant (2017); De Wolf, Hoxha en Fivet (2020); Malabi Eberhardt et al. (2020)). Daarom was **ons tweede onderzoeksdoel om een CE-LCA model te ontwikkelen voor gebouwcomponenten.**

Ontwerprichtlijnen op basis van LCA- en MSA-beoordelingen kunnen ontwerpers, beleidsmakers en andere besluitvormers ondersteunen om zo circulair mogelijke gebouwcomponenten ('het ideaal') te ontwerpen. We ontdekten dat bestaande ontwerprichtlijnen gebaseerd zijn op studies waarin noch meerdere gebouwcomponenten noch meerdere circulaire ontwerpopties werden vergeleken met elkaar. Ook werden verschillende beoordelingsmethoden toegepast en gaven deze studies tegenstrijdige milieu ontwerprichtlijnen. Daarom was **ons derde onderzoeksdoel het ontwikkelen van milieu ontwerprichtlijnen voor circulaire gebouwcomponenten door de milieuprestaties van meerdere circulaire ontwerpopties voor verschillende componenten te vergelijken met behulp van MSA en CE-LCA.**

Ten slotte moet de praktijk in staat zijn om circulaire gebouwcomponenten te maken die haalbaar zijn om te implementeren in de huidige projecten en bouwpraktijk. Bestaande haalbaarheidsstudies bekeken circulariteit op het niveau van het gebouw of de bouwsector en vergeleken noch meerdere gebouwcomponenten noch meerdere circulaire ontwerpopties met elkaar. Bovendien zijn ze niet gebaseerd op observaties maar op interviews, studies van afgeronde *cases* of literatuuronderzoek. Ze zetten barrières uiteen, maar identificeerden niet welke barrières relatief het meest belangrijk waren binnen het totale ontwikkelingsproces. Daarom was **het vierde onderzoeksdoel om te identificeren welke specifieke keuzes van stakeholders tijdens het ontwikkelingsproces hebben geleid tot circulaire gebouwcomponenten die haalbaar worden geacht om in projecten en de praktijk te implementeren, waarbij meerdere circulaire ontwerpopties en verschillende gebouwcomponenten worden vergeleken.**

1.2 Aanpak en onderzoeksmethoden

In dit onderzoek is een combinatie van ontwerpend onderzoek en actieonderzoek toegepast. Door samen met woningcorporaties en ketenpartners circulaire gebouwcomponenten te ontwerpen en te realiseren, hebben we geleerd hoe we deze kunnen ontwerpen en beoordelen. Daarnaast hebben we kennis gegenereerd over welke circulaire ontwerpopties resulteren in ideale en haalbare circulaire gebouwcomponenten.

Het toegepaste paradigma is 'ontwerpend-pragmatisme'. Om kennis te genereren van het ontwerp(en) gebruikten we de volgende stappen: (1) problemen identificeren en motiveren, (2) onderzoeksdoelen en planning definiëren, (3) ontwerp ontwikkelen, (4) ontwerp simuleren, (5) evalueren en (6) bevindingen communiceren (gebaseerd op Peffers et al. (2006) en van Aken en Romme (2009)). We combineerden de modellen van Geraedts en Wamelink (2009), NEN 2634, Roozenburg en Eekels

(1995) met *Technology Readiness Levels* om de ontwerpactiviteiten te begrijpen en te sturen. We selecteerden de meest geschikte onderzoeksmethoden om kennis per stap te extraheren. Én, we gebruikten meerdere methoden naast elkaar (zogenaamde methodologische triangulatie). In alle studies werd de actie-onderzoekscyclus '*design, propose, observe, reflect*' (aangepast van Carr en Kemmis (1986)) gebruikt om de kennis van stakeholders expliciet te maken. De toegepaste methoden worden verder beschreven in de resultaten.

2 Resultaten

2.1 Resultaat circulaire ontwerptool

Door middel van systematische analyse van 36 bestaande, circulaire ontwerptools identificeerden we de circulaire ontwerpkeuzes – ofwel ontwerpparameters – waarmee rekening moet worden gehouden bij het maken van een circulair ontwerp. Daarnaast hebben we voor iedere ontwerpparameter de aangedragen circulaire ontwerpopties in kaart gebracht. Door de geïdentificeerde ontwerpparameters en -opties te combineren en te specificeren, stelden we een ontwerptool voor circulaire gebouwcomponenten samen: de Circular Building Components (CBC)-generator. De CBC-generator bestaat uit een technische-, keten-, en business-model ontwerpgenerator. Elke generator bevat een matrix met de relevante circulaire ontwerpparameters (zie Tabel Sam.1) en circulaire ontwerpopties. Elke matrix wordt aangevuld met een ontwerp tabel en canvas. Verschillende varianten voor circulaire gebouwcomponenten kunnen worden gemaakt door de ontwerp tabel en canvas in te vullen door systematisch ontwerpopties te "*mixen en matchen*". Om de CBC-generator te illustreren en te testen, werd de tool toegepast bij de ontwikkeling van een voorbeeldcomponent 'de circulaire keuken' en getest in een studentenworkshop.

TABLE SAM.1 Circulaire ontwerpparameters opgenomen in de CBC-generator

Technisch modelparameters	Ketenmodel parameters	Businessmodel parameters
Materialen	Belangrijkste partners	Belangrijkste partners
Energie	Kernactiviteiten	Klantsegmenten
Systeemarchitectuur	Belangrijkste bronnen	Relaties met de toeleveringsketen
Aantal	Vervoer	Kostenstructuur
Levensduur & cycli	Proces energie	Inkomstenstromen
Fase levenscyclus		Waardeproposities
Circulaire ontwerpstrategie		Belangrijkste bronnen
		Kanalen
		Terugnamesystemen
		Adoptiefactoren

Waar bestaande tools niet compleet waren, noch specifiek ontwikkeld waren voor het ontwerpen van circulaire gebouwcomponenten, biedt de CBC-generator alle circulaire ontwerpparameters waarmee rekening moet worden gehouden. Ten tweede geeft de CBC-generator veel circulaire ontwerpopties per parameter. Ten derde ondersteunt de generator middels de ontwerp canvassen een systematische synthese van ontwerpopties tot een samenhangend en compleet circulair ontwerp. Als zodanig kan de CBC-generator de praktijk ondersteuning bieden bij het ontwikkelen van circulaire gebouwcomponenten. De CBC-generator biedt echter alleen ondersteuning bij het ontwerpen en nog niet bij de beoordeling van het meest circulaire ontwerp. Of het bijvoorbeeld meer circulair is om een component op te knappen of te recyclen, wordt niet duidelijk met deze tool. Bovendien laat de ontwikkelde tool niet zien wat logische combinaties van circulaire ontwerpopties zijn.

In samenwerking met de onderzoekers van het project ‘the Circular Kitchen’ (van Chalmers University of Technology en TU Delft) is de CBC-generator doorontwikkeld tot een kaartspel: ‘Cards for Circularity’ (Dokter, van Stijn, Thuvander, & Rahe, 2020). Het kaartspel werd getest in meerdere workshops met studenten en de praktijk om de adoptie van circulaire kennis in de ontwerppraktijk verder te onderzoeken (zie Figuur Sam.3).

FIG. SAM.3 Kaartspel ‘Cards for Circularity’ gebruikt tijdens het ontwerpen van een circulair ketenmodel voor de circulaire aanbouw

2.2 Resultaat Circulaire Economie Levenscyclus Analyse model

We analyseerden de belangrijkste principes van CE in gebouwcomponenten en bespraken hoe de huidige LCA-standaarden hiermee omgaan. We identificeerden de hiaten in de huidige standaard en definieerden eisen voor het LCA-model voor circulaire gebouwcomponenten. Vervolgens ontwikkelden we het Circulaire Economie Levens Cyclus Analyse (CE-LCA) model voor gebouwcomponenten. Dit model bouwt voort op bestaande LCA-normen die in de bouwsector worden toegepast: EN 15804 (2012) en EN 15978 (2011). In CE-LCA worden gebouwcomponenten beschouwd als een samenstelling van onderdelen en materialen met elk verschillende en meerdere gebruikscycli. De LCA-systeemgrens is uitgebreid om al deze cycli te omvatten (zie Figuur Sam.4). De milieueffecten kunnen worden verdeeld tussen de gebruikscycli met behulp van verschillende allocatie formules. Voor onderdelen en materialen met een korte levenscyclus, waarbij hergebruik en recycling de primaire productie met de huidige productieprocessen van hetzelfde 'ding' voorkomt, is een gelijke verdeling van de milieueffecten tussen alle cycli redelijk (en eenvoudig). De Circulaire Economie Lineair Degressieve (CE LD) allocatiebenadering van Malabi Eberhardt et al. (2020) is geschikt wanneer het gebruik en de waarde van materialen niet in elke cyclus hetzelfde is. De CE LD benadering wijst het grootste deel van de milieueffecten van initiële productie en constructie toe aan de eerste gebruikscyclus. Het aandeel van milieueffecten dat aan volgende cycli wordt toegewezen neemt lineair af. Omgekeerd geldt dat het grootste deel van de milieueffecten uit de afvalfase wordt toegewezen aan de laatste cyclus. De milieueffecten van waardebehoudsprocessen worden gelijkelijk verdeeld over alle gebruikscycli. Het CE-LCA model is getest op de circulaire keuken en geëvalueerd met 44 experts.

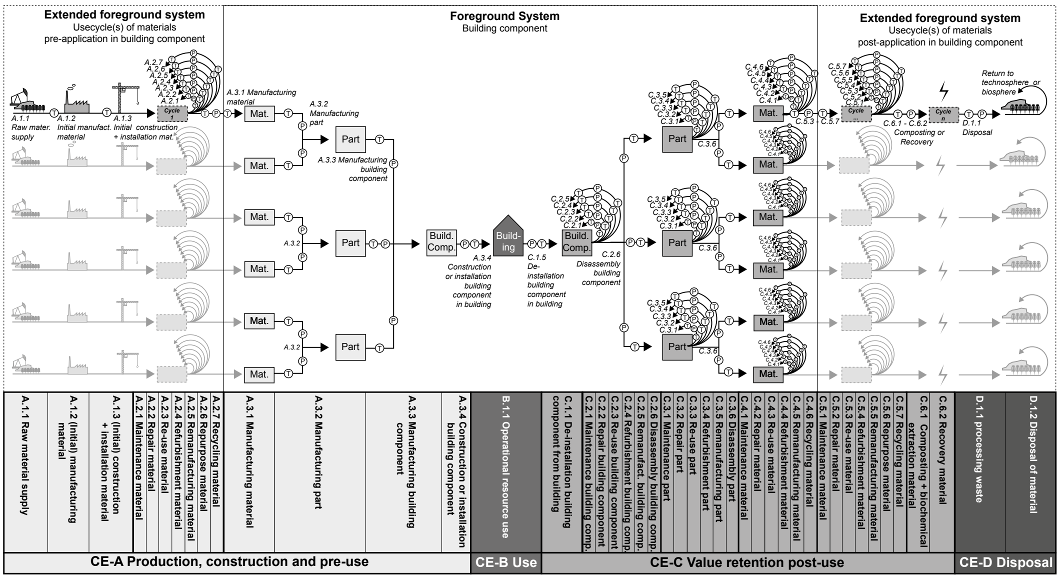


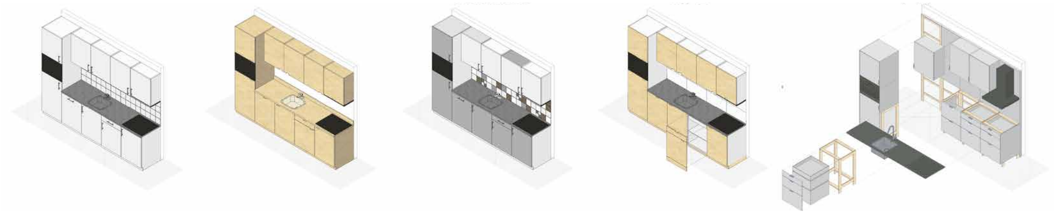
FIG. SAM.4 Circulaire economie Levenscyclus Inventarisatiemodel (voor een grotere afbeelding, zie Figuur 5.3)

TOC

Het CE-LCA model bleek vooral geschikt voor ex-ante beoordelingen waarin ontwerpscenario's worden vergeleken om te bepalen welke circulaire gebouwcomponenten de beste milieuprestaties hebben. De wetenschappelijke bijdrage van deze studie lag in het ontwikkelen van een model om LCA toe te kunnen passen op circulaire gebouwcomponenten met meerdere gebruikscycli en in onze discussie over de methodologische vraagstukken die daarbij ontstonden. Net als Allacker et al. (2017), De Wolf et al. (2020) en Malabi Eberhardt et al. (2020) constateerden we dat het in de praktijk moeilijk zal zijn om alle cycli van het gebouwcomponentensysteem te bepalen. Dit vergroot de onzekerheid, maakt het model gevoelig voor misbruik en kan het verminderen van de milieueffecten op zowel korte als lange termijn belemmeren. We zijn echter van mening dat het toepassen van CE-LCA, of equivalent multi-cyclische LCA, noodzakelijk is voor de transitie naar een 'echt' circulaire gebouwde omgeving. Zonder alle cycli mee te nemen in de beoordeling van de milieuprestatie, kunnen we geen nauwkeurig overzicht krijgen van de voor- en nadelen van circulariteit. Tegelijkertijd kan het CE-LCA-model worden doorontwikkeld om de onzekerheid in het model te verminderen en de nauwkeurigheid, bruikbaarheid en *fair-use* te verbeteren. Daarnaast moeten gebruikers zich bewust zijn van de waarde en de beperkingen van CE-LCA en het model op de juiste manier toepassen.

2.3 Resultaten milieu ontwerprichtlijnen voor circulaire gebouwcomponenten

We ontwikkelden milieu ontwerprichtlijnen door 4 circulaire ontwerpvarianten met een *business-as-usual* ontwerp te vergelijken voor twee gebouwcomponenten: een keuken (als voorbeeld van een gebouw component met een relatief korte levensduur) en een renovatiegevel (component met een gemiddelde levensduur). Zie Figuur Sam.5 voor de ontwerpvarianten en de toegepaste circulaire ontwerpopties per variant.



Variant 1
Business as Usual
Lineair ontwerp

Variant 2
BIO
Biobased, biologisch afbreekbare materi-alen, korte levensduur

Variant 3 Reclaim!
Hergebruikte materi-alen, korte levensduur

Variant 4
LIFE+
Optimaliseren van levensduur, materi-alen met een lange levensduur, *biobased*, biologisch afbreekbare materialen

Variant 5
Plug-and-play
Aanpasbaar modulair ontwerp, optimalisatie van levensduur, mate-rialen met een lange levensduur, vergemak-kelijken van reparatie, aanpassingen, herge-bruik en recycling

Variant 6
Business as Usual
Lineair ontwerp

Variant 7
BIO
Biobased, biologisch afbreekbare materi-alen, korte levensduur

Variant 8 Reclaim!
Hergebruikte materi-alen, gemakkelijk te demonteren

Variant 9
Product-2-product
Eenvoudig te de-demonteren en opnieuw te monteren, materialen met een lange levensduur, standaard onderdel-en, hergebruik van onderdelen

Variant 10
Plug-and-play
Aanpasbaar modulair ontwerp, standaard-maten, optimaliseren van levensduur, mate-rialen met een lange levensduur, vergemak-kelijken van reparatie, aanpassingen, herge-bruik en recycling

FIG. SAM.5 Ontwerpvarianten voor de circulaire keuken en renovatiegevel

We vergeleken de milieuprestaties van de ontwerpvarianten middels MSA en CE-LCA inclusief uitgebreide gevoeligheidsanalyse. Uit de analyse van 78 CE-LCA's en MSA's hebben we 8 lessen getrokken. We ontdekten dat de milieuprestaties voor beide gebouwcomponenten het meest verbeteren door circulaire ontwerpopties te combineren om de lussen zowel te vernauwen, te vertragen en te sluiten. Bovendien concludeerden we dat per gebouwcomponent verschillende combinaties van circulaire ontwerpopties een beter resultaat opleveren: componenten met een kortere levensduur profiteren meer van het vertragen en sluiten van toekomstige cycli; componenten met een gemiddelde levensduur hebben meer baat bij het nu verminderen van het materiaal gebruik en het vertragen van toekomstige lussen op de gebouwlocatie. We hebben de richtlijnen gevalideerd met 49 experts en door deze te vergelijken met de bestaande milieu ontwerprichtlijnen,

Onze ontwerprichtlijnen zijn niet volledig nieuw. De circulaire ontwerpopties zijn al eerder beschreven en delen van onze ontwerprichtlijnen overlappen met bestaande richtlijnen. Onze bijdrage bestond uit het vergelijken van de milieuprestaties van *meerdere* circulaire ontwerpopties voor *verschillende* gebouwcomponenten. Als zodanig hebben we een voorlopig antwoord gegeven op de vraag welke *specifieke* circulaire ontwerpoptie(s) de meeste milieubesparingen zouden opleveren voor de verschillende *specifieke* circulaire gebouwcomponenten. Het toepassen van onze ontwerprichtlijnen kan ontwerpers, beleidsmakers en andere beslissers ondersteunen om meer circulaire gebouwcomponenten te ontwikkelen. Toch benadrukken we dat onze richtlijnen als 'voorlopige' richtlijnen moeten worden gezien want het toepassen van circulaire ontwerpopties resulteerde niet altijd in betere milieuprestaties. Kantelpunten werden geïdentificeerd op basis van het aantal gebruikscycli, aannames in de levensduur en de toegepaste beoordelingsmethoden. Verdere ontwikkeling en toetsing van de gepresenteerde milieu ontwerprichtlijnen in de praktijk zou de generaliseerbaarheid ervan kunnen verbeteren en hun bruikbaarheid in de praktijk kunnen valideren.

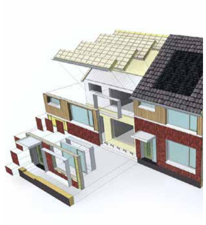
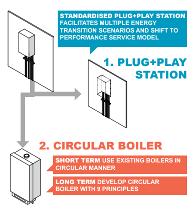
In samenwerking met onderzoekers van het project 'the Circular Kitchen' (van de TU Delft) zijn de MSA en CE-LCA resultaten van deze studie vergeleken met de uitkomsten van een economische prestatiebeoordeling met behulp van een Circulaire Economie Levens Cyclus Kosten model. We ontdekten dat een doelgerichte combinatie van zowel biologische als technische materialen, die na gebruik kunnen worden gescheiden, zowel de beste economische- alsook de beste milieuprestaties opleverden (zie Wouterszoon Jansen, van Stijn, Eberhardt, Gruis, & van Bortel, 2022). Samen met onderzoekers van de Universiteit van Aalborg ontwikkelden we aanvullende milieu ontwerprichtlijnen voor een circulaire hoofddraagstructuur (als voorbeeld van een gebouwcomponent met een lange levensduur). Dit onderzoek is gepubliceerd in Malabi Eberhardt, van Stijn, Kristensen Stranddorf, Birkved en Birgisdottir (2021) en sluit aan bij onze bevindingen. Ze ontdekten dat gebouwcomponenten met een lange levensduur – nog meer – profiteren van het nu verminderen van het materiaalgebruik en het vertragen van toekomstige lussen op de gebouwlocatie.

2.4 Resultaten cruciale stakeholderkeuzes bij de ontwikkeling van haalbare circulaire gebouwcomponenten

We presenteerden een longitudinaal onderzoek naar de keuzes van stakeholders in 5 ontwikkelingsprocessen van 8 circulaire gebouwcomponenten. De onderzoekers co-creëerden actief samen met de stakeholders van de initiatieffase tot en met de marktimplementatie en documenteerden de door de stakeholders gemaakte keuzes. Zie Tabel Sam.2 voor de ontwikkelde circulaire gebouwcomponenten. Door middel van iteratieve procesreflectie en -analyse identificeerden we die stakeholder keuzes die de gepercipieerde haalbaarheid van verschillende circulaire ontwerpopties binnen de diverse gebouwcomponenten beïnvloedde tijdens het ontwikkelingsproces. We hebben onze bevindingen gevalideerd met de stakeholders die betrokken waren bij het ontwikkelingsproces.

We ontdekten dat de combinaties van circulaire ontwerpopties die als haalbaar werden beschouwd verschilden voor verschillende typen circulaire gebouwcomponenten. Voor componenten met ‘product-achtige’ eigenschappen kan het nu vernauwen van lussen worden gecombineerd met het vertragen én sluiten van waarschijnlijke toekomstige lussen. Voor ‘gebouw-achtige’ componenten werd het nu vernauwen van lussen in combinatie met het vertragen van waarschijnlijke toekomstige cycli op de gebouwlocatie haalbaarder gevonden. Echter, de specifieke toepassing van de circulaire ontwerpopties en de context beïnvloedden wat de stakeholders als haalbaar beschouwden. We ontdekten tal van wisselwerkingen en synergiën tussen de circulaire ontwerpopties en hun haalbaarheid, afhankelijk van de toepassing en context. Bovendien veranderde wat als haalbaar werd beschouwd gedurende het ontwikkelingsproces: ambitieuzere combinaties van circulaire ontwerpopties werden in eerste instantie haalbaar geacht. Gedurende het proces werd de toepassing van circulaire ontwerpopties aangepast om aan te sluiten op het huidige business- en ketenmodel. Tot slot was de gepercipieerde haalbaarheid van circulaire ontwerpopties ook afhankelijk van hoe het ontwikkelingsproces was ingericht, van de betrokken stakeholders en individuen, en verder van keuzes die geen verband hielden met circulaire ontwerpopties.

TABLE SAM.2 Overzicht van de ontwikkelde circulaire gebouwcomponenten

Casus naam	Bedachte circulaire ontwerp opties gedurende ontwerp	Gerealiseerde circulaire ontwerp opties	Belangrijkste reden voor verschil tussen bedachte en gerealiseerde opties	Representatieve afbeelding ontwikkeld component
1 Circulaire keuken	Modulair ontwerp: frame met lange levensduur waaraan inbouw- en afwerkdelen worden bevestigd, hierdoor zijn reparatie en aanpassingen mogelijk; Keuken-als-een-service model	Keuken gemaakt van demontabele panelen waardoor reparatie mogelijk is	1. Frame van de keuken niet te produceren met huidige machinepark 2. Repareerbaarheid voor de opdrachtgever belangrijker dan (toekomstige) aanpasbaarheid	
2 Circulaire schil	NOM renovatieconcept met modulaire gevel en dak dat waarschijnlijke toekomstige aanpassingen en hergebruik mogelijk maakt; toepassing hergebruikte en bio-based materialen	Modulair renovatieconcept met als eerste stap een modulair dak dat waarschijnlijke aanpassingen mogelijk maakt; toepassing hergebruikte en bio-based materialen waar mogelijk	1. Verwerken van hergebruikte materialen met huidige machines lastig; geen garanties 2. Hoge initiële kosten renovatie gevel 3. Meer vraag naar dakrenovaties 4. Stap-voor-stap renovaties ondersteunen het realiseren van de energie transitie	
3 Circulaire aanbouw	Ontwerp met hergebruikte materialen en modules met standaard maatvoering die reparatie, aanpassingen en hergebruik mogelijk maken in de toekomst	Ontwerp met hergebruikte materialen en modules met standaard-maatvoering die reparatie, aanpassingen en hergebruik mogelijk maken in de toekomst	N.v.t.	
4 Circulaire NOM-light	NOM renovatie met gevel en dakrenovatie (buitenom); toepassing van meer circulaire materialen en demontabele verbindingen	Minder ingrepen toepassen om tot NOM niveau te komen; toepassing meer circulaire materialen	1. Component ontwikkeling niet rol van aannemer; dit leidde tot focus op vernauwen en sluiten van lussen nu 2. Initiële kosten van NOM renovatie met tweede schil te hoog 3. Minder gebouw componenten zijn vervangen om kosten en materiaal te besparen	
5 Circulaire cv-ketel	Modulair klimaatsysteem aanpasbaar aan toekomstige verwarmingsscenario's; modulaire cv-ketel die toekomstige reparatie, aanpassingen en hergebruik van de ketel en onderdelen mogelijk maakt	Ontwikkeling circulaire cv-ketel is gestopt na afronding principe ontwerp	1. 'Split-incentive": kosten voor het toepassen van circulaire ontwerpopties liggen bij fabrikant en voordelen bij installateur 2. Onzekerheid over gebruik aardgas voor verwarming in toekomst	

Niet al onze bevindingen zijn nieuw. Veel barrières die we tijdens ons literatuuronderzoek hebben gevonden, komen ook in deze studie weer naar voren. Wel hebben we in kaart gebracht welke *specifieke* keuzes, door welke stakeholder, op welk moment in het ontwikkelingsproces en om welke reden, de gepercipieerde haalbaarheid van verschillende circulaire ontwerpopties in verschillende typen gebouwcomponenten beïnvloedden. We ontdekten in onze studie vier essentiële redenen, die de haalbaarheid van circulaire ontwerpopties aanzienlijk hebben beïnvloed: (1) de aansluiting van het technische model op het huidige business-, en ketenmodel, (2) de mate waarin prioriteit gegeven wordt aan circulariteit, (3) de hoge mate van complexiteit en (4) eerdere ervaringen van de stakeholders. Toekomstig onderzoek en innovatie kunnen helpen om de bijbehorende barrières te overwinnen en zo meer circulaire gebouwcomponenten haalbaar te maken. We zijn echter voorzichtig met het generaliseren van onze bevindingen. Onze bevindingen blijven gebaseerd op situationele kennis en zijn mogelijkerwijs niet toepasbaar voor alle situaties, altijd en overal. Echter, de concrete kennis uit deze studie kan stakeholders in de praktijk wel ondersteunen bij het ontwikkelen van meer haalbare circulaire gebouwcomponenten.

3. Conclusie

De bouwindustrie speelt een cruciale rol in het duurzamer maken van de samenleving. Gebouwen kunnen circulair worden gemaakt door gebouwcomponenten te vervangen door meer circulaire gebouwcomponenten tijdens nieuwbouw, renovatie en onderhoud. Er zijn veel verschillende ontwerpvarianten mogelijk voor circulaire gebouwcomponenten. Er is weinig ervaring in de praktijk en weinig wetenschappelijke kennis over het ontwerpen en realiseren van circulaire gebouwcomponenten. Daarom hebben we in dit proefschrift de meest ideale – of wenselijke – circulaire gebouwcomponenten ontwikkeld die haalbaar – of waarschijnlijk – zijn om te worden geïmplementeerd binnen de huidige projecten en praktijk. Door deze gebouwcomponenten te ontwikkelen genereerden we kennis over 4 onderzoeksdoelen. (1) We hebben een tool ontwikkeld die het ontwerp van circulaire gebouwcomponenten ondersteunt. (2) Om de milieueffecten van circulaire gebouwcomponenten te beoordelen hebben we het Circulaire Economie Levens Cyclus Analyse (CE-LCA) model ontwikkeld. (3) We hebben milieu ontwerprichtlijnen opgesteld op basis van CE-LCA en MSA, waarbij we meerdere circulaire ontwerpopties voor twee verschillende gebouwcomponenten met elkaar hebben vergeleken. Ten slotte (4) identificeerden we de stakeholder keuzes die de gepercipieerde haalbaarheid van verschillende circulaire ontwerpopties binnen de ontwikkeling van 8 circulaire gebouwcomponenten beïnvloedden.

Maar, welke circulaire gebouwcomponenten waren nu het meest 'ideaal' en 'haalbaar'? Om de componenten die het gebruik van grondstoffen, de milieueffecten en de afvalproductie het meest verminderen te identificeren, richtten we ons op de bevindingen van onze derde studie. Uit de bevindingen van onze vierde studie hebben we conclusies getrokken over welke circulaire gebouwcomponenten het meest haalbaar zijn om te implementeren in projecten en de praktijk.

3.1 Tussen ideaal en haalbaar

We vergeleken de bevindingen van onze derde en vierde studie. Figuur Sam.6 laat zien welke circulaire ontwerpopties leidden tot betere milieuprestaties en welke werden beschouwd als haalbaarder om te implementeren. We vonden zowel overeenkomsten als verschillen.

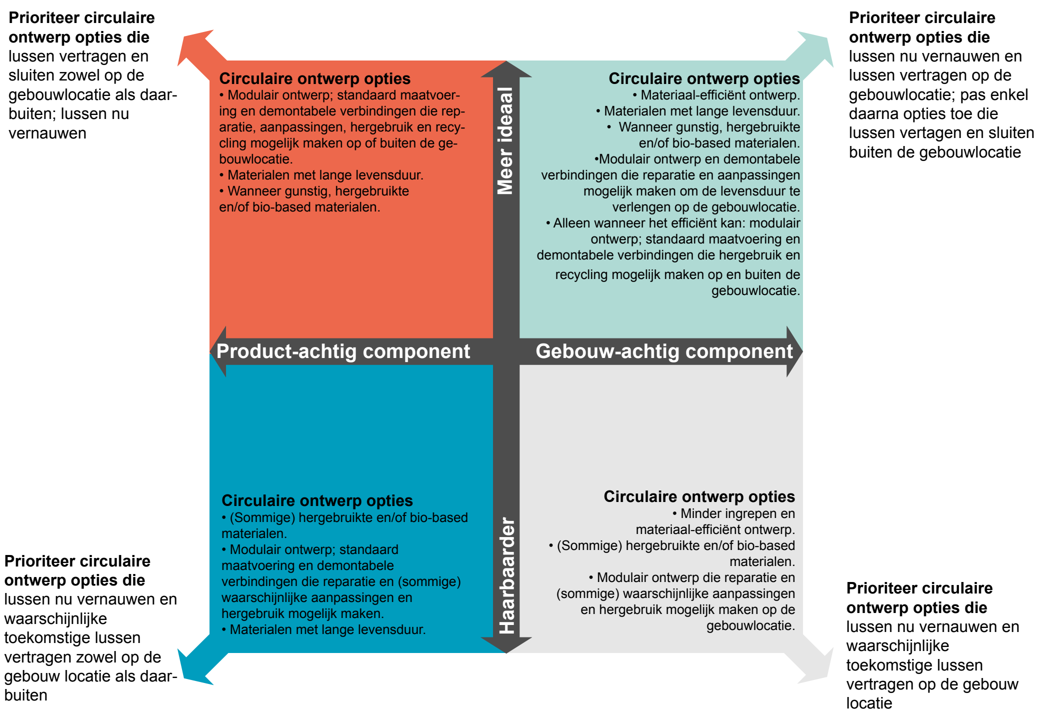


FIG. SAM.6 Circulaire ontwerpopties die als meer ideaal en haalbaar werden bevonden voor verschillende soorten gebouw-componenten

Ten eerste, vergelijkbare combinaties van circulaire ontwerpopties leidden tot betere milieuprestaties én werden als haalbaar beschouwd. Voor componenten met product-achtige eigenschappen (waaronder een kortere levensduur) werden circulaire ontwerpopties die lussen nu vernauwen en toekomstige lussen vertragen en sluiten, zowel wenselijk als haalbaar bevonden. Circulaire ontwerpopties die lussen nu vernauwen en toekomstige lussen op de gebouwlocatie vertragen waren zowel wenselijk als haalbaarder voor componenten met gebouwkenmerken (waaronder een langere levensduur). Ten tweede werden meer circulaire ontwerpopties wenselijk dan haalbaar geacht door de stakeholders. In het bijzonder geldt dit voor circulaire ontwerpopties die lussen vertragen of sluiten in de verre toekomst en die niet plaatsvinden op de gebouwlocatie. De kloof tussen 'meer circulair' en 'haalbaar om te implementeren' wordt beïnvloed door de mate waarin het keten-, en businessmodel moeten worden aangepast aan de circulaire ontwerpopties. Tot slot leverde ons onderzoek nog geen volledig 'ideaal' circulair gebouwcomponent ontwerp op. Sommige circulaire ontwerpopties resulteerden zelfs in een verslechterde milieuprestatie. De 'beter presterende' varianten reduceerden het gebruik van grondstoffen, de milieueffecten en de afvalproductie eveneens niet tot nul. Evenmin vonden we circulaire gebouwcomponenten die in absolute zin 'haalbaar' waren. We kunnen eerder spreken van min of meer circulaire componenten – die min of meer haalbaar zijn om te implementeren – afhankelijk van hoe circulaire ontwerpopties worden toegepast in de context. Wel concluderen we dat nu al meer circulaire gebouwcomponenten zouden kunnen worden ontwikkeld en geïmplementeerd in projecten en in de praktijk. Echter, niet elke circulaire ontwerpoptie is wenselijk en niet alles wat wenselijk is, is al haalbaar.

3.2 Wetenschappelijke bijdrage en implicaties voor de praktijk

De wetenschappelijke bijdrage van dit onderzoek als geheel is als volgt. Ten eerste bracht ons onderzoek de circulaire ontwerptheorie vanuit de context van consumentenproducten naar de gebouwde omgeving én, ten tweede, naar de renovatiecontext. Ten derde heeft dit onderzoek, door te focussen op het niveau van het gebouwcomponent, de kloof overbrugd tussen circulariteit op gebouw- en op materiaalniveau. Voortbouwend op de theorieën van Habraken (1961), Duffy en Brand (1994) en Kapteins (1989, p. 11), toonden we aan dat het gebouw moet worden beschouwd als een samenstelling van gebouwcomponenten, onderdelen en materialen tijdens alle bouwmanagement fasen om zo grondstoffen te laten cycleren op hun hoogste toepassings- en waarde niveau (zie Figuur Sam.7). Ten vierde heeft deze studie bijgedragen aan een verschuiving in de betekenis van het begrip duurzaamheid in bouwmanagement. In deze studie wordt duurzaamheid bekeken over de hele levenscyclus van het gebouw in plaats van alleen te concentreren op koolstofemissies door operationeel energieverbruik. We ontdekten wisselwerkingen en synergiën tussen beide duurzaamheidsperspectieven; we bevelen toekomstig onderzoek aan naar hoe beiden integraal te wegen tijdens de ontwerpfase. Ten vijfde toonde ons onderzoek het belang aan van het optimaliseren van meerdere cycli om gebouwcomponenten, onderdelen en materialen op hun hoogste toepassings- en waarde niveau te houden. Daarom zouden onze managementmodellen – op elk gebouwniveau – een multi-cyclische scope moeten bevorderen. Nieuwe samenwerkingsvormen moeten worden ontwikkeld waarbij continue waardebehoudsprocessen in een breed netwerk van stakeholders centraal staan. Ten zesde, de meeste onderzoeken naar de wenselijkheid of implementeerbaarheid van circulaire ontwerpopties waren gericht op enkelvoudige opties en/of keken naar enkelvoudige gebouwcomponenten. Door meerdere opties en componenten te vergelijken, voegde ons onderzoek vernieuwende inzichten toe aan het huidige kennisniveau. Tot slot, door het ontwikkelen van de *'Action Research through Design'*-benadering die in dit onderzoek wordt toegepast, heeft ons werk ook bijgedragen aan de kennis over 'hoe' onderzoek te doen. Bij uitstek voor onderzoek dat gericht is op het vinden van oplossingen voor complexe maatschappelijke uitdagingen.

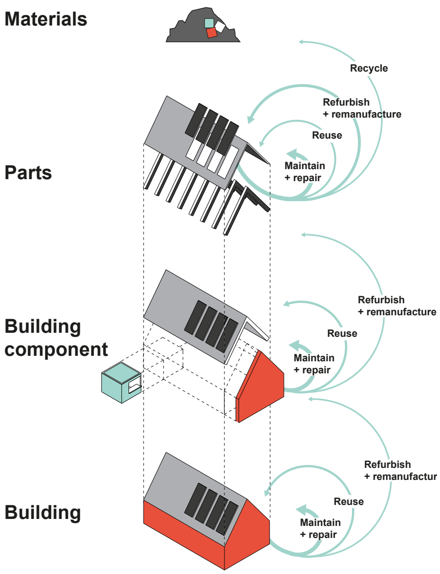


FIG. SAM.7 Circuleren op de hoogste toepasbaarheid en waarde door het gebouwcomponent, de onderdelen en materialen te beschouwen in relatie tot het gebouw

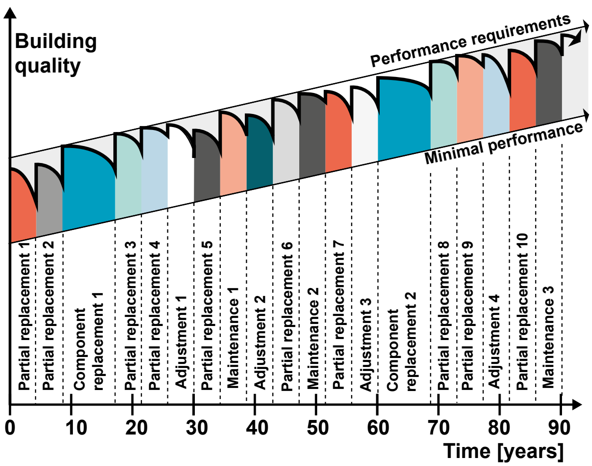


FIG. SAM.8 Hoog houden van de waarde van het gebouw door continue gedeeltelijke vervangingen en aanpassingen van onderdelen en materialen binnen een gebouwcomponent

De praktijkimplicaties van dit onderzoek zijn als volgt. Ten eerste kan ons onderzoek direct de praktijk ondersteunen bij het ontwikkelen van haalbare circulaire gebouwcomponenten door middel van de gepresenteerde ontwerptools, ontwerprichtlijnen en de reproduceerbare circulaire gebouwcomponenten. Ons onderzoek heeft ook direct bijgedragen aan het vergroten van de circulaire ontwerpervaring in de praktijk. Om stakeholders te helpen bij het ontwikkelen van meer circulaire en meer haalbare gebouwcomponenten in de toekomst, adviseren wij de volgende veranderingen in de praktijk. Ten eerste is meer circulaire kennis, vaardigheden en ervaring nodig in de keten. Ten tweede is de ontwikkeling van circulaire keten-, en businessmodellen nodig om meer circulaire ontwerpen te kunnen implementeren. De keten zou samenwerkingsverbanden met een multi-cyclisch perspectief in een breed netwerk van stakeholders moeten bevorderen. Ofwel dit vereist dat circulariteit wordt geïntegreerd in elke stap van het projectproces, ofwel dit vereist de ontwikkeling van reproduceerbare circulaire oplossingen welke project overstijgend inzetbaar zijn. Om het businessmodel circulair te maken, raden we aan om de waarde van een gebouw, de gebouwcomponenten, onderdelen en materialen over hun gehele levenscyclus te bekijken. Onderhoud moet niet worden beschouwd als een kostenpost, maar eerder als een manier om toekomstige investeringen te voorkomen (zie Figuur Sam.8). Ten derde kan de praktijk op korte termijn meer circulaire gebouwcomponenten realiseren door eerst 'laaghangend fruit' te implementeren. Bijvoorbeeld door het ontwerp te vereenvoudigen, samen te werken met lokale partners, te focussen op betaalbare opties en prioriteit te geven aan circulariteit nu en in de nabije toekomst. Ten slotte raden we de praktijk aan om te werken aan een gemeenschappelijk begrip van CE en om gemeenschappelijke doelen te stellen. We roepen iedereen op om verder te kijken dan circulariteit. Om het gebruik van grondstoffen, milieueffecten en afvalproductie in de gebouwde omgeving voldoende te verminderen, kunnen aanvullende strategieën gericht op 'consuminderen' nodig zijn.

Referenties

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment, 22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society, 61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition.* Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition
EN 15804. (2012). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.* Retrieved from https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019
EN 15978. (2011). *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.* Retrieved from European Committee for Standardization (CEN) website: https://infostore.saiglobal.com/preview/is/en/2011/i.s.en15978-2011-lc-2011-11.pdf?sku=1500481
Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
Heesen, R., Bright, L. K., & Zucker, A. (2019). Vindicating methodological triangulation. *Synthese, 196*(8), 3067–3081. https://doi.org/10.1007/s11229-016-1294-7
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings, 66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability, 13*(10), 5621. https://doi.org/10.3390/su13105621
Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability, 12*(22), 9579. https://doi.org/10.3390/su12229579
Ness, D. A., & Xing, K. (2017). Toward a resource-efficient built environment: A literature review and conceptual model. *Journal of Industrial Ecology, 21*(3), 572–592. https://doi.org/10.1111/jiec.12586
Peffers, K., Tuunanen, T., Gengler, C. E., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2006). The design science research process: A model for producing and presenting information systems research. *DESRIST International Conference on Design Science Research in Information Systems and Technology,* 83–106. Claremont, CA.
Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling, 135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027
Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production, 229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019
van Aken, J. E., & Romme, G. (2009). Reinventing the future: Adding design science to the repertoire of organization and management studies. *Organisation Management Journal, 6*(1), 5–12. https://doi.org/10.1057/omj.2009.1
van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling, 174*(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105683
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling, 161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

1 Introduction

Sections of this chapter have been shortened and will be published as part of van Stijn, A. (2023). Guidance in the application of Research through Design: the example of developing circular building components. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods.* Taylor & Francis.

A van Stijn[1,2]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

1.1 Towards a circular built environment through circular building components

One of humankind's most fundamental needs is to have a safe place to live, to be sheltered from outside influences and to be able to feel at home. It is from our homes that we engage with the outside world. This basic need is considered so universal that it is enshrined in the Universal Declaration of Human Rights. The building sector has a vital role in providing adequate homes for the world's population. However, this sector also consumes the largest share of resources and exerts great pressure on the environment (Munaro, Tavares, & Bragança, 2020; Zimmann, O'Brien, Hargrave, & Morrell, 2016). The building sector is said to be responsible for 40% of global material consumption and 40% of global waste (Ness & Xing, 2017). Moreover, the linear economy – in which we take, make, use and dispose resources – results in environmental impacts. The building sector is responsible for approximately 38% of all human-induced CO_2 emissions of which 10% can be attributed to the production of materials needed to build, maintain and renovate the built environment (United Nations Environment Programme, 2020). To top it all off, the global population is projected to grow to 9.6 billion by 2050 (United Nations, 2013); 3 billion citizens are expected to join the middle class by 2030 (Ellen MacArthur Foundation, 2013). Global material use is expected to more than double by 2060; a third of this rise is attributed to materials used in the building sector (United Nations Environment Programme, 2021). A radically different approach is needed to build, maintain and renovate buildings in the future.

The transition from a linear economy to a Circular Economy (CE) could support minimizing resource use, environment impacts and waste in the built environment. The CE proposes a more resource-effective model by decoupling economic growth from resource consumption (Ellen MacArthur Foundation, 2013). The model builds on previously developed schools of thought and there is no commonly accepted understanding of the concept (Kirchherr, Reike, & Hekkert, 2017). We understand 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”. (Geissdoerfer, Savaget, Bocken, & Hultink, 2017, p. 759). Narrowing loops is to reduce resource use or achieve resource efficiency. Slowing loops is to lengthen the use of a building, component, part or material. Closing loops is to (re) cycle materials from End of Life (EoL) back to production (Bocken, de Pauw, Bakker, & van der Grinten, 2016). Value Retention Processes (VRPs) – such as reuse, repair, refurbish, recycle and recover – operationalize narrowing, slowing and closing cycles (Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). An important premise is that the loops of the CE are powered by renewable, low-carbon energy (Peck, 2015) .The CE has been visualized in the ‘Butterfly model’ of the Ellen MacArthur Foundation (2013), see Figure 1.1. We refer to the scientific background (Chapter 2.1) for a more elaborate explanation of the effects of the linear economy and CE concept.

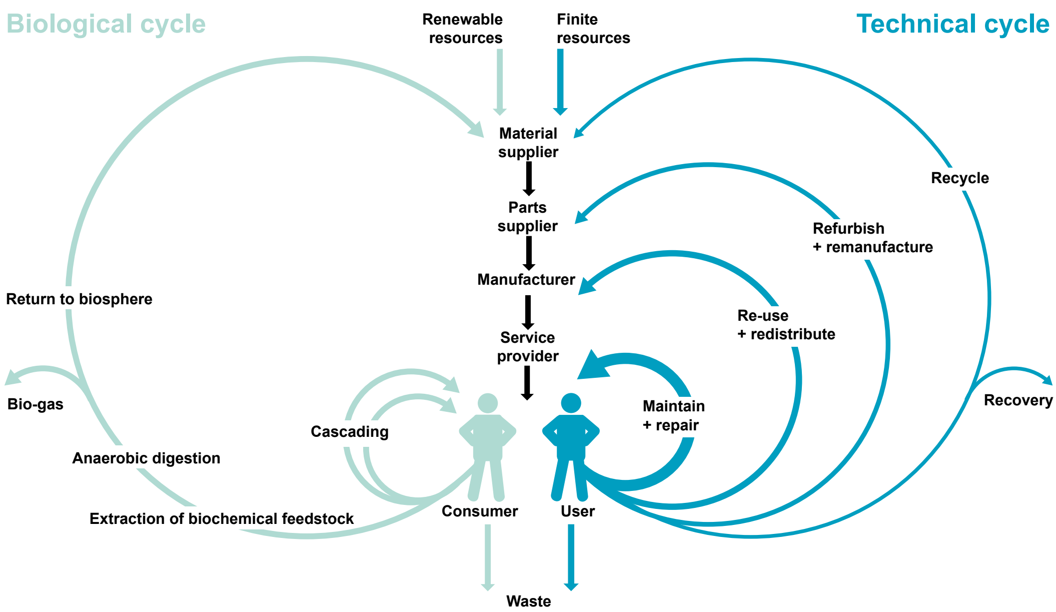


FIG. 1.1 Butterfly model representing the CE (adjusted from the Ellen MacArthur foundation (2013))

But how can we integrate circularity into buildings? The focus in the built environment has been on how we can best reuse waste material or recycling (see Figure 1.2). Recycling materials is the outer loop (or cycle) in the Butterfly model.

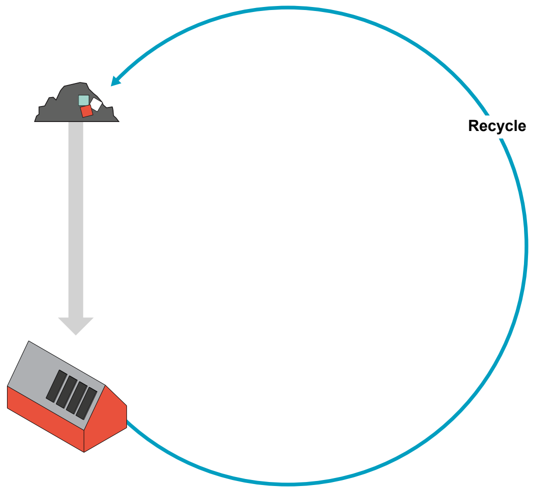


FIG. 1.2 Recycling from materials to buildings

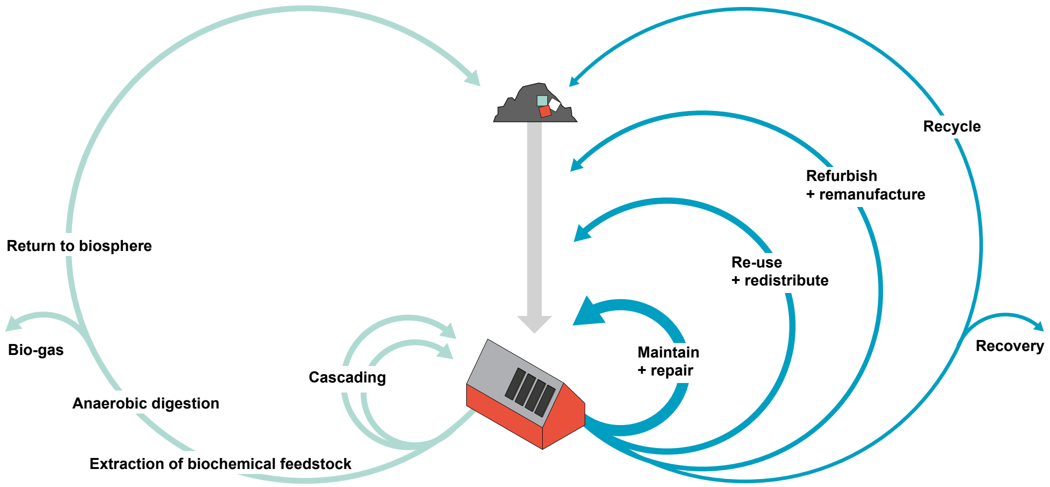


FIG. 1.3 Using inner loops to prevent waste

Although recycling is of vital importance to achieving a circular built environment, one of the most important principles of the CE is that we first make optimum use of the inner loops (see Figure 1.3). Loops such as repair, reuse, refurbishing and remanufacturing prevent waste as much as possible. Or, to utilize the biological cycles instead. Various authors have provided circular design strategies which can support narrowing, slowing and closing loops (e.g., Bakker, den Hollander, van Hinte and Zijlstra (2014), van den Berg and Bakker (2015) and Moreno, De los Rios, Rowe and Charnley (2016)). Circular design options such as designing lightweight components or using non-virgin, bio-based, or low-impact materials can support narrowing loops now. Making a modular design, standardizing sizes and applying demountable joints can slow loops by facilitating repair, reuse, and adjustments in the future. Applying recyclable or biodegradable materials which can be separated at EoL, can support closing future loops. In the scientific background (Chapter 2.2), we will elaborate further on key circular design theories.

Examples that apply circular design options in the building context already exist. In the scientific background we have included a systematic review of these examples (see Chapter 2.3). By categorizing the examples based on how they make the built environment more circular, we identified 17 different circular building approaches (see Chapter 2.3). We then analyzed which circular design options were applied in each approach; we identified which approach offers the most potential to narrow, slow and close loops. We found that most approaches focused on either narrowing and closing loops now or slowing them in the future; they rarely considered circularity on all levels of the building. The building approach which provided most potential to integrally narrow, slow and close cycles, modularized the building into building components. Buildings consist of different building components, such as kitchens, façades, and roofs. These components could be mass-produced (or replicated); they can be customized to fit different projects and user needs; they can be designed using circular design options to narrow, slow and close loops of the building component, parts and materials optimally. Buildings can gradually be made circular by replacing linear building components with more circular building components during new construction, natural maintenance and renovation moments. As such, circular building components offer a promising approach to integrate circularity into new and existing buildings (see Figure 1.4).

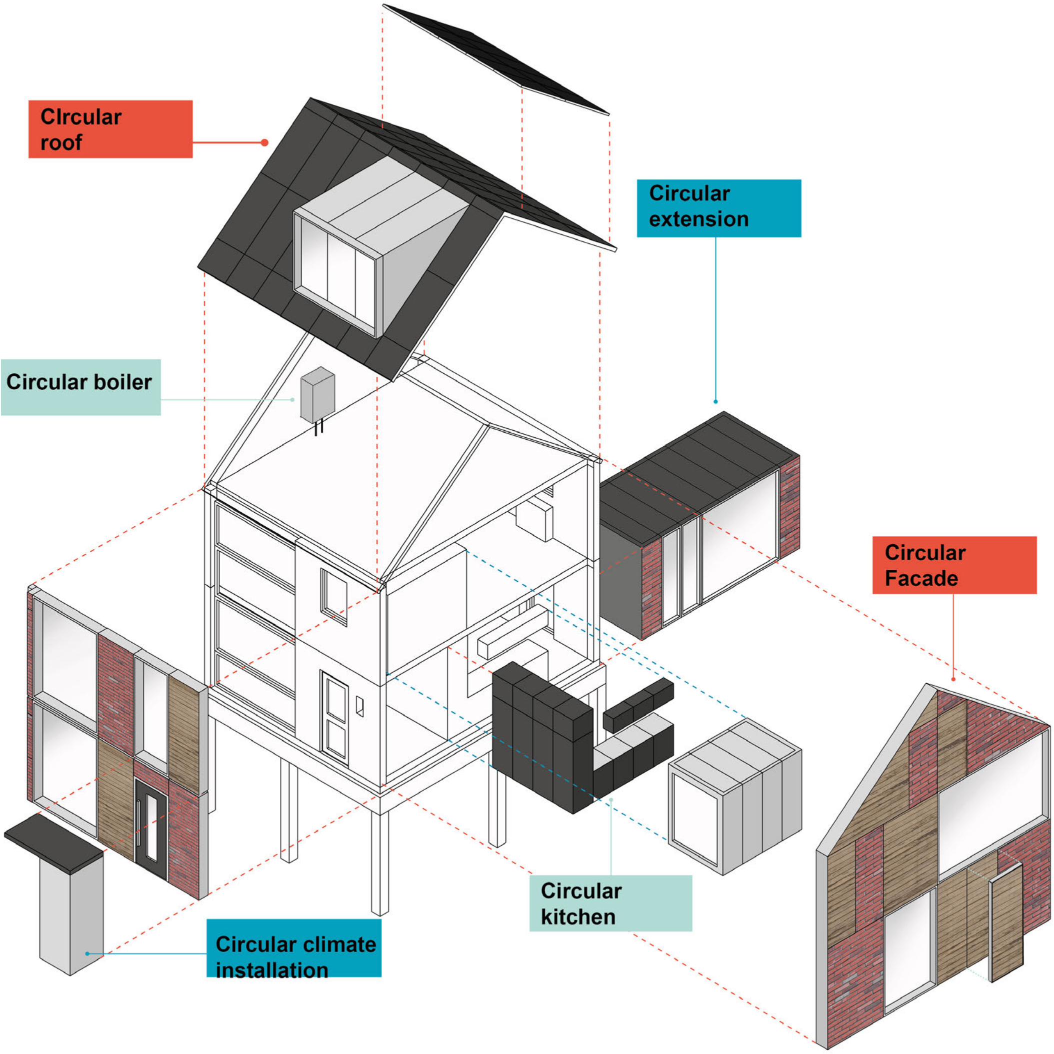


FIG. 1.4 Using circular building components to integrate CE into new construction, maintenance and renovation

1.2 Problem statement

There are many ways imaginable to integrate circularity into building components. For example, a façade which applies reclaimed materials now, a modular façade which will be updated and reused in the future, or a bio-based and biodegradable façade. Each façade variant could be considered more circular in their own respect. This raises many questions: how to design a circular building component; which design is the most circular and how can we make such a choice; which designs are feasible to realize?

At the start of this research, there was still little experience in practice with the design and realization of circular building components. Examples of circular building components were scarce; examples remained theoretical designs or were in prototype or piloting stage. For example, the 'Circular 2ND skin' proposed a first concept design for a circular renovation façade (Henry, 2018); the 'Circular retrofit lab' included first prototypes of several circular building components including partitioning walls (Paduart, 2016).

To support the development of circular building components, designers, policy makers, and other decision-makers could benefit from knowledge on how to design and realize them. However, there was also little scientific knowledge available on the design and realization of circular building components. Most research on circular design focused on consumer goods. Research applying principles of the CE in the built environment was in its infancy (Ness & Xing, 2017). Solutions for short-lived products are unlikely to be applicable to building components as they have their own distinct characteristics. The service life of most building components is much longer than those of consumer products (c.f. Brand, 1994). Building components – when combined into a building – create a unique, complex, long-lived and ever-transforming entity (Pomponi & Moncaster, 2017); Furthermore, the building sector has its own processes and culture. Brinksma (2017) evaluated to what extent energy renovation concepts – including roof, façade, floor and climate installation components – facilitated future adjustability. He tested 25 concepts on process, product and contextual characteristics. He concluded that the energy concepts scored well on reducing operational energy use but did not facilitate future adjustments. Although he proposed several circular design strategies to improve their adjustability, he did not provide any concrete design guidance. Cambier, Galle and De Temmerman (2020) also found that general circular design guidelines were available but specific design guidelines for circular building components were still lacking.

Therefore, the gap we addressed in this research is twofold. First, there was a lack of existing circular building components; to reduce resource use, pollution, emissions and waste, we needed to design and realize them. Second, there was a lack of knowledge on how to design and realize circular building components.

1.3 Design and research goals

In our research, we distinguished between a design goal and research goals. The design goal focused on developing circular building components. The research goals focused on generating knowledge through designing circular building components.

1.3.1 Design goal

On the one hand, we aimed at designing the most 'ideal' – or desirable – circular building components. We understood 'ideal' as the component which will reduce the resource use, environmental impacts and waste generation the most. With the term 'ideal' we explicitly do not mean an optimal solution for all, everywhere and always. Rather we see 'ideal' as a search for a 'desirable future reality' as described by de Jong (1992). Even if 'the ideal' does not exist, this aim allowed us to explore what is most desirable from a resource use, environmental impacts and waste perspective. On the other hand, we need components which are 'feasible' – or likely – to be implemented within current projects and practice. Implementation is vital to actually reduce resource use, environmental impacts and waste and, so, to create a circular built environment. Hence, **the goal of our design process was to develop 'ideal' and 'feasible' circular building components.** The circular components were developed focusing on the renovation of low-rise, post-war, social housing in the Netherlands. This is a logical initial context: the Netherlands has high ambitions in their policy on achieving circularity in the built environment of which housing forms an important part; social housing associations own approximately one-third of the housing stock; low-rise, post-war housing is in need of renovation in the coming decades. For more on the context of the component development we refer to Section 1.4.

TOC

TABLE 1.1 Developed circular building components

Case name	Developed components	Stakeholders	When
1. Circular kitchen[1]	(1) Circular kitchen component including cabinetry and appliances	Researchers: TU Delft[2] Knowledge institute: AMS-institute[2] Kitchen manufacturer 1: Bribus Keukens[2] Appliance manufacturer 1: ATAG[2] Worktop manufacturer 1: Topline Maatwerkbladen BV Contractor 1: Dirkzwager Groep[2] Housing association 1.1: Waterweg Wonen[2] Housing association 1.2: Eigen Haard[2] Housing association 1.3: Ymere[2] Housing association 1.4: Stichting Woonbedrijf SWS [2] Housing association 1.5: Woonstad Rotterdam Housing association 1.6: Portaal[2]	Jan 2017-Dec 2021 108 Co-creation sessions and contact moments
2 Circular skin[3]	Circular renovation concept to improve energy-efficiency of dwellings, including circular (2) renovation façade and (3) renovation roof components	Researchers: TU Delft[4] Knowledge institute: AMS-institute[4] Contractor 2: Dura Vermeer[4] Housing association 2: Ymere[4] Façade manufacturer 2: Barli Architect 2: Villanova architecten Reclaimed material broker 2: Repurpose Building physics consultant 2: Climatic Design Consult (CDC) Roof manufacturer 2: Linex	Jul 2017-Dec 2021 109 Co-creation sessions and contact moments
3 Circular dwelling extension[3]	(4) Circular dwelling extension component used to enlarge an existing dwelling	Researchers: TU Delft[4] Knowledge institute: AMS-institute[4] Housing association 3: Eigen Haard[4] Contractor 3: ERA Contour[4] Architect 3: DOOR architecten Carpenter 3: Van den Oudenrijn	Mar 2018-Aug 2021 87 co-creation sessions and contact moments

>>>

TOC

TABLE 1.1 Developed circular building components

Case name	Developed components	Stakeholders	When
4 Circular NZEB-light[3,7]	Net-Zero-Energy-Building (NZEB)[7] renovation concept including (5) climate installation, (6) renovation roof and (7) renovation façade components, optimized on circularity	Researchers: TU Delft[4] Knowledge institute: AMS-institute[4] Housing association 4: Wonion[4] Contractor 4.1: De Variabele Contractor 4.2: Te Mebel Vastgoedonderhoud BV Contractor 4.3: Rudie Jansen Schilders & Totaalonderhoud Contractor 4.4: Lenferink Vastgoedonderhoud Climate-inst. service provider 4.1: Wassink Installatie Climate-inst. service provider 4.2: Klein Poelhuis installatietechniek Climate-inst. service provider 4.3: WSI techniek	Oct 2017-Dec 2021 73 Co-creation sessions and contact moments
5 Circular central heating boiler[5]	(8) Circular central heating system focusing on a circular central heating boiler	Researchers: TU Delft[6] Knowledge institute: AMS-institute[6] Climate systems manufacturer 5: Remeha[6] Climate systems installer 5: Feenstra[6] Housing association 5: Waterweg Wonen[6]	Jan 2017-Sep 2017 9 sessions and contact moments

__1__ The circular kitchen was developed as part of the funded research project 'Circular components' and 'the Circular Kitchen (CIK);
__2__ Stakeholders who were committed partners in these projects.
__3__ The circular skin, circular dwelling extension and circular NZEB-light were developed as part of the funded research project 'REHAB';
__4__ Stakeholders who were committed partners in the REHAB project.
__5__ The circular boiler was developed as part of the funded research project 'Circular components'; __6__ Stakeholders who were committed partners in the circular components project.
__7__ NZEB renovation stands for the renovation ambition Net Zero Energy Building (in Dutch 'Nul Op de Meter') In NZEB renovations, a combination of renovation measures is applied to make the dwelling net zero energy, such as an exterior insulation skin, insulating glazing, a heat pump and PV panels (see more in Section 1.4). 'NZEB-light' refers to making a cost-efficient NZEB renovation concept.

We co-developed and tested 8 example circular building components in 5 stakeholder collaborations (see Table 1.1). These components were selected based on the interests of the involved housing associations and contractors, and their relevance to the renovation of Dutch, post-war, low-rise, social housing. Furthermore, this selection contained a wide spread of components with different characteristics in terms of technical design, supply-chain and business models.

1.3.2 Research goals

Through exploratory design and initial literature study, we identified 4 key questions in the design(ing) of circular building components; we developed these into our research goals. The first two of these research goals aimed to fill knowledge gaps in the design process and the latter two aimed to develop 'generalizable' knowledge from evaluating the developed circular building components. See Figure 1.5 for a scheme showing the relationship between our design goal and questions, design process, and the research goals. We distinguished the phases 'analysis', 'synthesis', 'simulation' and 'evaluation' in our design process, as described in the systematic design process of (e.g.,) Duerk (1993), Groat and Wang (2013), and Roozenburg and Eekels (1995). Note that Figure 1.5 simplifies our design process. In reality, many iterations of these phases occurred during the development of the circular building components.

To develop a circular component, we first needed to know 'how' to integrate circularity in the design of building components. We asked "which frameworks, methods or tools could support the 'synthesis' of circular building components?" Existing generative circular design frameworks were identified through a systematic literature review, including peer-reviewed, conference and professional sources. The frameworks were identified through Web of Science and Google Search engines using the following keywords: "circular economy" and "design" or "supply chain" or "business model" and "framework", "method" or "tool". We selected frameworks that support the design of a circular technical, industrial and/or business model and support the synthesis of a design proposal. We reviewed 36 frameworks and found that they remained fragmented and did not focus on building components (see also chapter 4.3). So, **our first research goal was to develop a synthesis tool for circular building components.**

After synthesizing different possible designs for circular building components, we needed to select the most circular building component – the 'ideal'. The question arose "which frameworks, methods or tools could help assess circularity in building components?" There were already many existing assessment methods and tools, however they remained fragmented (Sassanelli, Rosa, Rocca, & Terzi, 2019). They focused on a single, or a limited number of indicators. To assess circularity, a comprehensive, quantitative assessment method is needed (Bradley, Jawahir, Badurdeen, & Rouch, 2018; Buyle, Galle, Debacker, & Audenaert, 2019; Sassanelli et al., 2019). Multiple authors argue that integral circular assessment should include environmental, social and economic performance (Hunkeler, Lichtenvort, & Rebitzer, 2008; Sassanelli et al., 2019). Following our definition of CE, we considered that assessment should contain the environmental and economic perspectives.

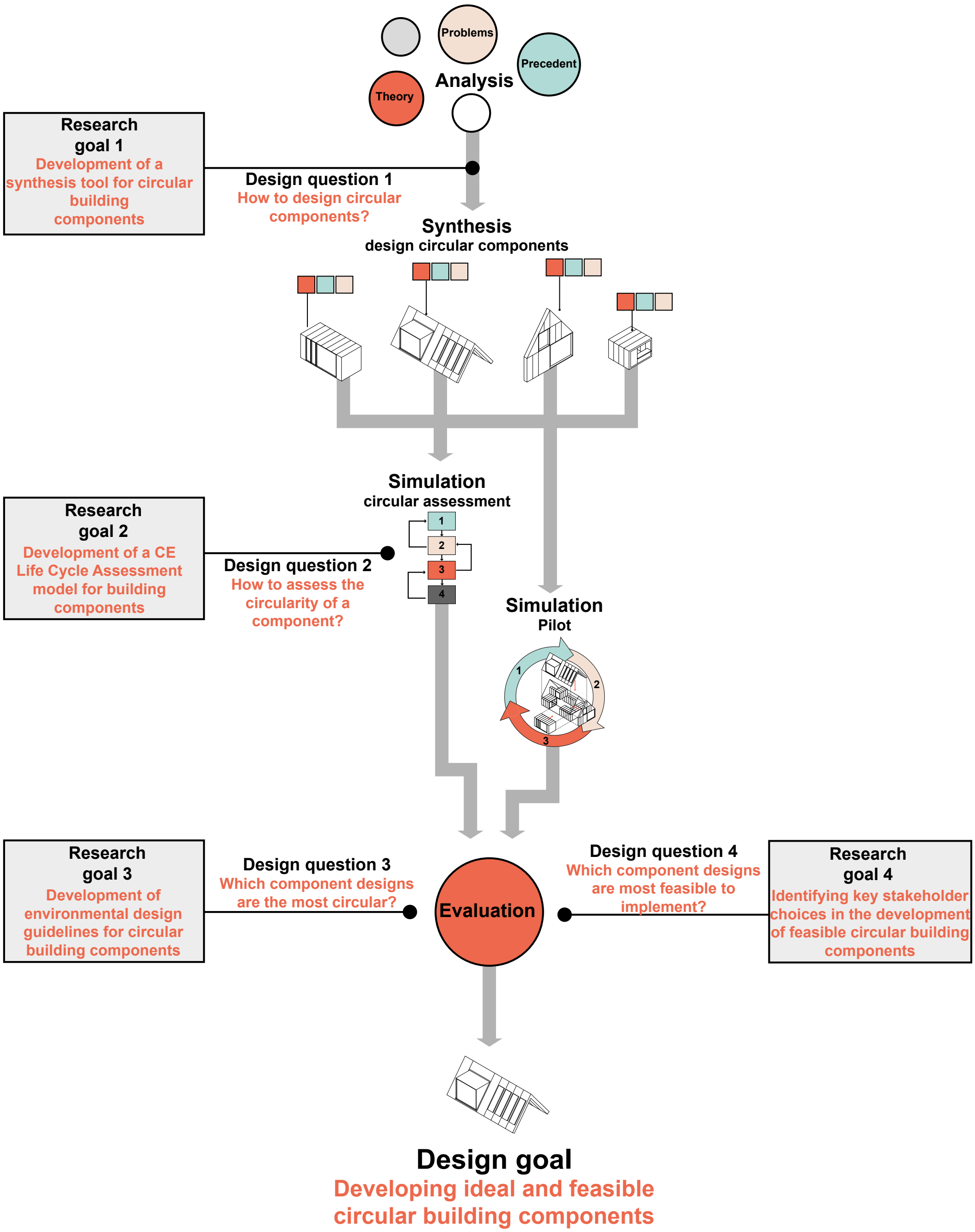


FIG. 1.5 Relationship between design goal and questions, design process and the research goals

Looking at the former, two methods are often identified to support environmental performance assessment in a CE context: Material Flow Analysis (MFA) and Life Cycle Assessment (LCA).

MFA can be used to analyse the resource use, consumption and quality of resource flows (e.g., virgin, renewable, recycled) over the lifecycle of the building component (Elia, Gnoni, & Tornese, 2017; Pomponi & Moncaster, 2017). There are two main types of LCAs: attributional and consequential LCA (Hauschild, Rosenbaum, & Olsen, 2018). Using attributional LCA we can account for the environmental impacts of resource flows that can be attributed to the lifecycle of a building component. Using consequential LCA, we can determine the environmental consequences of changes occurring in a building component system caused by varying the building component design (Finnveden et al., 2022, 2009; Malabi Eberhardt, Birgisdóttir, & Birkved, 2019). As such, consequential LCA may seem to better support decision-making between multiple design variants. Especially, if variants are optimizations of a business-as-usual design. However, the circular design variants assessed in this research varied on multiple design parameters simultaneously, resulting in an n-fold of (assumed) changes to the building component system. We considered that this complexifies the LCAs and hinders interpretation of the results. In line with Ekvall, Tillman, and Molander (2005) and Finnveden et al. (2022), we found that attributional LCA may also support decision-making and identifying the [design] variant with the lowest environmental impact. Furthermore, attributional LCA is more commonly applied in 'standard' LCAs in the building sector (Malabi Eberhardt, 2020). Therefore, we have chosen to focus on attributional LCA; any further mention of LCA in this dissertation refers to attributional LCA.

In standard LCAs in the building sector, environmental impacts are assessed over a single use-cycle of a building (component) (Hauschild, Rosenbaum, & Olsen, 2018; Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020; Suhariyanto, Wahab, & Rahman, 2017). Such LCAs do not fully capture the burdens and benefits of a CE (see Allacker, Mathieux, Pennington and Pant (2017); De Wolf, Hoxha and Fivet (2020); Malabi Eberhardt et al. (2020)). In a CE, building components should be considered as a composite of parts and materials with different and multiple use-cycles; to accurately compare their environmental performance, the LCA should include all these cycles. Therefore, **our second research goal was to develop a CE-LCA model for building components.**

Designers, policy makers, and other decision-makers could benefit from environmental design guidelines based on LCA and MFA assessments to support them in designing the most circular building components – ‘the ideal’. We found that existing environmental design guidelines for circular building components were based on assessments of singular building components, singular circular design options, applied different assessment methods and provided conflicting guidelines. Therefore, **our third research goal was to develop environmental design guidelines for circular building components through comparing the environmental performance of multiple circular design options for different components.** We compared their environmental performance through MFA and the CE-LCA model developed in research goal 2.

Finally, practice needs to be able to develop designs which are feasible to implement in projects and practice. Knowledge on which circular designs are feasible to implement remained limited. Existing studies on the feasibility of circular design options focused on building- or industry level, did not compare multiple circular design options and/or were based on interviews rather than observation. They listed barriers but did not identify their relative importance throughout the development process: what specific choices influenced how stakeholders perceive the feasibility of circular design options; when were these choices made; who made them; for what reason were these choices made as such? Therefore, **the fourth research goal was to identify which specific stakeholder choices throughout the development process led to circular building components which were considered feasible to implement in projects and practice, comparing multiple circular design options and different building components.**

1.4 Development context

The circular building components have been developed for the renovation of low-rise, post-war housing owned by Dutch social housing associations. This chapter briefly sketches this context and clarifies why this is a logical initial context for the development of circular building components. Furthermore, the knowledge we induced from the development of the 8 circular building components remains situated in this context. Our findings may not be generalizable to the development of other circular building components in other contexts. This description of the context may help to identify if and how conditions are similar or different.

1.4.1 The Netherlands, a favourable context for implementation of circularity

Governmental policy documents can provide a valuable insight in the priorities of countries and super national governmental bodies. The first country to implement the CE into national laws was Germany in 1996 with the enactment of the “Closed Substance Cycle and Waste Management Act” (Su, Heshmati, Geng, & Yu, 2013). Japan’s “Basic Law for Establishing a Recycling-Based Society” and China’s “Circular Economy Promotion Law of the People’s Republic of China” followed in 2002 and 2009, respectively (Geissdoerfer et al., 2017).

The European Union (EU) has also incorporated CE in their strategic goals in "the Circular Economy Strategy" (European Commission, 2015). In their policy, the EU has identified the built environment as a focus area. Looking at the member states of the EU, the Netherlands expressed the ambition to become ‘fully’ circular by 2050 (Ministry of infrastructure and the environment & Ministry of economic affairs, 2016). The Netherlands has since introduced "Circular transition agendas" (Rijksoverheid, n.d.). One solely focusses on the built environment and construction sector (see Transitieteam Circulaire Bouweconomie, 2018). CE has also gained momentum in Dutch practice observable by the growing number of CE conferences, networks, consultancy firms and practice publications. Both governmental policy and stakeholder interest make the Netherlands a favourable context for the development and testing of circular building components.

1.4.2 Renovation of housing

Housing forms an important part of the Dutch building stock. There are around 9 million addresses in the Netherlands of which nearly 8 million are residential (CBS, 2022). The Netherlands is experiencing a housing crisis. There is a need for 1 million new homes in the next decade (Coalitie Actieagenda Wonen, 2021). Simultaneously, the Netherlands is on the eve of a renovation wave in which existing dwellings are renovated to reduce their operational energy use. The governmental program "Versnelling verduuzaming gebouwde omgeving" (2022) contains the renovation aims for Dutch housing. Before 2030, the aim is to insulate 2.5 million owner-occupied homes and 1 million rental homes; 500.000 existing homes will transition from gas-fuelled climate installations to collective heat networks; in 1 million existing homes hybrid heatpumps will be installed. The priority of this program is on reducing operational energy use. Although renovations focusing on energy reduction can decrease operational

TOC

carbon emissions, they can add significantly to embodied impacts (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013). The governmental program therefore (briefly) states that applied renovation solutions should be circular. For this purpose, the Ministry of Interior Affairs is investigating if the norms regulating the environmental performance of materials used in buildings (the 'Milieu Prestatie Gebouw' or MPG) can be made stricter in 2025 (Rijksoverheid, 2021); they are researching if these norms can also become applicable to renovations. Such developments could increase the market demand for more circular renovation solutions, such as circular building components.

1.4.3 Social housing associations as initial target group

Social housing associations – and their tenants – were the primary target group for the circular building components. Social housing associations are a logical initial target group for several reasons. First, social landlords have a significant housing portfolio. In the Netherlands, one-third of the housing stock (i.e., ± 2,4 million homes) are owned by social housing associations. These large residential portfolios generate opportunities to have a significant impact on increasing resource efficiency and effectiveness. Furthermore, they create sufficient potential demand to make it attractive for supply chain partners to develop circular alternatives. Second, social landlords have the professional knowledge that is beneficial for implementing CE principles. Also, social landlords often work with a longer investment perspective than, for example, home-owners or private landlords. This generates a relatively favourable context for implementing CE principles. Finally, if circular business models indeed lead to a higher end-value of building materials and components, then the Total Costs of Ownership (TCO) or Total Cost of Use (TCU) may become lower, thus contributing to housing affordability.

1.4.4 The low-rise, post-war housing stock

This research focused on developing components for low-rise, post-war housing. The low-rise, post-war housing stock is a logical initial context for two reasons. First, the low-rise, post-war housing stock contains approximately 40% of the Dutch housing providing enough scaling potential for the developed circular building components. Second, dwellings from this era are more likely to be renovated due to their age and lower energy performance. However, the characteristics, renovation challenge and applied solutions vary in this housing stock.

The early post-war housing stock constructed from 1946 to 1969 was built to ease the housing shortage after World War II. There was both a shortage of construction materials and skilled construction workers. Incentivised by the government, the traditional construction practice was industrialised through standardised construction systems which aimed to produce as many dwellings, as fast and affordable as possible (Van Thillert, 2002). Housing constructed in this period is characterised by repetition and prefabrication. The early post-war housing makes up around one third of the total Dutch housing stock; a large part of this stock is still in ownership of the housing associations (Stutvoet, 2018). Stutvoet (2018), very aptly, summarized the challenge in the early post-war housing stock. The lifespan of these houses was meant to be 50 years. Yet, it is expected that they have to last for much longer than their intended lifespan (Thomsen, 2002; van Hal, 2008). If they are still in their original state, their technical and energetic performance is generally poor. Furthermore, the dwellings may not comply anymore to the changed requirements of present-day residents (de Vreeze, 2001; Liebregts & van Bergen, 2011).

Dwellings constructed between 1970 and 1990 form approximately 25% of the Dutch housing stock (CBS, 2011). The majority is located in ‘Bloemkoolwijken’ or ‘cauliflower neighbourhoods’ in English (Ubink & van der Steeg, 2001). These neighbourhoods were explicitly designed as a counter reaction to the monotonous housing of the early post-war living environments. The dwellings are characterised by low-rise, single-family dwellings and high-density, low-rise, multifamily housing with playful designs. Other parts of this housing stock can be found in city centres, as part of urban renewal projects. Due to the oil crisis in 1973, first energy-efficiency requirements were introduced for new construction. As a result, concrete floors were fitted with some insulation, double glazing became the standard for the ground floor and cavity walls were (partially) insulated.

In many dwellings, incremental improvements have been made. Housing associations agreed to improve the average energy performance of their housing stock to a ‘label B’ by 2021 (Minister voor Binnenlandse Zaken, Aedes, Vereniging Nederlandse Woonbond, & Vastgoed Belang, 2012). They applied measures such as placement of insulating glazing, applying cavity-wall, floor and roof insulation, installing photovoltaic (PV) panels and high-performance boilers. Energy label B was meant as an intermediate step towards CO_2 neutrality in 2050. However, applying incremental energy-efficiency measures can make future measures less feasible, creating a lock-in. To increase the pace in energy renovations, achieve a larger operational energy reduction and reduce costs, standardized renovation concepts were developed (Stutvoet, 2018). These concepts improve the energy performance of the building ‘in one go’ to net zero energy. They apply a combination of renovation measures such as renovating the exterior of the roof and façade, placing new window frames with triple glazing, installing PV panels and all-electric heat pumps. These concepts are named ‘Nul-Op-de-Meter (NOM) renovatie concepten' or ‘Net Zero Energy Building (NZEB) renovation concepts' in English. They were developed in the context of programs such as ‘Slim and Snel’, ‘the Stroomversnelling’ and ‘the Energiesprong’ (Stutvoet, 2018).

From our discussions with contractors and housing associations, we found that application of NZEB renovation concepts was still an exception in practice. The renovation practice is project driven; renovation ambitions and measures are determined per project. The NZEB concepts need to be an exact match for the project. Moreover, the costs of renovation to NZEB level can be recovered in the long-term but requires a high-up front investment. A compromise between the NZEB and incremental renovation was found in a ‘no-regret’ approach. No-regret renovations are aimed at getting a home in steps towards the desired end goal. Energy renovation measures which are considered feasible now are realized; renovation measures which are considered too expensive, risky or not mature are postponed to a later renovation cycle. However, the measures placed today already prepare and facilitate the envisaged next steps.

The developed NZEB renovation concepts and desired shift towards a no-regret approach formed the backdrop for the development of the circular building components. The idea of circular building components was in line with this ‘no regret’ approach, making it a logical next step for innovation. Instead of a ‘on-size-fits-all’ renovation concept, different circular building components can be mixed and matched to fit the specific ambitions within a renovation project. Furthermore, the components can be placed over multiple investment cycles to spread out the initial investment of renovation.

1.5 Approach and methods

This research looked past the existing to solve a problem in the built environment. Research which generates (practical) knowledge by action in reality, can be called ‘interventionist research’ (Lousberg & van Stijn, 2022). As these interventions need to be designed, such inquiries contain both research and design components. Frankel and Racine (2010) identified three types of relationships between these components: ‘Research for Design’ (RfD), ‘Research about Design’ (RaD) and

‘Research through Design’ (RtD). In RtD, the aim is to generate knowledge for a class of problems or products through design(ing) (Buchanan, 2001; Frankel & Racine, 2010). Applying Frankel and Racine’s (2010) framework, our research can be characterized as an RtD. By designing circular components, we learned how we should synthesize and assess them. In research goals 3 and 4, we used synthesis, simulation and evaluation of design variants to generate knowledge on developing ideal and feasible circular building components.

Our research also contained aspects of Action Research (AR). AR can be traced back to the ideas of Kurt Lewis (field of psychology) (Adelman, 1993), and has become a standard in organisational science (Huang, 2010). Like RtD, AR moves past research of the existing (typically the focus in empirical research): the goal is to change the existing reality to learn from it (Järvinen, 2007). Subsequently, the role of the researcher is active, instead of ‘only’ trying to understand the existing. The reflective cycle of ‘plan, act, observe, reflect’ (Carr & Kemmis, 1986) is used to extract knowledge; it is a highly contextualised research in which theoretic knowledge is induced. The proposed ‘changes’ in AR could be understood as the design proposals in RtD (see Figure 1.6). Next to the similarities between AR and RtD, there are distinct differences: in AR, the researcher involves the stakeholders who are affected by the research. This is not necessarily the case in RtD. Nevertheless, in our research, stakeholders played a key role in developing the designs of the circular building components and testing their environmental performance and feasibility in our third and fourth study (see Figure 1.7). Furthermore, they helped test and validate the results of all research goals. As we combined RtD with aspects of AR, we characterize our research approach as ‘Action Research-through-Design’ (ARtD).

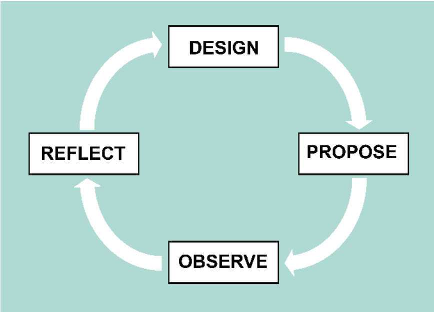


FIG. 1.6 Cycle of Action Research in RtD (Adapted from Carr and Kemmis (1986))

FIG. 1.7 Evaluation of the design variants of the circular skin by stakeholders during a workshop

1.5.1 Paradigm, ontological, epistemological and methodological considerations

In order to generate valid knowledge from the design(ing), a systematic ARtD approach is vital. In this section, we briefly describe the paradigm we adhered to. We reflect on what we considered is reality (i.e., ontology), how we knew something to be valid (i.e., epistemology) and how we went about finding knowledge (i.e., methodology). We refer to Chapter 3 for a more elaborate scientific background on our approach.

Both RtD and AR could be practised under various paradigms. Lousberg and van Stijn (2022) elaborated on this discussion and concluded that design-style interventionist research can be situated in the pragmatic paradigm. Pragmatism is characterised by its focus on the ‘problem at hand’ (Powell, 2001) and its pluralistic stance towards methods (Creswell, 2003). Methods are selected based on their ability to answer the research questions. Following Oquist (1978), AR can also correspond to the pragmatist view of how knowledge is produced and justified, and how theory and practice should relate. Van Stijn and Lousberg (2022) concluded that the pluralistic methodology of the researchers in RtD strongly suggests they are also pragmatists. Yet, they found this paradigm also underpinned with a ‘designerly truth’. In our research, we refer to and applied this sub-category of pragmatism, namely ‘designerly-pragmatism’.

How did we consider reality in our research (i.e., ontology)? We proposed an ontological model based on the models of Jonas (2006), de Jong (1992) and Duerk (1993). It shows ‘reality’ in RtD is transitional, linked to the stages of the design process. In our research this transitional view of reality is clearly visible: during ‘analysis’, we sought to understand how it is today (i.e., the existing), in ‘synthesis’, we investigated *possible* circular building components (i.e., the possible). However, the emphasis of our research lay in between revealing the *ideal* (i.e., desirable) and *feasible* (i.e., likely) reality during the ‘evaluation’ of the circular building components.

How did we know the knowledge we produced to be valid (i.e., epistemology)? Our research had both a research and design component. The former adhered to a pragmatic paradigm and the latter adhered to a designerly paradigm, each having their own criteria. The design activities underlied the research; we needed to make (the choices in) the design process understandable and retractable using criteria such as ‘strength of logic’ and ‘recoverability’ (Godin & Zahedi, 2014; Jonas, 2007). Concretely, this meant that we focused on understanding, planning and documenting our design process. For the research component, the appropriateness of the

TOC

methods was a vital criterion. Additionally, for each research goal, we aligned further validity criteria with the applied methods.

There are no agreed-upon research approaches and methods for an RtD. Yee (2010) even suggests that researchers should 'pick and mix' methods to develop a suitable model of inquiry. Lousberg and van Stijn (2022) pose the methods in RtD are pluralistic. Due to the wide range of research goals, we – indeed – found that our research methods varied per research goal. Yet, our overarching approach remained constant. The approach consisted of three elements (see Figure 1.8): (1) a research approach, (2) a systematic design approach, (3) and simulation and evaluation methods.

FIG. 1.8 Three parts of the applied approach

1.5.2 Research approach

Our research approach shows the steps on how we generated knowledge from the design process. We followed the models of Peffers et al. (2006), and van Aken and Romme (2009).

The research approach consisted of 6 steps (see Figure 1.9): in step 1, we identified problems and motivated why it is relevant to address them. In step 2, we defined the research goals and planning. In the planning we (tried to) plan the design process and determine which data was to be collected in the design process. In step 3, we developed the design. In step 4, we tested (i.e., simulated) the developed design. In step 5, we evaluated the tested design. From the evaluation, we derived knowledge. In step 6, we communicated the derived knowledge through, for example, academic papers and practice publications.

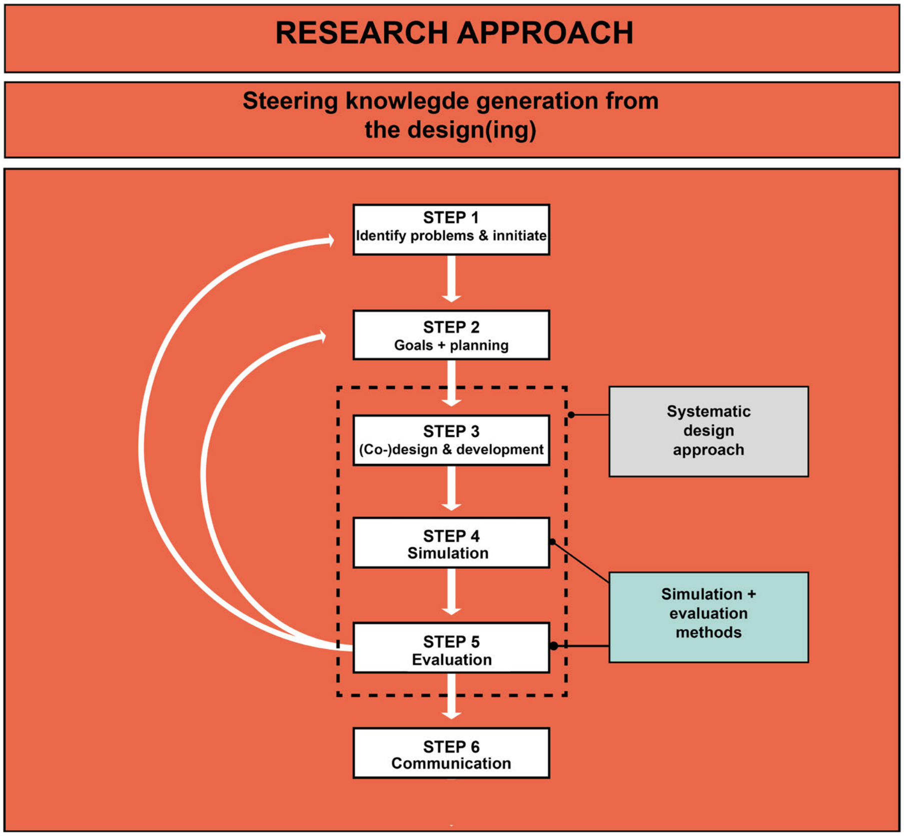


FIG. 1.9 Research approach

Although the steps themselves remained the same for all research goals, we specified the content of each step per research goal. In steps 3, 4, and 5 we determined how the design was developed (step 3); with what methods the design was tested (step 4) and with what criteria the design was evaluated (step 5). For each research goal, the research steps and applied methods are shown in Figure 1.11.

1.5.3 Systematic design approach

In step 2 of the research approach, the activities in the design process were planned. In design practice, the process of designing is often implicit (van Dooren, Boshuizen, van Merriënboer, Asselbergs, & van Dorst, 2014): it is the result which is communicated. However, for a valid RtD, understanding the activities in the entire

TOC

design process and knowing how they feed and drive the research is vital. We applied a systematic design approach to plan the development and testing of the circular building components (Figure 1.10).

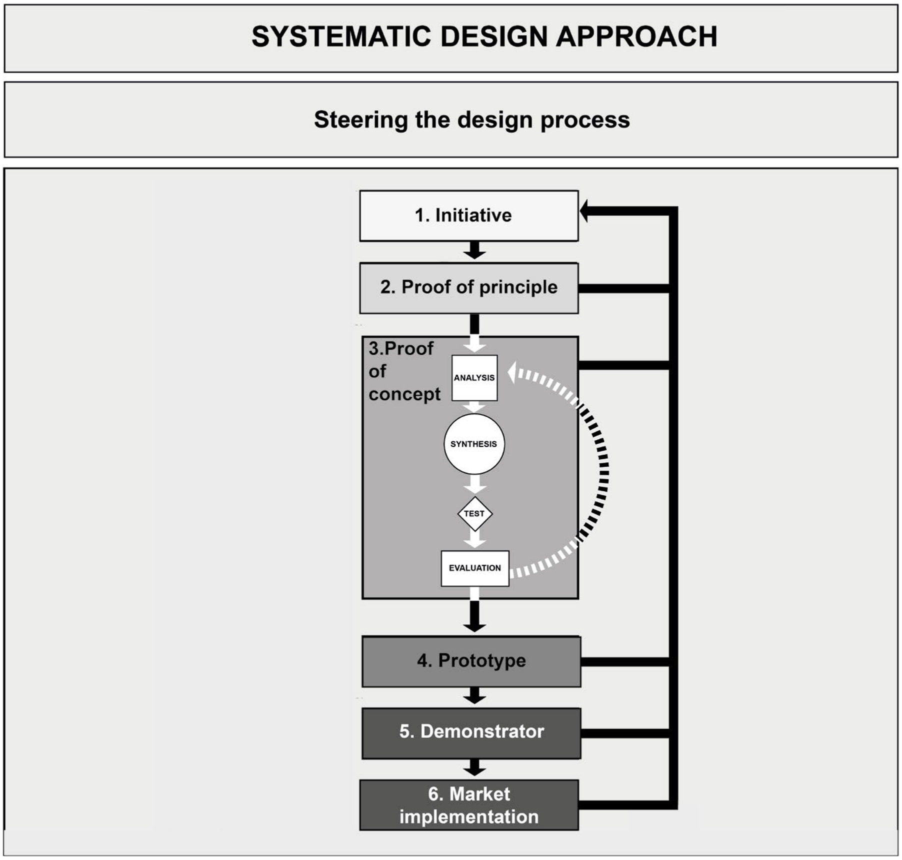


FIG. 1.10 Systematic design approach

We developed the building components following both product-innovation and building-project processes. Therefore, we merged the stages of the building design and realisation process models of Geraedts and Wamelink (2009) and NEN 2634, the product innovation phases model of Roozenburg and Eekels (1995) with Technology Readiness Levels. We distinguished the following (iterative) phases during the design process: (1) 'initiative', including start-up, analysis of the situation, and determining the program of requirements. (2) 'proof of principle' including sketch designs and variant studies, (3) 'proof-of-concept' including preliminary or definitive designs,

TOC

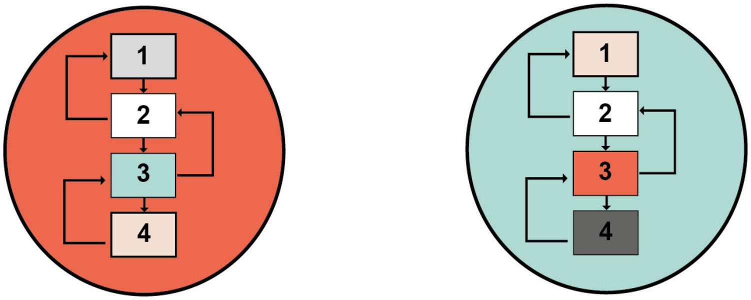
(4) ‘prototype’ including mock-ups, (5) ‘demonstrator’ including a test-home, pilots or a first project and (6) market implementation, meaning upscaling and application in multiple projects. In each stage we further distinguished 4 activities based on the Basic Design Cycle of Roozenburg and Eekels (1995): 'analysis', 'synthesis', 'simulation' (or test), and 'evaluation'.

Note that the real design process was not as sequential as planned; many iterations were needed and adjustment of the planning was an almost daily affair. Nevertheless, trying to steer the chaotic reality of the design process using the (overly structured) systematic design approach increased our understanding of the design process.

1.5.4 Simulation and evaluation methods

For each research goal, we selected the most suitable methods to derive knowledge from the design(ing). We understand methods as the ‘procedures and activities for selecting, collecting, organizing and analysing data’ (Blaikie, 2010, p. 8). Moreover, we used multiple methods in parallel (i.e., methodological triangulation). “The idea behind methodological triangulation is that the convergence of multiple methods upon a single conclusion better supports that conclusion than just one of those methods arriving at the conclusion.” (Heesen, Bright, & Zucker, 2019, p. 3068)

For each research goal, the research steps and applied methods are shown in Figure 1.11. These steps will be elaborated on further in the methods sections of Chapters 4-7.



Research goal 1

Development of a synthesis tool for circular building components

Steps

1. Identify problem | Review existing circular design frameworks to identify gaps existing tools and develop requirements tool.
2. Goals and planning
3. Analysis | Derive circular design parameters and options through systematic literature review existing tools.
3. Synthesis | Combine and specify parts of existing tools to develop the "circular building components generator" (CBC-generator).
4. Simulation | Apply tool in design of exemplary component and test tool in a workshop.
5. Evaluation | Evaluate developed tool to requirements (step 2) and with participants from workshop.
6. Communication | Publish in papers.

Research goal 2

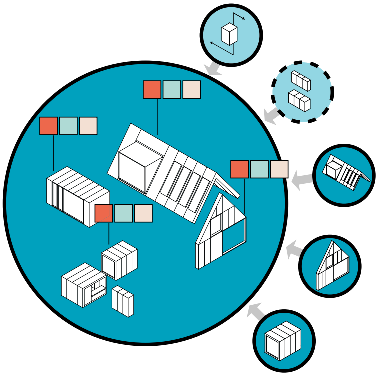
Developing a Circular Economy Life Cycle Assessment (CE-LCA) model for circular building components

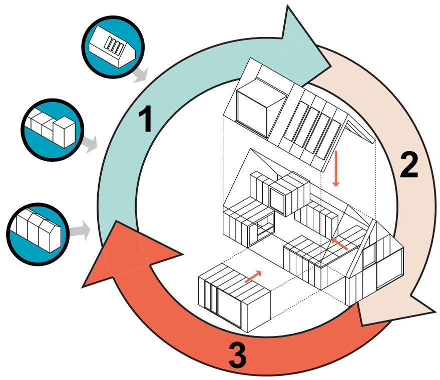
Steps

1. Identify problem | Compare key Circular Economy principles with existing LCA standards to identify gaps and requirements for the CE-LCA model.
2. Goals and planning
3. Synthesis | Develop initial CE-LCA model for circular building components.
4. Simulation | Test CE-LCA model in assessment of an exemplary circular building component.
5. Evaluation | Evaluate developed CE-LCA to requirements and reflect in expert sessions.
6. Communication | Publish in papers.

FIG. 1.11 Detailed research steps and applied methods per research goal

TOC





Research goal 3

Developing environmental design guidelines for circular building components

Steps

1. Identify problem | Study existing environmental design guidelines for building components to identify knowlegde gaps.
2. Goals and planning
3. Synthesis | Synthesize design variants for example circular building components.
4. Simulation | Assess the environmental perfor-mance of the circular building component design variants.
5. Evaluation | Quantitative derision environmental design guidelines from the assessment results and induction of lessons-learned.
5. Evaluation | Evaluate the environmental design guidelines with stakeholders and in expert sessions.
6. Communication | Publish in papers.

Research goal 4

Identifying key stakeholder choices in the development of feasible circular building components

Steps

1. Identify problem | Study existing literature on feasibility of building components to identify knowlegde gaps.
2. Goals and planning
3. Synthesis | Develop example circular building components together with stakeholders and work towards implementation in (partial) pilots and renovation projects.
4. Simulation | Test feasibility of design variants with stakeholders in co-creation workshops throughout the development and realization process.
5. Evaluation | Analyse choices and reasoning of stakeholders on feasibility of design variants; identify key stakeholder choices.
5. Evaluation | Evaluate identified key choices with stakeholders.
6. Communication | Publish in papers.

TOC

1.6 Scientific relevance

This study contributes to the scientific body of knowledge in the following ways.

First, most CE and circular design theories were focussed on the context of consumer products; research applying principles of the CE in the built environment was in its infancy (Ness & Xing, 2017). In this research, we explored circular design theories in the context of the built environment. This allowed us to add to existing CE and circular design theories; it provided us with the opportunity to reflect upon existing theories describing how we design, build and manage the built environment.

Second, existing studies on circular design in the built environment focused on building or material level; they focused on developing solutions for new construction rather than renovation and maintenance. In this study we developed knowledge on the design and realization of circular building components in the context on housing renovation.

Third, most research on sustainability in the built environment has focused on reducing carbon emissions from operational energy-use. In the context of Dutch social housing renovation, the emphasis on increasing the energy performance will remain a priority in the coming years. By developing circular building components in this context, we extended the theoretical perspective from reducing operational energy use to considering the environmental impacts of the materials used in the building.

Fourth, the few studies which have investigated the environmental performance or feasibility of circular design options in building components, have investigated singular circular design options and/or looked at singular building components. By developing and testing multiple components and including multiple circular design options, we compared them. Additionally, we also took multiple perspectives, comparing which circular designs were 'ideal' and which were 'feasible' to implement.

Fifth, through developing and testing in long-term co-creation with stakeholders from practice, our research provided more realistic and relevant knowledge on how to design a circular building component; how to select the most circular design; which circular design is the most circular and; which designs are feasible to realize in practice.

Finally, with this research we contributed to the body of knowledge on RtD methodology. RtD is a relatively young field and still in development (Dalsgaard, 2010; Findeli, 1998; Forlizzi, Stolterman, & Zimmerman, 2009; Meijers et al., 2015; Stappers & Giaccardi, 2017). For RtD, no agreed-upon research model exists and there is no overall consensus on definitions, paradigms or applied methods (Buchanan, 1992, 2001; Chow, 2010; Frankel & Racine, 2010; Godin & Zahedi, 2014; Langrish, 2016; Markussen, Krogh, & Bang, 2015; Stappers & Giaccardi, 2017; Zimmerman, Forlizzi, & Evenson, 2007). We experienced that these gaps can frustrate the application of RtD by beginning designer-researchers. In this research we further developed and exemplified the RtD approach.

1.7 Societal relevance

The societal relevance lies, firstly, in the development of feasible, circular building components. Through their potential implementation, we can directly contribute to reducing resource use, pollution, emissions and waste in the built environment. However, their development may have a wider influence on practice. These components can also serve as examples and may even be replicable in other projects. Our example components can also serve as a source of inspiration for those developing other circular components in the future. By co-developing these components together with practice stakeholders, experience with circular design was increased in practice as well as in science; practitioners will take this know-how with them in future projects. Second, by increasing concrete knowledge on the design and realisation of circular building components our research can support designers, policy-makers and other decision-makers in the built environment to develop more circular building components.

Integrating circularity in building components can also deliver other benefits for housing associations, residents, contractors, manufacturers and other stakeholders in the supply chain. We saw that developing circular building components can bring parallel opportunities to innovate and improve the business-as-usual practice. First, one of the key circular design strategies to slow future loops is to standardise building components. This increases opportunities for mass-production. Shifting from traditional construction to mass-production has the potential to boost productivity in the building sector by up to ten times (Barbose et al., 2017). This can contribute to solving the growing capacity problems in the sector (Economisch

TOC

Instituut voor de Bouw, 2018). Second, developing replicable building components may reduce the length and costs of the renovation process as solutions need not be developed from scratch for each individual project. Replicable components can also lead to a higher construction quality (de Ridder, 2011) as components can be continuously improved. If costs and benefits of circular building components are considered over the lifecycle, the Total Cost of Ownership (TCO) or Total Cost of Use (TCU) of building components may decrease. This leaves housing associations with more money left for their core tasks. Fourth, by applying replicable circular building components, the uncertainty of renovations can be reduced. Investment costs, TCO/TCU, product functionality and environmental impact can all be known up-front. This makes it easier for housing associations (and homeowners) to initiate and approve the renovation. Fifth, a circular business case can also lead to benefits for contractors, manufacturers, supplier and other supply-chain partners compared to a linear component. For example, they can gain from longer-term relationships with their clients, a larger market-share and more stable income source. Sixth, circular building components could significantly increase the choice and flexibility for users. A modular renovation allows users to determine the moment of renovation, when it is financially possible and convenient for them. If the components are designed for adjustments, it allows users to customise the building components to their needs and style now and in the future. Likewise, a modular renovation with circular building components gives more flexibility to housing associations as they can spread investments over multiple renovation cycli. Adjustable components may allow housing associations to adapt their housing portfolio to changing housing trends in the future. Finally, renovating with circular components could allow a different cycle of interventions in our housing stock. At the present day, improving a dwelling is a cumbersome process (Brinksma, 2017). So, we let the dwelling degrade far enough to justify the intervention. On average we only renovate dwellings in cycles of 25-30 years (Brinksma, 2017). A circular component which facilitates repair, reuse and adjustments could potentially allow more frequent, smaller improvements of parts of the building. As such we can keep the dwelling as a whole ‘up to the current need’ for much longer. This, in turn, could improve the living quality for residents.

1.8 Reading guide

This dissertation is structured as follows: in Chapter 2, we provided a scientific background. We discuss the concepts, theories and examples underpinning this research. We elaborated on CE, circular design and reviewed existing circular building examples. In Chapter 3, we also provided a methodological scientific background by reviewing RtD theory and positioning our approach in the methodological dialogue. In Chapter 4, we investigated how we can design circular building components by developing a circular design tool for building components. In Chapter 5, we explored how we can assess which component is most 'ideal' focusing on environmental impact assessment. We developed the Circular Economy Life Cycle Assessment (CE-LCA) model for building components. In Chapter 6, we researched which circular building component designs were most 'ideal', focusing on their environmental performance. By comparing the environmental performance of multiple circular design options for different circular building components using MFA and CE-LCA, we developed environmental design guidelines for circular building components. In Chapter 7, we investigated which specific stakeholder choices throughout the development process led to circular building components which were considered 'feasible' to implement in projects and practice, comparing multiple circular design options and different building components. In Chapter 8 we summarized and discussed our findings per research goal. We then shared our conclusions on our main goal: the development of ‘ideal’ and ‘feasible’ circular building components. We discussed the scientific contribution of our findings and provided recommendations for further research. Finally, we shared practice implications and recommended how practice can develop and implement more circular building components.

To increase the readability and consistency of our texts, we have used "we" throughout this dissertation. However, "we" can refer to different author(s). At the start of each chapter, we have indicated the author(s) who have contributed to that chapter.

References

Adelman, C. (1993). Kurt Lewin and the origins of Action Research. *Educational Action Research*, *1*(1), 7–24. https://doi.org/10.1080/0965079930010102

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, *22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Bakker, C., den Hollander, M., van Hinte, E., & Zijlstra, Y. (2014). *Products That Last*. Delft: TU Delft Library & Marcel den Hollander IDRC.

Barbose, F., Woetzel, J., Mischke, J., João Ribeirinho, M., Sridhar, M., Parsons, M., … Brown, S. (2017). *Reinventing construction: A route to higher productivity*. Retrieved from www.mckinsey.com/mgi.

Blaikie, N. (2010). *Designing social research: The logic of anticipation* (second edi). Cambridge, UK: Polity Press.

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bradley, R., Jawahir, I. S., Badurdeen, F., & Rouch, K. (2018). A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation. *Resources, Conservation and Recycling*, *135*, 141–149. https://doi.org/10.1016/j.resconrec.2018.01.017

Brand, S. (1994). *How Buildings Learn*. New York: Viking.

Brinksma, H. (2017). *Toekomstbestendig Renoveren*. Retrieved from http://www.lesvosnews.net/articles/news-categories/politiki/dimoskopisi-gia-galino-kalogiroy-voyleytes-lesvoy-ereyna-tis-kapa

Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design Issues*, *8*(2), 5. https://doi.org/10.2307/1511637

Buchanan, R. (2001). Design research and the new learning. *Design Issues*, *17*(4), 3–23. https://doi.org/10.1162/07479360152681056

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019). Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, *218*, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306

Cambier, C., Galle, W., & De Temmerman, N. (2020). Research and development directions for design support tools for circular building. *Buildings*, *10*(142), 1–20. https://doi.org/10.3390/buildings10080142

Carr, W., & Kemmis, S. (1986). *Becoming critical*. Lewes: Falmer Press.

CBS. (2011). Statistisch jaarboek. Retrieved June 17, 2018, from http://www.cbs.nl/statistischjaar-boek2011

CBS. (2022). StatLine - Voorraad woningen en niet-woningen; mutaties, gebruiksfunctie, regio. Retrieved July 20, 2022, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81955NED/table?fromstatweb

Chow, R. (2010). What Should be Done with the Different Versions of Research-Through-Design? In C. Mareis, G. Joost, & K. Kimpel (Eds.), *Entwerfen - Wissen - Produzieren* (pp. 1–12). https://doi.org/10.14361/transcript.9783839414637.145

Coalitie Actieagenda Wonen. (2021). *Samen werken aan goed wonen: Actieagenda Wonen.*

Creswell, J. W. (2003). *Research design: Qualitative, quantitative and mixed methods approaches* (second edi). London: Sage.

Dalsgaard, P. (2010). Research in and through design. *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction - OZCHI '10*, 200. https://doi.org/10.1145/1952222.1952265

de Jong, T. M. (1992). *Kleine methodologie voor ontwerpend onderzoek*. Amsterdam: Boom Meppel.

de Ridder, H. (2011). *Legolisering van de bouw*. Retrieved from https://vindboek.nl/legolisering-van-de-bouw-9789078171157

de Vreeze, A. S. G. (2001). *6,5 miljoen woningen: 100 jaar woningweten wooncultuur in Nederland*. Rotterdam: Uitgeverij 010.

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Duerk, D. (1993). *Architectural programming: Information management of design*. Wiley.

Economisch Instituut voor de Bouw. (2018). *Trends op de bouwarbeidsmarkt 2018-2023*. Retrieved from https://www.eib.nl/publicaties/arbeidsmarkt/trends-op-de-bouwarbeidsmarkt-2018-2023-2/

Ekvall, T., Tillman, A. M., & Molander, S. (2005). Normative ethics and methodology for life cycle assessment. *Journal of Cleaner Production*, *13*(13–14), 1225–1234. https://doi.org/10.1016/j.jclepro.2005.05.010

Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

European Commission. (2015). Closing the Loop - an EU Action Plan for the Circular Economy. In European Commission (Ed.), *614 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels.

Findeli, A. (1998). A quest for credibility: Doctoral education and research in design at the university of montreal. In R. Buchanan, D. Doordan, L. Justice, & V. Margolin (Eds.), *Doctoral Education in Design: Proceedings of the Ohio Conference* (pp. 99–116).

Finnveden, G., Arvidsson, R., Björklund, A., Guinée, J., Heijungs, R., & Martin, M. (2022). Six areas of methodological debate on attributional life cycle assessment. *E3S Web of Conferences*, *349*(03007), 1–6. https://doi.org/https://doi.org/10.1051/e3sconf/202234903007

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, *91*, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Forlizzi, J., Stolterman, E., & Zimmerman, J. (2009). From design research to theory: Evidence of a maturing field. *Proceedings of the 3rd Conference of the International Association of Societies of Design Research (IASDR'09): Rigor and Relevance in Design*, (October 2015), 2889–2898. https://doi.org/10.1016/j.biopsych.2008.07.017

Frankel, L., & Racine, M. (2010). The complex field of research: for design, through design, and about design. In E. Durling, D., Bousbaci, R., Chen, L, Gauthier, P., Poldma, T., Roworth-Stokes, S. and Stolterman (Ed.), *Design and Complexity - DRS International Conference 2010*. Retrieved from https://dl.designresearchsociety.org/drs-conference-papers/drs2010/researchpapers/43

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Godin, D., & Zahedi, M. (2014). Aspects of research through design : A literature review. In A. Lim, Y., Niedderer, K., Redström, J., Stolterman, E. and Valtonen (Ed.), *Design's Big Debates - DRS International Conference 2014* (pp. 1667–1680). Retrieved from https://dl.designresearchsociety.org/drs-conference-papers/drs2014/researchpapers/85

Groat, L. N., & Wang, D. (2013). *Architectural research methods* (second edi). Hoboken, NJ: John Wiley & Sons, Inc.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment: Theory and practice. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3

Heesen, R., Bright, L. K., & Zucker, A. (2019). Vindicating methodological triangulation. *Synthese*, *196*(8), 3067–3081. https://doi.org/10.1007/s11229-016-1294-7

Henry, Q. (2018). *Circular Facade Refurbishment*. Delft: MSc thesis, Delft University of Technology.

Huang, H. B. (2010). What is good action research? Why the resurgent interest? *Action Research*, *8*(1), 93–109. https://doi.org/10.1177/1476750310362435

Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). Environmental life cycle costing. In *Environmental Life Cycle Costing*. https://doi.org/10.1201/9781420054736

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Järvinen, P. (2007). Action research is similar to design science. *Quality and Quantity*, *41*(1), 37–54. https://doi.org/10.1007/s11135-005-5427-1

Jonas, W. (2006). Research through design through research: A problem statement and a conceptual sketch. *2006 DRS International Conference in Lisbon*. Retrieved from http://unidcom.iade.pt/drs2006/wonderground/proceedings/fullpapers/DRS2006_0230.pdf

Jonas, W. (2007). Design Research and its meaning to the methodological development of the discipline. In R. Michel (Ed.), *Design Research Now* (pp. 187–206). https://doi.org/10.1007/978-3-7643-8472-2_11

Langrish, J. Z. (2016). *The Design Methods Movement: From Optimism to Darwinism.* 1–13. Retrieved from https://static1.squarespace.com/static/55ca3eafe4b05bb65abd54ff/t/574f0971859fd01f18ec-63c1/1464797554420/222+Langrish.pdf

Liebregts, M., & van Bergen, Y. (2011). *Pamflet renovatie als Hollands herontwerp.* Boxtel: Aeneas.

Lousberg, L. H. M. J., & van Stijn, A. (2023). Positioning interventionist research methods. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods.* Taylor & Francis.

Malabi Eberhardt, L. C., Birgisdóttir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. *Building Research and Information, 47*(6), 666–680. https://doi.org/10.1080/09613218.2018.1517458

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Malabi Eberhardt, L. C. (2020). *Qualifying circular economy in building design practice: Developing Life Cycle Assessment design concepts that support implementation of circular economy in the building sector.* Aalborg: Aalborg University Press.

Markussen, T., Krogh, P. G., & Bang, A. L. (2015). On What Grounds ? An intra-disciplinary account of evaluation in research through design. *IASDR 2015 Congress*, 1–16. Brisbane, Australia: Queensland University of Technology.

Meijers, A., van Eijk, D., Hummels, C., Rapp, C., Schrijver, L., Teunissen, J., … van Kersen, J. (2015). *Call NWO creative industries: Research through design.* Den Haag: NWO, NRPO SIA & STW.

Minister voor Binnenlandse Zaken, Aedes, Vereniging Nederlandse Woonbond, & Vastgoed Belang. (2012). *Convenant Energiebesparing Huursector*. Den Haag.

Ministerie van Binnenlandse zaken en koninkrijkrelaties - Volkshuisvesting en ruimtelijke ordening. (2022). *Volkshuisvesting en ruimtelijke orde.* Den Haag: Ministerie van Binnenlandse zaken en koninkrijkrelaties - Volkshuisvesting en ruimtelijke.

Ministry of infrastructure and the environment, & Ministry of economic affairs. (2016). *The Netherlands circular in 2050.* 72. Retrieved from https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/documenten/rapporten/2016/09/14/circulaire-economie

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability*, *8*(937), 1–15. https://doi.org/10.3390/su8090937

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*, *260*. https://doi.org/10.1016/j.jclepro.2020.121134

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Oquist, P. (1978). The epistemology of Action Research. *Acta Sociologica*, *21*(2), 143–163. https://doi.org/10.1177/000169937802100204

Paduart, A. (2016). Circular Retrofit Lab. Retrieved October 28, 2022, from https://www.bamb2020.eu/topics/pilot-cases-in-bamb/retrofit-lab/

Peck, D. (2015). *Prometheus Missing: Critical Materials and Product Design.* https://doi.org/10.4233/uuid

Peffers, K., Tuunanen, T., Gengler, C. E., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2006). The design science research process: A model for producing and presenting information systems research. *DESRIST International Conference on Design Science Research in Information Systems and Technology*, 83–106. Claremont, CA.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Powell, T. C. (2001). Competitive advantage: logical and philosophical considerations. *Strategic Management Journal*, *22*(9), 875–888. https://doi.org/10.1002/smj.173

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Rijksoverheid. (n.d.). Omslag naar circulaire economie versnellen. Retrieved October 28, 2022, from https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/omslag-naar-circulaire-economie-versnellen

Rijksoverheid. (2021, March 11). Milieuprestatie voor gebouwen wordt 1 juli 2021 aangescherpt. Retrieved October 28, 2022, from https://www.rijksoverheid.nl/actueel/nieuws/2021/03/11/milieuprestatie-voor-gebouwen-wordt-1-juli-2021-aangescherpt
Roozenburg, N. F. M., & Eekels, J. (1995). *Product design: Fundamentals and methods*. Chichester: Wiley.
Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019
Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In M. Soegaard & R. Friis-Dam (Eds.), *The Encyclopedia of Human-Computer Interaction*. Retrieved from https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design
Stutvoet, E. (2018). *Energietransitie: Omarm de complexiteit*. Delft University of Technology, Delft.
Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: Moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020
Suhariyanto, T. T., Wahab, D. A., & Rahman, M. N. A. (2017). Multi-life cycle assessment for sustainable products: A systematic review. *Journal of Cleaner Production*, *165*, 677–696. https://doi.org/10.1016/j.jclepro.2017.07.123
Thomsen, A. (2002). De waarde van het bestaande: 10 redenen voor renovatie. *Paper Presented at the VIBA Jubileum Symposium*. Utrecht.
Transitieteam Circulaire Bouweconomie (2018). *Transitie-Agenda Circulaire Bouweconomie*. Retrieved from http://www.debouwagenda.com/actueel/downloads+en+brochures/handlerdownloadfiles.ashx?idnv=955001
Ubink, M., & van der Steeg, T. (2001). *Bloemkoolwijken: Analyse en Perspectief*. Amsterdam: SUN.
United Nations. (2013). *World Population Prospects The 2012 Revision Highlights and Advance Tables*. Retrieved from https://population.un.org/wpp/Publications/Files/WPP2012_HIGHLIGHTS.pdf
United Nations Environment Programme. (2020). *2020 Global status report for buildings and construction: towards a zero-emissions, efficient and resilient buildings and contruction sector*. Nairobi: United Nations Environment Programme.
United Nations Environment Programme. (2021). *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Retrieved from https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction
van Aken, J. E., & Romme, G. (2009). Reinventing the future: Adding design science to the repertoire of organization and management studies. *Organisation Management Journal*, *6*(1), 5–12. https://doi.org/10.1057/omj.2009.1
van den Berg, M. R., & Bakker, C. A. (2015). A product design framework for a circular economy. *PLATE Product Lifetimes And The Environment 2015*, 365–379. Nottingham: Nottingham Trent University.
van Dooren, E., Boshuizen, E., van Merriënboer, J., Asselbergs, T., & van Dorst, M. (2014). Making explicit in design education: Generic elements in the design process. *International Journal of Technology and Design Education*, *24*(1), 53–71. https://doi.org/10.1007/s10798-013-9246-8
van Hal, A. (2008). *Uitdagend en waardevol*. Delft: Delft University of Technology.
van Stijn, A., & Lousberg, L. H. M. J. (2023). Approaching Research through Design in the field of Architecture and the Built Environment: Relating to the history, key theories and discourse. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods*. Taylor & Francis.
Van Thillert, C. C. A. M. (2002). *Consumentgerichte industrialisatie in de woningbouwsector*. Delft University of Technology.
Wamelink, H., Geraedts, R., Hobma, F., & Lousberg, L. (2009). *Inleiding Bouwmanagement*. Delft: VSSD.
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857
Yee, J. S. R. (2010). Methodological innovation in practice-based design doctorates. *Journal of Research Practice*, *6*(2), 1–23. Retrieved from https://files.eric.ed.gov/fulltext/EJ935247.pdf
Zimmann, R., O'Brien, H., Hargrave, J., & Morrell, M. (2016). *The Circular Economy in the Built Environment*. https://doi.org/http://dx.doi.org/10.1016/j.ecoser.2013.04.008
Zimmerman, J., Forlizzi, J., & Evenson, S. (2007). Research through design as a method for interaction design research in HCI. *SIGCHI Conference on Human Factors in Computing Systems*. San Jose, USA.

2 Scientific background

Approaches to circularity

The review of circular building approaches in Section 2.3 has been published as a part of van Stijn, A., & Gruis, V. H. (2019). Circular Housing Retrofit Strategies and Solutions: Towards Modular, Mass-Customised and 'Cyclable' Retrofit Products. *IOP Conference Series: Earth and Environmental Science, 290*(1), 012035. https://doi.org/10.1088/1755-1315/290/1/012035

A van Stijn[1,2]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

In this scientific background chapter, we introduce key concepts, theories and examples underpinning our research. In Section 2.1, we elaborate on the linear economy, introduce the Circular Economy (CE) concept and discuss the relationship between CE and sustainability. Section 2.2 discusses key theories on circular design. In Section 2.3, we review and categorize existing examples in the built environment which apply circular design strategies; through analysis, we identify gaps and promising initial directions to integrate CE into the built environment and – specifically – in the renovation of Dutch, post-war, low-rise, social housing.

2.1 A background on circular economy

Without claiming to be comprehensive, this section introduces the CE concept in more detail. In Section 2.1.1 we elaborate on the effects of the current linear economy to show why the transition to a CE is needed; in Sections 2.1.2-3 we introduce and define the CE. In Sections 2.1.4-5 we discuss Value Retention Processes (VRPs) as a key concept to operationalise the CE. In Section 2.1.6, we relate the CE concept to the sustainability concept. In Section 2.1.7, we provide a short conclusion of this background on CE.

2.1.1 From a linear economy…

Throughout most of the past century real resource prices declined, supporting economic growth (McKinsey Global Institute, 2011). Low resources prices in relation to high labour costs have fuelled a wasteful economic model. This economic model has been described as a linear economy, or ‘take-make-use-dispose economy’ (Ellen MacArthur Foundation, 2013). See Figure 2.1 for a visualisation of the linear economy. Companies extract materials, use energy and resources to manufacture products or construct buildings. The consumer owns the product and then disposes of it when it is broken, has lost its economic value or no longer serves the user’s needs.

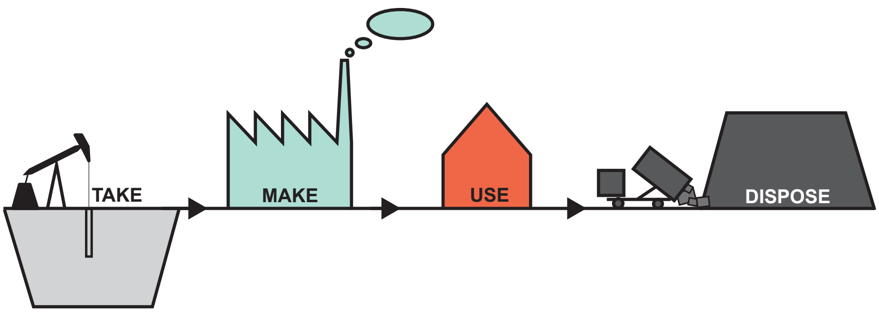


FIG. 2.1 The linear economy of ‘take-make-use-dispose’

Economic growth in the linear economy is created by increasing sales of materials, parts, products and buildings throughout the supply chain. Subsequently, growth comes from the extraction of more resources, the use of more energy and the generation of more waste.

At the front-end of the linear economy, more-and-more resources are extracted. The building sector is said to be responsible for 40% of global material consumption (Ness & Xing, 2017). Around 10% to 15% of building materials are directly wasted during construction activities (Ellen MacArthur Foundation, 2015). Humanity already consumes more than the Earth's ecosystems can sustainably (re)generate and, subsequently, erodes and depletes the world's natural resource capital (Ellen MacArthur Foundation, 2013). Increased demand for resources can also cause increased prices and price volatility (McKinsey Global Institute, 2011). It is not likely that we will run out of resources in the coming decade. However, mining all resources in the earth may not be technically or economically viable. For example, reserves for zinc and chromium, used in (e.g.,) rainwater drainage, roofing, façade cladding and climate installations, are predicted to be depleted in 2030 and 2033, respectively. Reserves for copper – used in pipes and electronic parts in buildings – are estimated to last until 2054 (Remondis Group, 2022). For some resources, supply risks are related to geopolitical and economic changes (Peck, 2015). We speak of 'critical materials' when materials which have supply risks have significant strategic and economic importance and, currently, cannot be replaced by other materials. The European Union list of critical raw materials (2020) now contains 30 materials. For example, lithium, a material used in batteries is included on this list. Lithium batteries may play a crucial role in the transition from fossil fuels to sustainable energy in the built environment.

Taking, making, using and disposing of resources also results in environmental impacts, such as carbon emissions. Energy is used to extract resources, to manufacture materials, to construct and demolish buildings, and dispose of materials. This energy use – and the related environmental impacts – are embodied in the building. This has been referred to as 'embodied energy', 'embodied carbon', or if more environmental impacts are considered 'embodied impacts'. Next to their embodied energy, buildings consume energy throughout the use phase. All in all, the building sector is responsible for approximately 38% of all human-induced CO_2 emissions of which 10% can be attributed to the production of materials needed to build, maintain and renovate the built environment (United Nations Environment Programme, 2020). Carbon emissions from operational energy use represent a larger share than embodied carbon. So, research, practice and regulations initially focussed on operational energy reduction. However, various studies have now shown that the embodied energy could be a larger share than initially thought (Itard, 2009; Pomponi & Moncaster, 2016). The importance of embodied carbon grows when the energy-mix has a larger share of renewable energy; when dwellings are made more

TOC

energy efficient as both the operation energy use is lowered and more (impactful) materials are added (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013; Pomponi & Moncaster, 2016).

Finally, the linear economy generates waste throughout the take, make, use and disposal stages. The building sector is said to generate 40% of global waste (Ness & Xing, 2017). Globally, 54% of demolition materials are landfilled. Due to the presence of toxic elements, most materials are unsuitable for reuse (Ellen MacArthur Foundation, 2015). Recycling rates are only high for a few waste flows: those that are generated in large, homogeneous volumes. Waste may not be easy to separate into homogenous material flows or it is not technically or economically viable to recycle. Also, recycling may actually be 'downcycling'. For example, concrete demolition waste may be recycled as road-fill. Although this means that the material has a second use, the second use is likely also its last application. We speak of downcycling when the value of the material after recycling is lower than before.

'Eco-efficiency' principles or 'Lean manufacturing' principles have been introduced to reduce resource use, environmental impacts and waste generation in the linear economy; and to minimise costs throughout the supply chain. However, this will ultimately only optimise a model which incentivises the use of more and more resources. Pressure on resources and the environment is expected to rise as the world's population is predicted to increase to around 9.6 billion people in 2050 (United Nations, 2013); the middle-class population is expected to rise with 3 billion by 2030 (Ellen MacArthur Foundation, 2013). In Asia and Africa, the building stock is expected to double by 2050 (United Nations Environment Programme, 2021). In nations in the northern hemisphere, 75–90% of the existing building stock will be still be standing in 2050 (IEA, 2014; Pomponi & Moncaster, 2017). To reduce carbon emissions from operational energy use, energy renovations of existing buildings are stimulated. Such renovations require an influx of building materials now. Global material use is expected to more than double by 2060; a third of this rise is predicted to come from materials used in the building sector (United Nations Environment Programme, 2021). A radically different approach is needed to build, maintain and renovate buildings in the future.

2.1.2 … to a circular economy!

The CE proposes an alternative, more resource-effective economic model by decoupling resource consumption from economic growth.

TOC

The CE is not a new concept and is based on a combination of previously developed schools of thought. These include 'Industrial Ecology (IE)' (Ayres & Ayres, 2002; Graedel & Allenby, 2003) 'Regenerative design' (Lyle, 1994), 'The performance economy' (Stahel, 2006), 'Biomimicry' (Benyus, 1997), and 'Cradle-to-Cradle' (C2C) (McDonough & Braungart, 2002). In turn, their ideas can be traced back to works such as "Silent Spring" by Carson (1962), "The Economics of the Coming Spaceship Earth" by Boulding (1966) and Commoner's (1971) "Four Laws of Ecology" (Bocken, de Pauw, Bakker, & van der Grinten, 2016).

The CE is based on the following main principles: "(1) preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimizing resource yields by circulating products, components, and materials at the highest utility and value at all times in both the technical and biological cycles; and (3) fostering system effectiveness by revealing and designing out negative externalities." (Ellen MacArthur Foundation, 2013). Figure 2.2 shows the 'Butterfly model' by the Ellen MacArthur Foundation (2013), which provides a well-known representation of the CE.

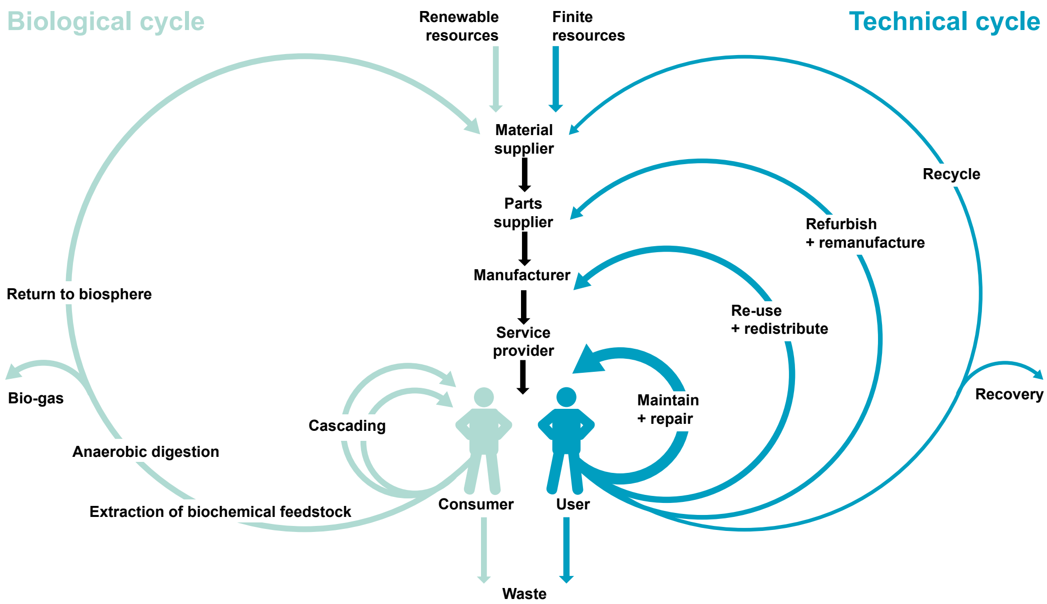


FIG. 2.2 The butterfly model (Adapted from the Ellen MacArthur Foundation (2013))

The CE concept is quickly gaining momentum. The efforts of the Ellen MacArthur Foundation have popularised the concept in practice. The CE has been included in governmental policy (see Section 1.4.1). At the start of this research, scientific publications on CE were increasing. In 2014, 30 peer-reviewed articles on CE were published and more than 100 in 2016 (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). However, research on CE in the context of the built environment was still at its infancy (Ness & Xing, 2017).

2.1.3 Defining circular economy

There is no consensus on the definition of CE. Kirchherr, Reike and Hekkert (2017) conclude that there are more than 114 definitions of the CE in use. Some definitions interpret the CE in a narrow way: to create an economic model which incentivises resource efficiency and effectiveness. This interpretation focuses on the 'planet' and 'prosperity' perspectives. On the other hand, some definitions propose a much wider interpretation of the CE model by including the 'people' perspective. Although a wider definition might be more holistic it also risks making the transition to a CE more complex.

For the purpose of this research a clear definition is required. We have chosen to apply a definition which is comprehensive but applies a narrow focus. This allows us to focus on facilitating and incentivizing reducing resource use, environmental impacts and waste in the development of circular building components. Following the definition of Geissdoerfer et al. (2017, p. 759), we understand CE as "a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". The fundamental strategies narrowing, slowing and closing loops were introduced by Bocken et al. (2016) (see Figure 2.3). 'Narrowing loops' is to reduce resource use, or achieve resource efficiency. 'Slowing loops' is to slow down the flow of resources through extension or intensification of the utilization period. 'Closing loops' is to (re) cycle materials from end-of-life back to production.

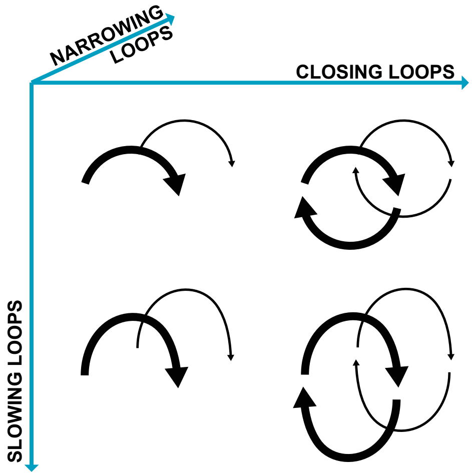


FIG. 2.3 Narrowing, slowing and closing the loop framework. Image adapted from Bocken et al. (2016) Journal of Industrial and Production Engineering © copyright #2016, reprinted by permission of Informa UK Limited, trading as Taylor & Taylor & Francis Group, http://www.tandfonline.com

2.1.4 Value retention processes

Loops can be narrowed, slowed and closed through Value Retention Processes (VRPs), or R-imperatives (Blomsma, Kjaer, Pigosso, McAloone, & Lloyd, 2018; Nasr et al., 2018; Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Different R-frameworks have been proposed, such as the 3R, 4R, 6R, and 9R frame. The source from which the R-frames originated cannot easily be traced (Kirchherr et al., 2017; Sihvonen & Ritola, 2015; Yan & Wu, 2011). The 3R framework includes the actions (1) Reduce, (2) Reuse and (3) Recycle. The more extensive frameworks are the 6R frame by Sihvonen and Ritola (2015) and the 9R frame by van Buren, Demmers, van der Heijden and Witlox (2016) and Potting, Hekkert, Worrell and Hanemaaijer (2017). The various frameworks do not only vary in number of R-imperatives, but also in their meaning. The models show a hierarchy in R's: the first Rs are 'more circular' than the last. For example, it is considered more circular to not built a house at all than to recycle its materials after use.

There is no consensus amongst researchers and practitioners on which framework to use. We combined the framework of narrowing, slowing and closing loops with the VRPs from the 9R-framework by Potting et al. (2017); we specified the definition of each VRP to the context of building components. See Figure 2.4 for the VRP framework we applied in this dissertation.

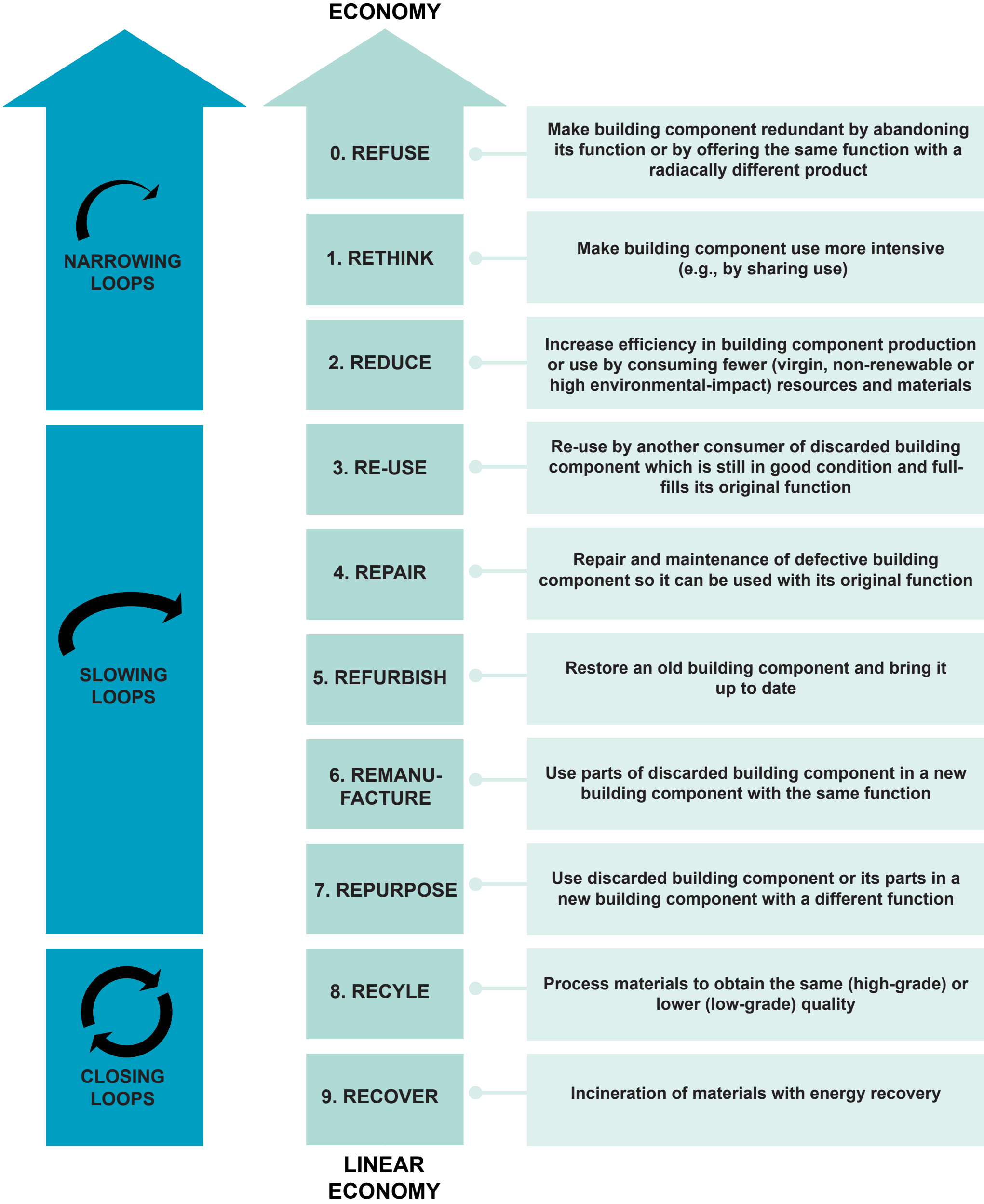


FIG. 2.4 Value Retention Process (VRP) framework applied in this dissertation

2.1.5 Open loops vs closed loops

Loops in the CE can be ‘open loops’ or ‘closed loops’ influencing what shape a CE will take.

In recycling theory, closed loops refer to recycling for the same quality or use (Huysveld, Hubo, Ragaert, & Dewulf, 2019). In circular supply chains, closed loops may refer to VRPs realised by the industry(partners) involved in the original production (French & LaForge, 2006; Genovese, Acquaye, Figueroa, & Lenny Koh, 2017). Resources are cycled within a closed network of supply-chain partners and might even be kept in their ownership. For example, Apple products are designed so they can only be repaired and refurbished by Apple’s specialists. Their products have ‘unique’ joints which can only be opened using special tools. Moreover, they have discouraged do-it-yourself repairs through voiding the warranty when a product is opened by the user or third parties. Likewise, Mitsubishi offers elevators through their ‘M-use®’ leasing model. They maintain ownership of the building component and, hence, keep the resources in their value chain. Through a closed-loop approach, it is easier to control the flow of resources to ensure they are cycled at highest utility and value. It also gives suppliers and manufacturers a clear incentive to develop designs which can be easily repaired, reused, refurbished and recycled. On the other hand, in a closed-loop CE, control and ownership of resources may become consolidated in the hands of (a few) corporations.

In an open-loop CE, resources cycle from user to user through platforms and companies which offer make, use and re-make services. Fab-labs can provide tools with which one ‘can manufacture almost anything’ (Gershenfeld, 2005; Toxler, 2011). Makerspaces (e.g., RDM-makerspace in Rotterdam) are places in which people with shared interests can gather to work on projects while sharing ideas, equipment, and knowledge (adapted from: Oxford english dictionary, 2018). Platforms such as Air-B&B facilitate the sharing of buildings between users. Platforms, such as ‘e-bay’ or ‘Marktplaats’, allow users to re-sell their resources. Maintenance companies or repair cafes provide services and/or open platforms to repair products. The open-loop CE can ensure continuing access to resources and the means of production. However, fragmentation of stakeholders might make resource flows harder to control, inhibiting the cycling of resources at their highest utility and value.

2.1.6 On the relationship between circular economy and sustainability

In Section 2.1.2 we proposed that the CE model can help the transition to a more resource effective society. Next to the CE concept, the term 'sustainability' can also be used when searching for ways to take better care of our environment. Both the CE and sustainability concepts have increasingly gained traction with academia, industry, and policymakers (Geissdoerfer et al., 2017). In this section we define the term sustainability, identify its similarities and differences with the CE concept and discuss the relationship between both. Our purpose is to clearly frame the CE concept as applied in this research and, so, to provide more transparency on our research scope.

The term sustainability originates from the French verb *soutenir*, meaning to hold up or support. The concept originates from 18th century forestry and was written down in 'Sylvicultura oeconomica' (von Carlowitz, 1713). Herein sustainability is the principle that the amount of wood harvested should not exceed the amount that can grow again. The concept's uptake can be traced back to increasing evidence of global environmental risks, such as ozone depletion, climate change, and biodiversity loss. These risks have been systematically investigated since the 1960s. Their findings raised the question if prosperity growth could be maintained into the future (Geissdoerfer et al., 2017). Commoner (1971) and Holdren and Ehrlich (1974) captured the causes behind environmental impact in the following equation: $I = P \times A \times T$. In which I is the environmental impact; P is the population; A is the affluence rate and T the technological advancement. The sustainability concept was coined as a solution. The Brundtland Commission provided the most commonly accepted definition of sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development (WCED), 1987) Within a sustainable development, the performance on three pillars is balanced: the so-called triple bottom line of people, planet and profit (Elkington, 1997).

So how does the CE concept relate to sustainability? As applied definitions on CE and sustainability vary, so does their relationship. Looking at how the concept of sustainability was understood in the 'sylvicultura oeconomica', we might argue that CE and sustainability are closely related concepts indeed. Geissdoerfer et al. (2017) extensively discussed the similarities and differences between both concepts. They found similarities in the need for an integral and systemic approach and a global, multi-stakeholder commitment. Yet, sustainability and CE have different origins, goals, motivations, system prioritisations, institutionalisations, beneficiaries, timeframes and perceptions of responsibilities. Notably, sustainable development has

TOC

an open-ended goal: it can include a multitude of goals and these goals can change over time and according to the context. The CE concept has a close-ended goal. It focuses on narrowing, slowing closing resource loops.

In line with the findings of Geissdoerfer et al. (2017), we conclude that sustainability and CE are related but should not be confused. We understand CE as the sustainability of resource use, in which a 'prosperity' incentive is sought that drives improvements for the 'planet'.

2.1.7 Conclusions on the background to circular economy

Without claiming to be comprehensive, this section introduced the Circular Economy (CE) concept in more detail. We elaborated on the effects of the current linear economy to show why the transition to a CE is needed. We introduced the CE concept and have chosen to apply the definition of Geissdoerfer et al. (2017, p. 759) in this research: "a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". We discussed Value Retention Processes (VRPs) or 'R-imperatives' as key actions to operationalise the loops in a CE. We developed a VRP framework for use in this research: we combined the framework of narrowing, slowing and closing loops by Bocken et al. (2016) with the 9R-framework by Potting et al. (2017). We discussed 'open loops' and 'closed loops' in a CE. We discussed the effects of both loop types on who controls resources and if resources are likely to be cycled at highest utility and value. Finally, we related the CE concept to the sustainability concept. In line with the findings of Geissdoerfer et al. (2017), we concluded that sustainability and CE are related but should not be confused. We understand CE as the sustainability of resource use, in which a 'prosperity' incentive is sought that drives improvements for the 'planet'.

2.2 Approaches in circular design

In Section 2.1, we found that the transition towards a CE requires us to narrow, slow and close resource loops; VRPs can help to achieve this. But how can we *design* to facilitate and stimulate these VRPs? In this section we elaborate on key circular design theories and explore their applicability to the development of circular building components. In Section 2.2.1 we discuss the concept of a ‘systems approach’ and develop a systems model for use in this dissertation. In Section 2.2.2, we briefly explain the term ‘integral approach’ and discuss how we understand this approach in the context of circular building component design. In Section 2.2.3, we provide a background on circular design strategies. Building on existing research, we propose a framework of circular design strategies and provide definitions used in this research. In Section 2.2.4, we elaborate on existing theories on circular business models and explore how these are applicable in the development of circular building components. In Section 2.2.5, we provide a short conclusion for the abovementioned sections.

2.2.1 A systems approach

Various authors suggest that making a circular design requires a 'systems approach'. See for example Bocken et al. (2016), Geldermans (2016), Mendoza, Scharmina, Gallego-Schmid, Heyes and Azapagic (2017), Mestre and Cooper (2017), Pomponi and Moncaster (2017), Saidani, Yannou, Leroy and Cluzel (2017) and Pieroni, McAloone and Pigosso (2019)). A systems approach means that the whole design system is considered. Design in the built environment stretches from the super-national scale to the material scale. These scales (or system layers) are traditionally divided into design specialisations, such as urban-designer, architect, building construction specialist, interior designer, window-frame designer, etc. Each of the elements of the building system has their own characteristics and lifespan, but are joint to each other (c.f. Brand, 1994; Habraken, 1961).

The model of Jager (2002) shows how the system of the building is related with the product level (see Figure 3.3). His model dissects the building layer into a tree of products and parts. Geldermans (2016) proposes a circular design matrix. In this matrix designers divide the building into ‘site’, ‘structure’, ‘skin’, ‘setting’, ‘service system’, and stuff; these ‘s-layers’ are then further divided into components, parts and materials. The matrix forces designers to consider the loops of each element of

TOC

the building system in cohesion. This way of designing prevents that one element (accidentally) becomes a 'weak link'. Weak links may cause premature obsolesce of a larger part of the building system or even the entire system. With a systems approach the scope of the design is stretched: the effects of design choices are considered in the wider system. For example, cotton clothes may be recycled to cotton insulation. When applied in a building this material may be considered a circular choice. It is a recycled material and – as such – has a low environmental impact. However, when increasing application of this insulation material triggers the production of more, impactful, virgin-cotton clothing, another insulation material may become a more circular choice. A systems approach ensures that no undesirable rebound effects are caused, or environmental burdens shifted from one system to the next.

Building on these above-mentioned models we propose that circular design requires a systems approach, in which we distinguish system-layers from the planetary scale to the material scale. Although we focus on the design of the building component, the cohesion and relation with the other system layers should always be considered. See Figure 2.5.

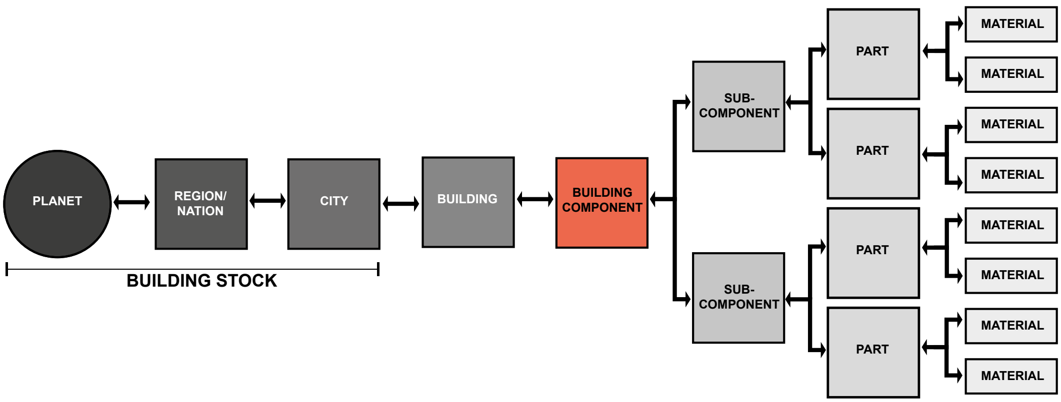


FIG. 2.5 Systems approach for circular design in the built environment: focussing on building component level

2.2.2 Integral approach

Many authors suggest that an integral approach is needed to make a circular design. (e.g.,Bocken et al. (2016), Mendoza, Scharmina, Gallego-Schmid, Heyes and Azapagic (2017), Mestre and Cooper (2017), Pomponi and Moncaster (2017), Saidani, Yannou, Leroy and Cluzel (2017)). Bakker, den Hollander, van Hinte and Zijlstra (2014), Bocken et al. (2016) and Moreno, De los Rios, Rowe, and Charnley (2016) proposed that the circular business model and the circular technical design need to be considered simultaneously. The design facilitates circularity; the business model incentivises it. For example, if the business model makes it cheaper to buy a new building component, part or material, then it is unlikely that these will be repaired. Even though they may have been designed for easy repairs. Bocken et al. (2016) concluded that, next to designing the business model and design model, the supply-chain (or industrial) model needs to be considered as well. In a circular supply chain, the circular activities are organised.

In line with these authors, we pose that an integral approach is needed to make a circular building component design which facilitates, incentivises and organises VRPs along its lifecycle. In this integral approach the technical model (i.e., design), the supply-chain model and the business model are developed in cohesion. See also Figure 2.6.

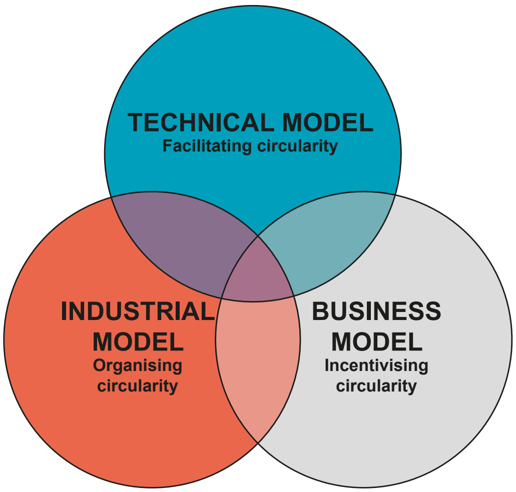


FIG. 2.6 Integral approach for circular building component design

TOC

2.2.3 Circular design strategies

To facilitate VRPs in the technical model, various authors have proposed circular design strategies. For examples we refer to Bakker et al. (2014), Bocken et al. (2016), Moreno et al. (2016), van den Berg and Bakker (2015) and Gerritsen (2015). These strategies often re-frame and build upon the so-called Design-for-X strategies (DfX). Examples of DfX's are 'Design for Recycling' and 'Design for Disassembly'.

A well-cited framework is that of Bocken et al. (2016). It builds upon literature and describes 6 product design strategies to slow loops: (1) design for attachment and trust, (2) design for reliability and durability, (3) design for ease of maintenance and repair, (4) design for upgradability and adaptability, (5) design for standardisation and compatibility, and (6) design for dis-, and re-assembly. They included the following design strategies to close loops: (7) design for a technological cycle, (8) design for a biological cycle, and (9) design for dis-, and re-assembly. Just as the VRP framework knows a hierarchy of R-imperatives, so is this circular design strategies framework ranked. The first circular design strategies keep the product longer in its original form. The less intervention is needed to keep a product functioning, the more circular a strategy is considered. Notably, Bocken et al. (2016) did not include design strategies to narrow loops. But the authors suggest that narrowing loops would involve resource efficiency measures in the technical design and manufacturing processes. In the frameworks of van den Berg and Bakker (2015), and Gerritsen (2015), circular design strategies are further specified with circular design options. For example, applying standardised measurements is a circular design option to design for standardisation and compatibility. By providing design options, these frameworks give more concrete support in designing a circular product.

The abovementioned frameworks were developed to support circular product design. However, these strategies can be found as well in example cases in the built environment context (see more in Section 2.3). In our research, we investigated which circular design strategies and options lead to more ideal and feasible circular building components. For the sake of clarity, we provided a framework of circular design strategies and definitions as applied in this research (see Figure 2.7). Our framework builds upon the framework of Bocken et al. (2016): we have added circular design strategies to narrow loops; we adjusted the definitions of each strategy to make them applicable to the building component context.

Loop	Strategy	Definition
Narrowing loops	Design for material reduction	Designing so that the amount of materials, the use of virgin-, finite materials, and/or material with a high environmental impact is reduced in the building component during manufacturing, construction, use or VRP processes.
	Design for energy reduction	Designing so that the amount of energy used - or environmental impact of the energy used - during manufacturing, construction, use or VRP processes of the building component are reduced.
Slowing loops	Design for attachment	Designing for attachment and trust refers to creating building components that will be loved, liked or trusted longer.
	Design for durability and reliability	A durable building component is designed for long-life and is developed so it can take wear and tear without breaking down. Reliability refers to designing for a high likelihood that a building component will operate throughout a specified period without experiencing a chargeable failure.
	Design for standardisation and compatibility	Creating building components with parts or interfaces that fit other building components as well.
	Design for ease of maintenance and repair	Design for maintenance and repair enables building components to be kept in good condition and repaired when broken.
	Design for upgradability and adaptability	Designing building components to allow for future modifications and improvement to prevent premature obsolecance. Adaptability (or adjustability) refers to the ability to modify the component. Upgradability is the ability to improve the quality, value, and effectiveness or performance.
	Design for dis-, and re-assembly	Design in which the building component, parts and materials can be separated and reassembled easily.
Closing loops	Design for technical cycles	Designed in such a way that the materials ("technical resources") can be continuously and safely recycled into new materials, parts or building components.
	Design for biological cycles	Designed with safe and healthy materials ("biological nutrients") that create food for natural systems across their life cycle.

FIG. 2.7 Circular design strategies framework and definitions applied in the development of circular building components. Building on Bocken et al. (2016)

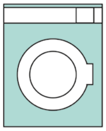
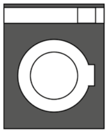
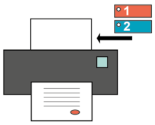
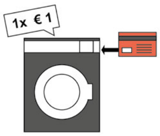
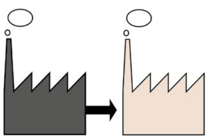
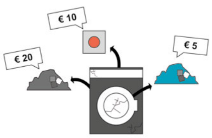
2.2.4 Circular business model types

To incentivise that the VRPs in a circular building component design are realised throughout its lifecycle, a supporting circular business model is needed which can generate value from the VRPs. A business model is the organisational and financial architecture which determines how an organisation converts resources and capabilities into economic value (Teece, 2010). A well-known definition is provided by Ostwalder and Pigneur (2010, p. 14): “a business model describes the rationale of how an organization creates, delivers, and captures value.” The more radical the design, the greater the likelihood that changes are required to the existing business model. The move to a CE requires a new way of thinking and doing business. In a circular business model, a company creates, captures, and delivers value whereby the business rationale incentivises narrowing, slowing and closing resource loops. A large part of the literature on circular business models provides typologies and taxonomies in the context of products (Pieroni et al., 2019).

In Table 2.1, we provide an overview of different circular business models mentioned in literature. The first two models can incentivise to narrow the loop. In (1) ‘the sufficiency model’, products promote the reduction of end-user consumption through increasing durability, reparability and upgradability, by providing service warrantees, and taking a non-consumerist approach to marketing and sales (Bocken et al., 2016). Examples of such a model are premium, high-service and high-quality brands, such as Patagonia (Bocken et al., 2016). In (2) ‘the sell more, sell green model’ – also named the ‘circular supply model’ – the business model is based on the fast sales of products. However, these products have no environmental impacts. Moreno et al. (2016) mentions selling renewable energy as an example. This exemplifies the ‘trickiness’ of this circular business model. Renewable energy does reduce the environmental impacts compared to energy generated by fossil fuels. However, it does not nullify impacts.

TOC

TABLE 2.1 Overview circular business model types

Narrowing loops		**1. The sufficiency model** Reduction of end-user consumption	(Bocken et al., 2016)
		**2. Sell more, sell green!** Fast sale of products with no environmental impact	(Bakker et al., 2014; Moreno et al., 2016)
Slowing loops		**3. The classic long-life model** a long product-life, is designed for durability and repair	(Bakker et al., 2014; Bocken et al., 2016)
		**4. The hybrid model** Sale of a durable product with a short-life consumable	(Bakker et al., 2014; Den Hollander & Bakker, 2016)
		**5. The gap-exploiter model** Capturing value through extending a product, component, part or material lifespan	(Bakker et al., 2014; Bocken et al., 2016; Den Hollander & Bakker, 2016; Moreno et al., 2016; Weetman, 2017)
		**6. The access model** Profits are made by selling access rather than ownership	(Bakker et al., 2014; Bocken et al., 2016; Moreno et al., 2016; Tukker, 2004)
		**7. The performance model** The product's performance is sold rather than the product itself	(Bakker et al., 2014; Bocken et al., 2016; Tukker, 2004)
Closing loops		**8. Industrial symbiosis model** Residual outputs are used as feedstock for another process	(Bocken et al., 2016)
		**9. Resource value model** Capturing value through recovering resources and reselling them	(Bocken et al., 2016; Moreno et al., 2016; Weetman, 2017)

Models 3 to 7 incentive slowing loops. (3) ‘The classic long-life model’ is based on a product which has a long service life and is designed for durability and repair (Bocken et al., 2016). Sales of the product is the main income source. These product brands have a reputation of ‘value for money’. The product is not considered as cheap, but it lasts (Bakker et al., 2014). Examples are the appliances offered by Miele with a 20-year service life and luxury watches from Rolex which are promised to last beyond a human lifetime (Bocken et al., 2016). In the building context, Grohe faucets are applied for their long-life reputation. (4) ‘The hybrid model’ sells a (more) durable product which cannot function without a consumable with a shorter service life. The source of revenue is the repeating sales of the fast-cycling consumables (Bakker et al., 2014). Examples are coffeemachines with single-dose coffee pads, printers with toner cartridges (Bakker et al., 2014), game consoles and games (Bakker et al., 2014) and a car and its maintenance parts (Bakker et al., 2014). (5) ‘The gap-exploiter model’ is known under different names, including ‘the extending-product-value model’, ‘the refill and maintain model’, ‘the reuse and resell model’, ‘the remanufacture model’ and ‘the product life-extension model’. In his model value is captured through extending a product’s, component’s, part’s or material’s lifespan. The gap-exploiter is the person or company, which comes in between the production and end-of-life. They earn their money through VRPs such as repair, reuse, refurbish and remanufacture. The main revenue of the gap-exploiter comes from (re)selling products, parts and services. For example, companies which refill ink cartridges (Bakker et al., 2014), maintenance services, shoe repair-shops (Bakker et al., 2014), reclaimed construction material harvesters and redistributors (Weetman, 2017), second hand distributors including occasion dealerships, goodwill shops and antique shops (Weetman, 2017), and smartphone refurbishment companies (Bocken et al., 2016). (6) ‘The access model’ is also named a ‘sharing platform model’, ‘use-oriented product service system’ or ‘extending product value model’. Profits are made by providing access to a product rather than selling its ownership. Examples of financial arrangements to provide access include product lease, pay-per use arrangements, rent, and pooling (Tukker, 2004). In the access model getting the required performance of the product is still the responsibility of the customer. The customer needs to choose the right product to fullfill their needs. Examples of this model are car and bike sharing services, such as Greenweels, Mo-bikes, and NS-bikes (Bakker et al., 2014), clothing hire or lease services such as tuxedo hire and leasing jeans (Bocken et al., 2016), online entertainment platforms such as Netflix, and renting a home. In (7) ‘the performance model’, the product’s performance rather than the product itself is sold. The performance model can also be named a ‘performance-oriented product service system’. Examples of financial arrangements include performance lease, and pay-per-performance (Tukker, 2004). Users only choose for a certain quality of the service. The supplier or the service provider can determine the type of product which delivers the promised

TOC

performance. Examples of this model are laundry and dry-cleaning services (Bocken et al., 2016) or Pay-per-lux by Phillips.

Circular business models 8 and 9 incentivise closing loops. (8) The industrial symbiosis model or 'circular supply model' closes loops by linking production processes. Waste from one process is used as feedstock for another process. An industrial symbioses generally works best when these processes are located in close proximity to each other (Bocken et al., 2016). An example, is using residual heat of industry for the heating of dwellings. (9) The resource value model has also been named the 'circular supply model' and the 'recovery and recycling model'. In this model products and resources are recovered at the product's EoL. Value is generated by recycling them or reselling them to a third-party for recycling (Weetman, 2017). Examples are the practices of waste recycling companies (Weetman, 2017).

Although we were able to include some examples of circular business models in the built environment context, the abovementioned models were developed mainly in the context of products. Models for short-lived products might not be directly transferable to the building context. A building and its components have their own distinct characteristics. The service life of most building components is much longer than those of consumer products (c.f. Brand, 1994). Building components – when combined into a building – create a unique, complex, long-lived and ever-transforming entity (Pomponi & Moncaster, 2017); Furthermore, the building sector has its own processes and culture in the supply chain. However, these models underline the importance of finding mechanisms to incentivise narrowing, slowing and closing loops; these models provide examples of such mechanisms which we built upon in the development of the circular building components and the research in this dissertation.

2.2.5 Conclusions on circular design approaches

In this section, we introduced several key circular design theories which can help facilitate, organise and incentivise VRPs; we explored their applicability in the design of circular building components. In Section 2.2.1 we discussed the concept of a 'systems approach'. We developed a systems model distinguishing system layers from the planetary scale to the material scale. Although we focus on the design of the building component, the cohesion and relation with the other system layers should always be considered. In Section 2.2.2, we briefly explained the term 'integral approach'. We proposed that circular building component designs should facilitate, incentivise and organise VRPs in the technical model (i.e., design), the supply-chain model and the business model in cohesion. In Section 2.2.3, we provided a background on circular design strategies. Building on the framework of Bocken et al. (2016), we proposed a framework of circular design strategies and provided definitions used in this research. In Section 2.2.4, we discussed existing theories on circular business models and provided an overview of 9 circular business models. Although these models were developed mainly in the context of products, they provided examples of mechanisms to incentivise narrowing, slowing and closing loops. The abovementioned circular design theories have played an important role in the development of circular building components in this dissertation; we built upon these theories in the research presented in the following chapters.

2.3 Approaches to a circular economy in the built environment

We can find various examples in the built environment which implement the circular design strategies as introduced in Section 2.2.3. In this section, we systematically reviewed these examples. The aim of this review was threefold. First, we aimed to identify existing examples which integrate circular design strategies and options into the built environment context. Second, we aimed to categorise these examples into different approaches on how to integrate CE into the building context. Third, we aimed to identify gaps and promising initial directions to integrate CE into the built environment and – specifically – the context of renovation of Dutch, low-rise, post-war housing.

2.3.1 Methods

The review consisted of the following steps. First, we developed a framework to analyse circular building examples. We used the circular design strategies framework proposed in Section 2.2.3 as a basis. Through literature study and brainstorming, we specified each circular design strategy with concrete circular design options. Second, we identified existing examples in the built environment which applied one or more circular design strategies and options. Examples included theories, publications, groups, movements, designs, pilots or projects. We distinguished between 'pré-circular building examples' and 'circular building examples'. 'Pré-circular examples' stem from before the conceptualisation of the CE model and – although, often for other motivations – apply similar design strategies and options. The selection of pré-circular examples builds upon Brinksma (2017). In his work, he extensively reviewed approaches aimed at making buildings adaptable in the future. We added several international examples to his selection. The circular building examples were identified through case study analysis. In Google search engine, various combinations of the following keywords (in English and Dutch) were entered: 'circular' and 'building', 'building system', 'house', 'retrofit' or 'renovation'. A first selection yielded 98 results; we selected 19 examples based on if they applied one or more circular design strategies. Third, the selected circular building examples were analysed by identifying which of the circular design strategies and options were applied. Based on the combinations of circular design strategies and options applied – and their rationale for doing so – we categorized the examples into different approaches. Each approach represents a different pathway by which the built environment can be made circular. Through this analysis we identified gaps in existing approaches and promising initial directions to integrate CE into the built environment and – specifically – the context of renovation of Dutch, low-rise, post-war housing.

In Section 2.3.2, we describe the resulting (pré)circular building approaches. In Section 2.3.3, we identify initial promising directions and gaps using the findings of the analysis. In Section 2.3.4 we explore how the identified initial directions can be applied in the context of renovation of Dutch, low-rise, post-war housing. In Section 2.3.5, we share conclusions and discuss our findings.

2.3.2 Description of circular building approaches

We visualised the pré-circular building approaches and circular building approaches in Figures 2.8-16 and Figures 2.17-24, respectively. In Table 2.2 and 2.3, we described each approach and the pathway by which the approach achieves circularity; we provided the examples categorised under each approach. For pré-circular approaches we also briefly explained the reasoning for applying circular design strategies.

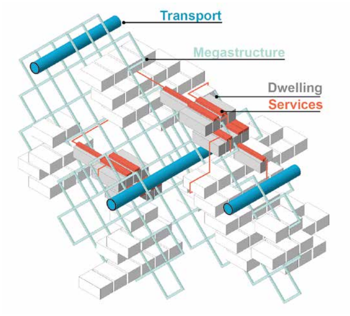


FIG. 2.8 Visualisation ‘flexible urban megastructures’ approach

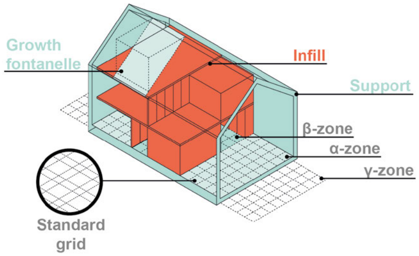


FIG. 2.9 Visualisation ‘open building’ approach

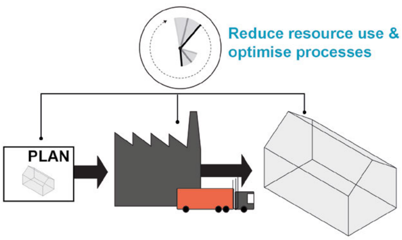


FIG. 2.10 Visualisation ‘lean construction’ approach

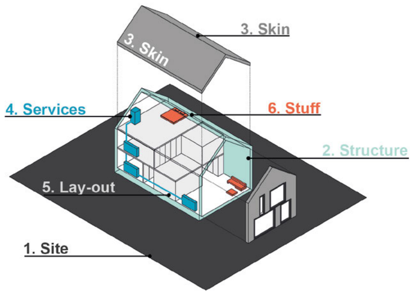


FIG. 2.11 Visualisation ‘shearing layer’ approach

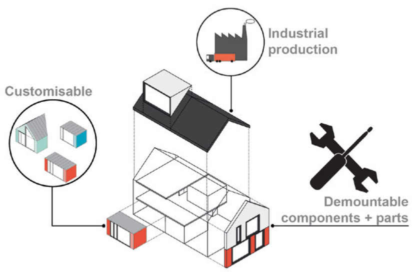


FIG. 2.12 Visualisation ‘Industrial, Flexible, Demountable (IFD) building’ approach

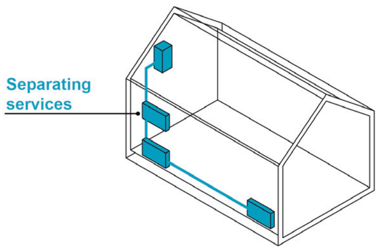


FIG. 2.13 Visualisation ‘slimbouwen’ approach

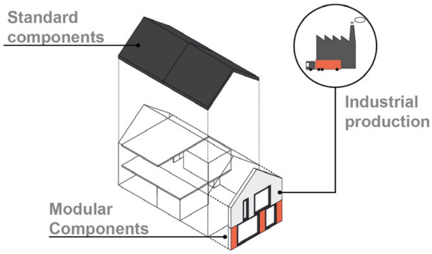


FIG. 2.14 Visualisation 'conceptual building and renovation' approach

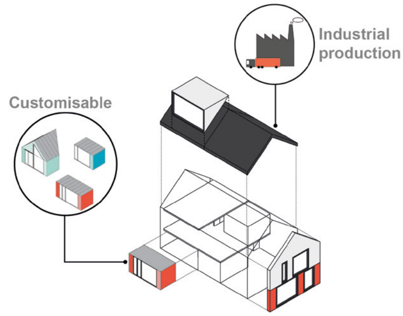


FIG. 2.15 Visualisation 'mass-customisation in dwelling construction' approach

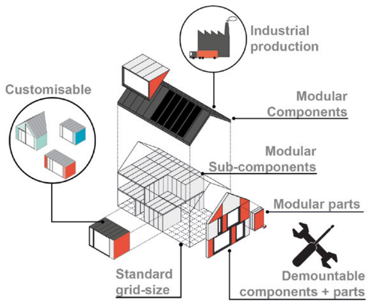


FIG. 2.16 Visualisation 'legolisation in construction' approach

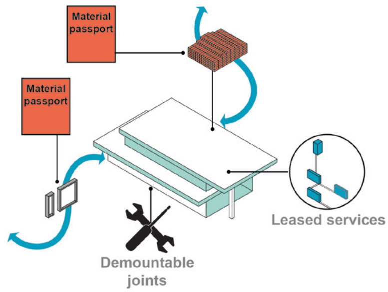


FIG. 2.17 Visualisation 'building as material bank' approach

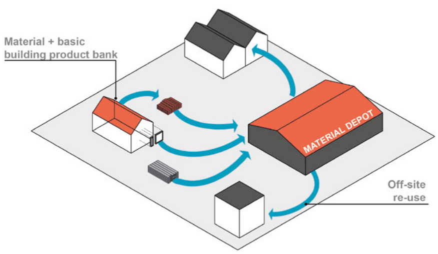


FIG. 2.18 Visualisation 'reusing materials locally' approach

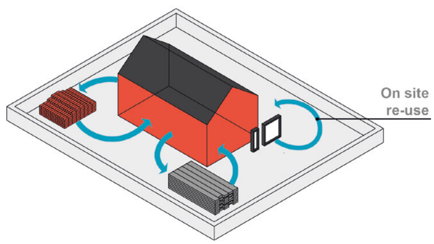


FIG. 2.19 Visualisation 'reusing materials on-site' approach

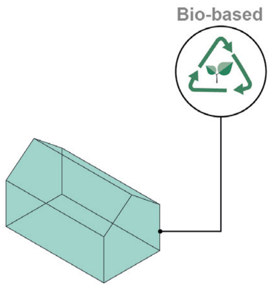


FIG. 2.20 Visualisation 'bio-based construction systems' approach

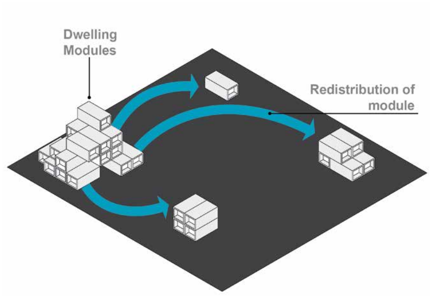


FIG. 2.21 Visualisation 'movable container homes' approach

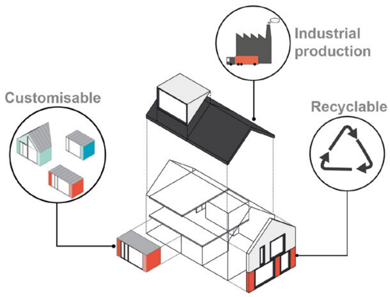


FIG. 2.22 Visualisation 'mass-customisable and 'cyclable' (MCC) building systems' approach

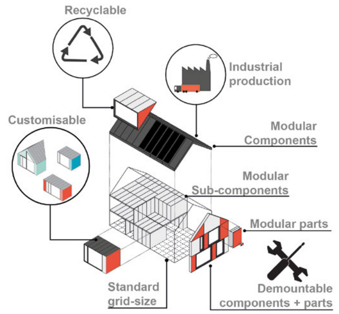


FIG. 2.23 Visualisation 'modular, mass-customisable and 'cyclable' (MMCC) building systems' approach

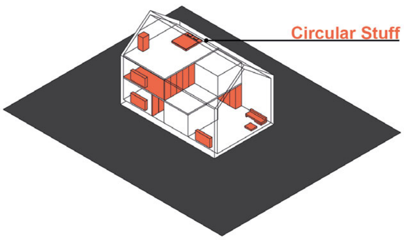


FIG. 2.24 Visualisation 'circular stuff' approach

TABLE 2.2 Description pré-circular building approaches

Name approach	Origin	Description approach and pathway to circularity	Examples
1.1 Flexible urban mega-structures	Reaction to the static, inflexible post-war mass housing	Avant-gardist designs of ever-evolving cities applying permanent mega-structures and interchangeable infill.	Work from Archigram and Metabolists; projects including: plug-in-city, Archigram, 1961; Habitat '67, Safdie, 1967; Nakagin Capsule Tower by Kenzo Tange, 1972.
1.2 Open building	Reaction to the inability of residents to influence the post-war built environment	Built environment is separated into layers (e.g., tissue, support, infill); buildings are zoned and standard sizing ('modular coordination') are introduced to allow for user customisation and future adaptations.	Habraken (1961); work of Stichting Architecten Research (SAR); work of Stichting Open Building (SOB), Molenvliet by van der Werf, 1969-1976; Lunetten by van der Werf, 1971-1982.
1.3 Lean construction	In reaction to economic and environmental inefficiency of traditional construction	Application of lean manufacturing principles to construction to optimise construction processes, reduce material and energy use.	Koskela (1992)
1.4 Shearing layers	Applying theories of ecologist and system theorist in buildings	Building is divided into 6 shearing layers based on expected lifespan: (1) site, (2) structure, (3) skin, (4) services, (5) space plan and (6) stuff. Separating layers improves future repairability and adaptability, preventing premature obsolesce.	Brand (1994)
1.5 Industrial, flexible and demountable building (IFD)	Building on ideas Open Building, IFD aimed to better fulfil clients demands in a construction project	IFD unites industrialisation of the building process, flexibility (i.e., customisation), and demountability to allow future changes.	Maskerade+ concept by van der Breggen architecten, 2003; Trento® concept by Nijhuis, n.d.
1.6 Slimbouwen	In reaction to the economic and environmental inefficiency of traditional construction; increasing importance of climate installations	A strategy separating the building into layers corresponding to separate steps in the construction processes; focus on decoupling piping to make building process more efficient and improve adaptability.	Lichtenberg (2005); Comfort+ concept by Lichtenberg (2010)
1.7 Conceptual building and renovation	Reaction to the high costs, length, mistakes and nuisance of supply-oriented construction processes	Client-friendly, cost-efficient and fast construction process in which buildings are constructed and renovated with standardised, building components; buildings can be adjustable by changing components in future.	Component renovation (CR+) by Bouwhulpgroep (n.d.).

>>>

TOC

TABLE 2.2 Description pré-circular building approaches

Name approach	Origin	Description approach and pathway to circularity	Examples
1.8 Mass-customisation in dwelling construction	Uniting principles of mass-production and customisation in construction	Dwelling concepts or components which are (to an extent) standardised, customisable and mass-producible.	Boklok by IKEA, 1996; Selekthuis by Nieuwenhuis groep, 1985; B8U bathroom by ERA Contour, et al., 2016; Instant house by Sass, 2005; Wikihouse, 2011; Katerra, 2015.
1.9 LEGO-lisation in construction	Reaction to the traditional and project-based construction industry	Buildings are constructed (and renovated) with customisable, standardised, prefabricated, demountable modules. The modules are subdivided into sub-components, parts, etc. Optimise the building process, increases quality and adaptability and reduces material use and costs.	De ridder (2011), Pop-up house, 2012;

TABLE 2.3 Description circular building approaches

Name approach	Description approach and pathway to circularity	Examples
2.1 Building as material banks (BAMB)	Circular pilots focussing on buildings as material banks, energy neutrality and demountability. Reused and recycled components and materials are applied; demountable joints are applied to facilitate future reuse and recycling; service components are leased. Component- and material passports are used.	Circl pavilion, ABN AMBRO, 2017
2.2 Reusing materials locally	Instead of demolishing dwellings and disposing of materials, dwellings are disassembled (as much as possible); components and materials are reused locally.	Circular demolition, Woonbron, n.d..
2.3 Reusing materials on site	Focusses on reuse and recycling of components and materials in housing renovation and renewal. A figurative 'fence' is placed around the site: what is demolished is reused on site. The approach is often combined with reducing material and energy flows (e.g., water, food, and energy) and/or striving towards local self-sufficiency.	Stadstuim Overtoom, Eigen Haard, 2012-2016; Superlocal, Heemwonen, 2018-2020; Heuvelstraat, Wonion, 2018.
2.4 Bio-based construction systems	Housing construction and renovation systems which reduce environmental impact and facilitate closing the loop by applying bio-based and biodegradable materials. In some cases, the systems are also modular, standardised and/or adaptable to future changes.	Bio-based retrofit, Woonbron, n.d.; Biological house by GXN; Bio-based building blocks
2.5 Movable container homes	Building systems which consist out of 'container-style' housing modules. These modules are built with non-toxic, bio-based and/or highly recyclable technical materials. Whole containers can be placed to fulfil temporary housing needs. If needs change in the future, the whole container can be moved elsewhere. The modules themselves are more or less customisable and adaptable. Modules can be linked in different configurations. Layout and finishes are customisable and (to some extend) adaptable to future changes.	Finch modules; Woody®
2.6 Mass-customisable, 'cyclable' (MCC) building systems	Standardised building systems which can be customised to fit the wishes of the client. The system applies circular materials to narrow and close the loop of the building and its materials. The system is modular during construction to facilitate fast construction but not to facilitate future adaptability.	Sustainer homes
2.7 Modular, mass-customisable and 'cyclable' (MMCC) building systems	Highly modular building systems which integrates mass-customisation and circular design strategies to narrow, slow and close the loop of the building, (sub)components and materials. The system consists of customisable, standardised, prefabricated, demountable modules. The modules themselves are modular, standardised, and demountable; more circular materials are applied. The design facilitates repair, reuse, updates and recycling.	Bilt house; Circle house, GXN, 2018; Circular Retrofit Lab; Fijn Wonen Circulair; PD lab, TU/e and University of Twente & industry partners, 2017; Circular retrofit lab; the circular 2knd Skin façade
2.8 Circular stuff	Pilot projects in which circular stuff (e.g., fridge, washing machines, furniture, decorations) is introduced in the home. Often the product is offered through a product-service-system (e.g., lease).	Circulaire huurwoning, de gemeenschap, 2018; Besparen in huis, Eigen Haard, 2013

2.3.3 Findings analysis (pré)circular building approaches: promising initial directions and gaps

The analysis of the (pré-)circular building approaches is included in Table 2.4. Table 2.4 shows that pré-circular building approaches 1.1-1.2 mainly facilitate future adaptability. In approaches 1.4-1.9, facilitating future adaptability is extended with standardisation and customisability. Approach 1.3 focusses on narrowing the resource loop, particularly in the construction process. Approaches 2.1-2.3 and 2.8 focus on narrowing and closing the material loop through (local) reuse and recycling of components and materials. Alternatively, 2.4 aims to narrow and close the loop by applying bio-based materials. Approaches 2.5-2.7 integrate design strategies to narrow, slow and close loops.

The analysis shows that most of the approaches remain fragmented: they focus either on narrowing and closing the loop, or slowing the loop. For example, the circular approaches 2.1-2.3, narrow and close material loops. However, no design strategies are implemented to slow resource loops on building or component level. Hence, premature obsolesce is not prevented. Subsequently, material depletion, emissions and waste generation are not fully minimized. Similarly, focussing only on slowing the loop will still result in material depletion, emissions and waste, just at a slower pace. None of the analysed approaches have yet applied all circular design strategies and options, optimising loops on all levels of the building. Yet, these approaches do provide useful partial examples to integrate CE into the built environment context.

TABLE 2.4 Analysis (pré-)circular building approaches

Circular design strategies					Pré-Circular Building Approaches									Circular Building Approaches							
	Ccircular Design Str.	Circular design options	Sources		1.1 Megastructures	1.2 Shearing layers	1.3 Lean constr.	1.4 Open Building	1.5 IFD	1.6 SlimBouwen	1.7 Conceptual	1.8 Mass-custom.	1.9 LEGO-lisation	2.1 BAMB	2.2. Reusing locally	2.3 Reusing on-site	2.4 Bio-based	2.5 Movable cont.	2.6 MCC system	2.7 MMCC system	2.8 Circular stuff
Narrowing loops	Material reduction	Reducing use material in production		.	.	.	x	.	x	x	~	x	.	.	.	.	~	x	~	~	.
		Minimizing material		.	~	.	~	.	.	x	.	~	.	.	.	.	.	x	~	~	.
		Reducing packaging material		.	.	.	~	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Reducing material during use		.	.	.	.	.	.	.	.	.	.	x	.	x	.	.	.	.	.
		Non-virgin materials		.	.	.	.	.	.	.	.	.	.	x	x	x	.	~	x	x	x
		Bio-based materials		.	.	.	.	.	.	.	.	.	.	x	.	~	x	x	x	~	x
		Non-toxic materials		.	.	.	.	.	.	.	.	.	.	.	.	.	x	x	.	.	.
		Reducing critical material		.	.	.	.	.	.	.	.	.	.	.	.	.	.	~	x	~	.
	Energy reduction	Minimizing energy use in production		.	.	.	x	.	.	x	.	.	.	.	.	.	.	.	.	.	.
		Reduce energy during use-phase		.	.	.	.	.	.	.	.	.	.	x	.	~	~	x	x	x	x
		Use renewable energy		.	.	.	.	.	.	.	.	.	.	x	.	~	.	~	x	x	.

>>>

TOC

TABLE 2.4 Analysis (pré-)circular building approaches

Circular design strategies					Pré-Circular Building Approaches									Circular Building Approaches							
	Ccircular Design Str.	Circular design options	Sources		1.1 Megastructures	1.2 Shearing layers	1.3 Lean constr.	1.4 Open Building	1.5 IFD	1.6 SlimBouwen	1.7 Conceptual	1.8 Mass-custom.	1.9 LEGO-lisation	2.1 BAMB	2.2. Reusing locally	2.3 Reusing on-site	2.4 Bio-based	2.5 Movable cont.	2.6 MCC system	2.7 MMCC system	2.8 Circular stuff
Slowing loops	Design for attachment*	Design for easy use		.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
		Add surplus quality	1	.	.	.	.	x	.	.	.	.	.	.	.	.	x	x	~	.	.
		Designed for long emotional desirability & user trust	1,2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Design for long-life	Critical part dimen-sioned for unintended use	1-3	x	.	.	x	x	.	.	.	.	.	.	.	.	.	.	.	.	.
		Timeless (base) design	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Reduced moving / electric parts	1,2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Long life materials with resistance to wear (i.e., reduce coated, plaited, painted or discolouring mater.)	1-4	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Compatible materials & fasteners	2-5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Design for standardisation and compatibility	Part standardisation	2,5	.	.	.	.	.	.	.	x	x	.	.	.	~	x	x	x	.	.
		(sub)component stan-dardisation	1,7	.	.	.	~	x	.	x	x	.	.	.	.	x	x	.	x	.	.
		Building standardi-sation	1,7	~	.	.	~	x	.	x	x	.	.	.	.	~	x	x	.	.	.
		Measurement stan-dardisation	7	~	.	.	x	.	.	.	x	x	.	.	.	~	x	x	x	.	.
		Joint standardisation	2, 7-9	~	.	.	x	x	x	x	x	x	.	.	.	~	x	x	x	.	.
		Tool standardisation		.	.	.	.	.	.	.	x	.	.	.	.	.	.	.	.	.	.
		Interface standardi-sation	2,5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Performance test standardisation	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

>>>

TOC

TABLE 2.4 Analysis (pré-)circular building approaches

Circular design strategies					Pré-Circular Building Approaches									Circular Building Approaches							
	Ccircular Design Str.	Circular design options	Sources		1.1 Megastructures	1.2 Shearing layers	1.3 Lean constr.	1.4 Open Building	1.5 IFD	1.6 SlimBouwen	1.7 Conceptual	1.8 Mass-custom.	1.9 LEGO-lisation	2.1 BAMB	2.2. Reusing locally	2.3 Reusing on-site	2.4 Bio-based	2.5 Movable cont.	2.6 MCC system	2.7 MMCC system	2.8 Circular stuff
Slowing loops	Design for easy maintenance and repair	Access. parts for maintenance	1, 2, 4-9	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Enclosed repair instructions	10	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Minimised number of parts	2, 4-8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Optimised sequence for repair	1,2,5,8	.	.	.	x	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Designed for on-site maintenance	2,5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Maintenance-proof materials	2,5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Live monitoring of performance	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	Design for upgrades and adjust-ments	Uncomplicated design	1,2,5,11	.	.	.	x	.	.	.	.	.	.	.	.	~	x	.	x	.	.
		Modular design	1,2, 5-7	x	.	.	x	x	.	~	x	x	.	.	.	x	x	x	x	.	.
		Parts separated based on lifespan	2,8,12	x	x	.	x	x	x	.	.	x	.	.	.	.	~	.	x	.	.
		Component / part passport	1	.	.	.	.	.	.	.	.	.	x	.	.	.	.	x	~	.	.
		Facilitate customis-ation	1	.	.	.	x	x	.	x	x	x	.	.	.	~	x	x	x	.	.
		Facilitate future changes	1,2,7	x	x	.	x	x	x	.	x	x	.	.	~	~	~	~	x	.	.

>>>

TOC

TABLE 2.4 Analysis (pré-)circular building approaches

Circular design strategies					Pré-Circular Building Approaches									Circular Building Approaches							
	Ccircular Design Str.	Circular design options	Sources		1.1 Megastructures	1.2 Shearing layers	1.3 Lean constr.	1.4 Open Building	1.5 IFD	1.6 SlimBouwen	1.7 Conceptual	1.8 Mass-custom.	1.9 LEGO-lisation	2.1 BAMB	2.2. Reusing locally	2.3 Reusing on-site	2.4 Bio-based	2.5 Movable cont.	2.6 MCC system	2.7 MMCC system	2.8 Circular stuff
Closing loops	Design for disassembly	Easy de-, & re-mount-able joints	1,2,5-8,13	x	.	.	x	x	x	.	.	x	x	.	~	~	x	~	x	.	.
		Minimised number of comp./parts/joints/ tools	1,2,4,6,8,9, 11	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		No wet-joints	2,5,7	.	.	.	.	x	.	.	.	x	x	.	.	.	~	.	x	.	.
		No adhesives	2,5	.	.	.	.	x	.	.	.	x	x	.	.	.	~	.	x	.	.
		Sequence of dis-, & reassembly	1,2,8	.	.	.	.	x	.	.	.	x	.	.	.	.	~	.	x	.	.
		Dis-, & reassembly instructions		.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	~	.	.
		Easy access to joints	1,2,4-6,8	.	.	.	x	x	x	.	.	x	.	.	.	.	~	.	x	.	.
	Design for recycling	Biodegradable materials	7	.	.	.	.	.	.	.	.	.	x	.	.	x	x	x	x	x	.
		Recyclable materials	7	.	.	.	.	.	.	.	.	.	x	.	.	.	~	x	x	x	.
		Separable materials	1,7	.	.	.	.	.	.	.	.	.	x	.	.	.	~	.	x	.	.
		Material passport	10	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.	~	.	.
		Limited number & common materials	1,2,6,8,11, 13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Recycle compatible materials	2,8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		Grouped critical/ valuable/toxic mat.	1,2,6-8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
		No paint & coating	1,2,6-8,13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	~	.	.
		Fast disassembly		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

* *(Bakker et al., 2014; Bocken et al., 2016)*
x *Principle is applied according to the case designs and/or according to consulted case literature.*
~ *Principle is applied to some extend or only in part of the cases.*
. *Indicates that the circular design strategy is not applied in the approach.*

From all the approaches, the ‘modular, mass-customisable, ‘cyclable’ building system’ (2.7) approach integrates - by far - the most design strategies and options to narrow, slow and close the loop. In this approach, the building is modularized into standardized and demountable building components; these components are modular, standardised and demountable themselves. Low-impact, bio-based, biodegradable, non-virgin, and/or highly recyclable materials are used. The building, components and parts are customisable up front; they can be repaired, reused, adjusted and recycled. This seems to provide the most potential to keep the building,

building components, parts and materials cycling at highest utility and value. As such, it provides a promising direction to integrate circularity both into new and existing buildings.

2.3.4 Circular building components for housing renovation

In Chapter 1.4, we described the renovation challenge in the context of Dutch, low-rise, post-war, social housing. In this section, we explore how a 'modular, mass-customisable, cyclable' building system could be applied in this context (see Figure 2.25).

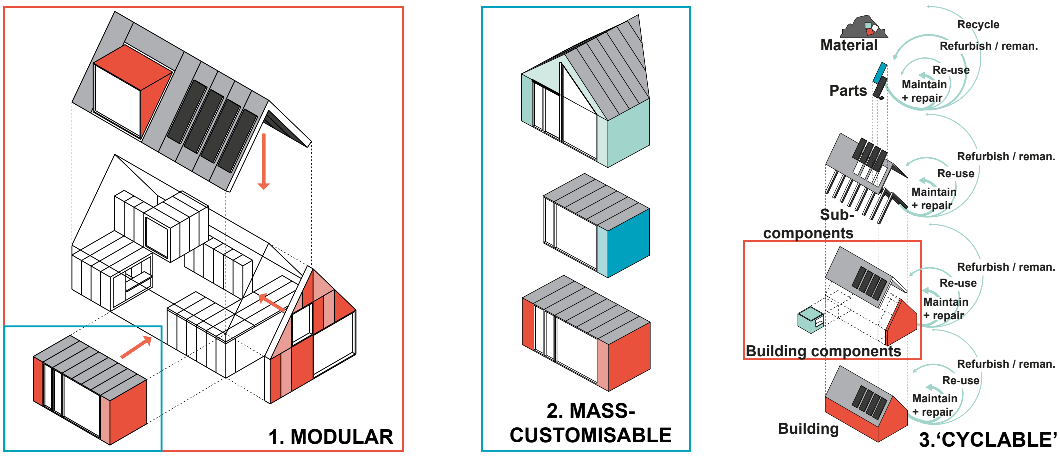


FIG. 2.25 (1) Modular, (2) mass-customisable, and (3) cyclable renovation using circular building components

A modular renovation solution can facilitate component-by-component renovation. A dwelling consists of different building components, such as kitchens, façades, and roofs. The dwelling can gradually be made circular by replacing linear building components with more circular building components during natural maintenance and renovation moments. A modular renovation can also help to spread the renovation investment over multiple cycli. This can increase the feasibility of Net Zero Energy Building (NZEB) renovations.

A renovation solution which is mass-customisable combines the principles of mass production with the advantages of product customisation. Customising the building components can help to fit them onto different existing dwellings and to adjust the renovation to the specific needs of different housing associations and users. Mass-production of building components may refer to both replicability of the design and/or prefabrication of components in a manufacturing facility. This can increase the quality of the renovation components; it can reduce the risk, costs, length of renovation and nuisance for tenants. Furthermore, design options facilitating mass-customisation synergise with circular design principles such as: improving product quality, modularity, product and (sub)component standardisation, and offering adjustments to users.

To make the building components themselves circular, the technical, supply-chain and business model need to be designed to integrally narrow, slow and close the loops on the building component, part and material level. However, examples of circular building components remain scarce. The 'Bilt House' (Reynaers Aluminium, 2017) (See Figure 2.26) and the 'Circle House'(GXN, 2018) examples provide components developed for the construction of new buildings; only initial pilots have been built. The two examples which target renovation provide only partial and theoretic solutions. The example of the 'circular retrofit lab' (Paduart, 2016) tests various components for renovation in a test pavilion (See Figure 2.27). Furthermore, their approach has – in part – been project-driven, which limits the replicability of their tested solutions. The 'Circular 2ND skin façade' by Henry (2018) is a design for a circular façade component. This façade component has been specifically developed as an alternative to the (linear) façades used for NZEB renovations in housing. However, this design remains a design concept and has not been piloted or realised.

FIG. 2.26 Modular, mass-customisable, cyclable building systems – BILT concept house. Photo by Reynaers Aluminium.

FIG. 2.27 Prototype of a demountable partitioning-wall component in the circular retrofit lab

TOC

2.3.5 Conclusions and discussion on approaches to a circular economy in the built environment

In this section, we identified existing examples which integrate circular design strategies and options into the built environment context. Through systematic analysis and categorisation of these examples we identified 17 different approaches on how to integrate CE into the building context. We found that most approaches focused on either narrowing and closing cycles now or slowing them in the future; they rarely considered all building levels. The building approach 'modular, mass-customisable and cyclable building systems' provided most potential to narrow, slow and close cycles. In this approach the building is modularised into building components; these building components are designed according to circular design options as well. This offers a promising approach to integrate circularity into buildings and renovation of Dutch, post-war, low-rise, social housing. However, existing examples of circular building components were either developed for new construction, remain fragmented or theoretical designs.

We emphasize that this review is systematic and extensive, yet we do not claim it is exhaustive. This review focussed on circular design strategies for the technical model; other circular design options can be identified in literature (see also chapter 3). The selection of (pré-)circular building approaches was extensive but not exhaustive. Other (pré-)circular approaches could provide valuable insights. However, this method allowed us to make a 'quick' shifting to identify promising initial directions. Also, future research is needed to validate the identified initial direction by developing and testing circular building components.

References

Ayres, R. U., & Ayres, L. W. (2002). *A Handbook of Industrial Ecology.* Northampton, MA.: Edward Elgar Publishing.

Bakker, C., den Hollander, M., van Hinte, E., & Zijlstra, Y. (2014). *Products That Last.* Delft: TU Delft Library & Marcel den Hollander IDRC.

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature.* New York: William Morrow.

Blengini, G. A., Latunussa, C. E. L., Eynard, U., Torres de Matos, C., Wittmer, D., Georgitzikis, K., … Pennington, D. (2020). *Study on the EU's list of Critical Raw Materials (2020) Final Report*. https://doi.org/10.2873/904613

Blomsma, F., Kjaer, L., Pigosso, D., McAloone, T., & Lloyd, S. (2018). Exploring circular strategy combinations - Towards understanding the role of PSS. *Procedia CIRP*, *69*(May), 752–757. https://doi.org/10.1016/j.procir.2017.11.129

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Boulding, K. E. (1966). The economics of the coming spaceship earth. In H. Jarrett (Ed.), *Environmental Quality in a Growing Economy*. Baltimore: Johns Hopkins University Press.
BouwhulpGroep. (n.d.). BouwhulpGroep | Architectuur | Renovatie. Retrieved July 24, 2022, from https://www.bouwhulp.nl/onderzoekers2.html
Brand, S. (1994). *How Buildings Learn*. New York: Viking.
Brinksma, H. (2017). *Toekomstbestendig Renoveren*. Retrieved from http://www.lesvosnews.net/articles/news-categories/politiki/dimoskopisi-gia-galino-kalogiroy-voyleytes-lesvoy-ereyna-tis-kapa
Carson, R. (1962). *Silent spring*. New York: Houghton Mifflin.
Commoner, B. (1971). The closing circle: Man, nature and technology. In *The Closing Circle: Man, Nature and Technology*. USA: Alfred A. Knopf, Inc.
de Ridder, H. (2011). *Legolisering van de bouw*. Retrieved from https://vindboek.nl/legolisering-van-de-bouw-9789078171157
Den Hollander, M., & Bakker, C. (2016). Mind the Gap Exploiter: Circular Business Models for Product Lifetime Extension. *Proceedings of the Electronics Goes Green*. Berlin.
Elkington, J. (1997). *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Oxford: Capstone.
Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition
Ellen MacArthur Foundation. (2015). *Growth within: a circular economy vision for a competitive europe*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf
French, M. L., & LaForge, R. L. (2006). Closed-loop supply chains in process industries: An empirical study of producer re-use issues. *Journal of Operations Management*, *24*(3), 271–286. https://doi.org/10.1016/j.jom.2004.07.012
Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
Geldermans, R. J. (2016). Design for change and circularity - Accommodating circular material & product flows in construction. *Energy Procedia*, *96*, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153
Genovese, A., Acquaye, A. A., Figueroa, A., & Lenny Koh, S. C. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega (United Kingdom)*, *66*, 344–357. https://doi.org/10.1016/j.omega.2015.05.015
Gerritsen, M. (2015). *Circular Design Checklist*. The Netherlands: Reversed Concepts.
Gershenfeld, N. (2005). *FAB: The coming revolution on your desktop: From personal computers to personal fabrication*. Cambridge: Basic Books.
Graedel, T. E., & Allenby, B. R. (2003). *Industrial ecology*. Prentice Hall.
GXN. (2018). *Circle House: Denmark's first circular housing project*. Denmark: KLS PurePrint.
Habraken, N. J. (1961). *Supports: An Alternative to Mass Housing*. London: Routledge.
Henry, Q. (2018). *Circular Facade Refurbishment*. Delft: MSc thesis, Delft University of Technology.
Holdren, J. P., & Ehrlich, P. R. (1974). Human Population and the Global Environment: Population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force. *American Scientist*, *62*(3), 282–292. Retrieved from https://www.jstor.org/stable/27844882#metadata_info_tab_contents
Huysveld, S., Hubo, S., Ragaert, K., & Dewulf, J. (2019). Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. *Journal of Cleaner Production*, *211*, 1–13. https://doi.org/10.1016/j.jclepro.2018.11.110
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026
IEA. (2014). *Technology roadmap: Energy efficient building envelopes*. Paris: International Energy Agency.
Itard, L. C. M. (2009). Embodied and operational energy use of buildings. *Lifecycle Design of Buildings, Systems & Materials*, 77–84.
Jager, A. (2002). Industrial design methods. In T. M. de Jong & D. J. M. van der Voordt (Eds.), *Ways to study and research* (p. 367). Delft: DUP Science.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Koskela, L. (1992). *Application of the new production philosophy to construction, Technical report No. 72* (Vol. 72). California: Center for integrated facility engineering, Standford University.

Lichtenberg, J. (2005). *Slimbouwen*. Boxtel: Aeneas.

Lichtenberg, J. (2010). Bouwdossier deel 1. In *Het advies. Thermische en akoestische verbetering*. BouwIQ.

Lyle, J. T. (1994). *Regenerative design for sustainable development*. John Wiley.

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. New York: North Point Press.

McKinsey Global Institute. (2011). *Resource Revolution: Meeting the world's energy, materials, food, and water needs*. McKinsey Global Institute:

Mendoza, J. M. F., Sharmina, M., Gallego-Schmid, A., Heyes, G., & Azapagic, A. (2017). Integrating backcasting and eco-design for the circular economy: The BECE framework. *Journal of Industrial Ecology*, *21*(3), 526–544. https://doi.org/10.1111/jiec.12590

Mestre, A., & Cooper, T. (2017). Circular product design: A multiple loops life cycle design approach for the circular economy. *The Design Journal*, *20*(sup1), S1620–S1635. https://doi.org/10.1080/14606925.2017.1352686

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability*, *8*(937), 1–15. https://doi.org/10.3390/su8090937

Nasr, N., Russell, J., Bringezu, S., Hellweg, S., Hilton, B., & Kreiss, C. (2018). *Redefining value: The manufacturing revolution. Remanufacturing, refurbishment, repair and direct reuse in the circular economy*. Nairobi, Kenya.

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. Hoboken, NJ: John Wiley and Sons.

Oxford english dictionary. (2018). In *Oxford English Dictionary*. Oxford: Oxford University Press.

Paduart, A. (2016). Circular Retrofit Lab. Retrieved October 28, 2022, from https://www.bamb2020.eu/topics/pilot-cases-in-bamb/retrofit-lab/

Peck, D. (2015). *Prometheus Missing: Critical Materials and Product Design*. https://doi.org/10.4233/uuid

Pieroni, M. P. P., McAloone, T. C., & Pigosso, D. C. A. (2019). Business model innovation for circular economy and sustainability: A review of approaches. *Journal of Cleaner Production*, *215*, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036

Pomponi, F., & Moncaster, A. (2016, October 1). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, Vol. 181, pp. 687–700. https://doi.org/10.1016/j.jenvman.2016.08.036

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Remondis Group. (2022). Shortage of raw materials. Retrieved July 18, 2022, from https://www.remondis-sustainability.com/en/sharing/shortage-of-raw-materials/

Reynaers Aluminium. (2017). BILT: circulair en flexibel woningbouwsysteem. Retrieved November 4, 2022, from https://www.reynaers.nl/inspiratie/aluminium-referentie-projecten/sliding-folding-bilt-circulair-en-flexibel#

Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F. (2017). How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. *Recycling*, *2*(6), 1–18. https://doi.org/10.3390/recycling2010006

Sihvonen, S., & Ritola, T. (2015). ScienceDirect Conceptualizing ReX for aggregating end-of-life strategies in product development. *Procedia CIRP*, *29*, 639–644. https://doi.org/10.1016/j.procir.2015.01.026
Stahel, W. R. (2006). *The performance economy*. Palgrave Macmillan.
Teece, D. J. (2010). Business Models, Business Strategy and Innovation. *Long Range Planning*, *43*(2–3), 172–194. https://doi.org/10.1016/J.LRP.2009.07.003
Toxler, P. (2011). Libraries of the peer production era. In B. van Abel, R. Klaassen, L. Evers, & P. Troxler (Eds.), *Open design now*. Retrieved from http://opendesignnow.org/index.html%3Fp=411.html
Tukker, A. (2004). Eight Types of Product Service Systems. *Business Strategy and the Environment*, *13*, 246–260. https://doi.org/10.1002/bse.414
United Nations. (2013). *World Population Prospects The 2012 Revision Highlights and Advance Tables.* Retrieved from https://population.un.org/wpp/Publications/Files/WPP2012_HIGHLIGHTS.pdf
United Nations Environment Programme. (2020). *2020 Global status report for buildings and construction: towards a zero-emissions, efficient and resilient buildings and contruction sector*. Nairobi: United Nations Environment Programme.
United Nations Environment Programme. (2021). *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Retrieved from https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction
van Buren, N., Demmers, M., van der Heijden, R., & Witlox, F. (2016). Towards a circular economy: The role of Dutch logistics industries and governments. *Sustainability*, *8*(647), 1–17. https://doi.org/10.3390/su8070647
van den Berg, M. R., & Bakker, C. A. (2015). A product design framework for a circular economy. *PLATE Product Lifetimes And The Environment 2015*, 365–379. Nottingham: Nottingham Trent University.
von Carlowitz, H. C. (1713). *Sylvicultura Oeconomica: Hausswirthliche Nachricht und Naturmaßige Anweisung zur Wilden Baum-Zucht*. Leipzig: Johann Friedrich Braun.
Weetman, C. (2017). *A circular economy handbook for business and supply chains : repair, remake, redesign, rethink*. Retrieved from https://books.google.nl/books?hl=nl&lr=&id=DU2iDQAAQBAJ&oi=fnd&pg=PR9&ots=JdPy4iPB3I&sig=S3Ykx9rWM0fbcfFNtCU4TVOxgvg&redir_esc=y#v=onepage&q&f=false
World Commission on Environment and Development (WCED). (1987). *Brundtland report: Our Common Future*. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/07488008808408783
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857
Yan, J., & Wu, N. (2011). Technology Supporting System of Circular Economy of Mining Cities. *2011 Asia-Pacific Power and Energy Engineering Conference*, 1–5. https://doi.org/10.1109/APPEEC.2011.5749062

3 Methodological scientific background

Approaching Research through Design

This chapter will be published (in a shortened version) in van Stijn, A., Lousberg, L.H.M.J., 2023. Approaching Research through Design in the field of Architecture and the Built Environment: Relating to the history, key theories and discourse, in: Lousberg, L.H.M.J., Chan, P., Heintz, J. (Eds.), *Interventionist Research Methods.* Taylor & Francis.

A van Stijn[1,2] and L H M J Lousberg[1]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

This chapter contains a methodological scientific background focussing on Research through Design (RtD). We applied this approach in our research. In this chapter, we provide an overview of the development of RtD, introduce key theories and relate these to the field of architecture and the built environment; we develop our RtD approach in relation to the discourse.

3.1 Approaching Research through Design: relating to the history, key theories and discourse

In this dissertation, we research the development of 'ideal' and 'feasible' circular building components. We therefore move past researching the existing. Instead, interventions in the existing are proposed. If (practical) knowledge is generated through action in reality, we speak of 'interventionist research' (Lousberg & van Stijn, 2022). These interventions need to be designed (Hauberg, 2011). Subsequently, our research contains both research and design components.

Scholars categorised different types of research with a design component (e.g., Buchanan, 2001; Cross, 1999; Duchhart, 2011; Findeli, 1998; Forlizzi, Stolterman, & Zimmerman, 2009; Frankel & Racine, 2010; Frayling, 1993; Friedman, 2008; Nijhuis & de Vries, 2019; Stappers & Giaccardi, 2017). Following the categories of Frankel and Racine (2010), we distinguish: 'Research for Design' (RfD), 'Research about Design' (RaD) and 'Research through Design' (RtD). RaB refers to research conducted to understand design(ing) (Frankel & Racine, 2010); RaB includes research on design(ing) done by other disciplines such as economics, history, sociology, psychology, and semiotics (Findeli, 1995). RfD provides the knowledge to make an informed decision in design projects (Downton, 2003; Forlizzi et al., 2009; Frankel & Racine, 2010). In other words, the research serves the development of a specific design for a specific context (Frankel & Racine, 2010). In RtD, the aim is to generate 'generalizable' knowledge for a class of problems or products through design(ing) (Buchanan, 2001; Frankel & Racine, 2010). Note that the main object is development of knowledge, not just the development of the design itself. Following this categorization, we can characterize our research as RtD.

RtD is a relatively young field and still in development (Dalsgaard, 2010; Findeli, 1998; Forlizzi et al., 2009; Meijers et al., 2015; Stappers & Giaccardi, 2017). In recent years, a considerable amount of contributions have been made to further the body of knowledge (Findeli, Brouillet, Martin, Moineau, & Tarrago, 2008; Hensel, 2013; Markussen, Krogh, & Bang, 2015). Yet, it remains – as is aptly described by Markussen, Krogh and Bang (2015) – a 'murky' field. In the works on RtD we find no overall consensus on definitions, paradigms or applied methods (Buchanan, 1992, 2001; Chow, 2010; Frankel & Racine, 2010; Godin & Zahedi, 2014; Langrish, 2016; Markussen et al., 2015; Stappers & Giaccardi, 2017; Zimmerman, Forlizzi, & Evenson, 2007).

Various disciplines have their own literature on, and various approach(es) to RtD – specifically tailored to the subject matter and traditions in the field (Melles, 2008). Our research takes place in the field of Architecture and the Built Environment (ABE). However, relevant theory is often discussed in the context of other design disciplines and not 'contextualised' to the field of ABE. Furthermore, literature on RtD for the field of ABE remains rather fragmented. We found that a cohesive overview of theories and methodological discussions is lacking. Furthermore, we often miss a clear link between the theoretical discourse on RtD and the concrete knowledge which can guide those attempting an RtD (Andriessen, 2008; Reeker, Langen, & Brazier, 2016). The lack of methodological overview, awareness and cohesion could hinder (rigorous) application, recognition of the approach and further advancement of the research field (Chow, 2010; Forlizzi et al., 2011; Godin & Zahedi, 2014; Meijers et al., 2015; Zimmerman, Stolterman, & Forlizzi, 2010). The idea of a more uniform understanding of RtD and development of a common RtD approach is not undisputed (e.g., see Gaver (2012) and Buchanan (2001)). However, we – and other designer-researchers – need to be able to relate to the theoretical discourse to apply RtD in the field of ABE.

In this chapter, we provide an overview of the development of RtD and introduce key theories, relating these to the field of ABE. We highlight important shifts in the methodological debate and show the status quo in the discourse. We aim to develop our RtD approach in relation to the discourse; by doing so, we also aim to help other beginning designer-researchers to position themselves in the methodological dialogue. The remainder of this chapter is structured as follows: in Section 3.2, without claiming to be comprehensive, we provide a historical overview of the development of Design Research – the field in which RtD is rooted – and introduce key theories. In Section 3.3, we discuss different categories of Design Research 'introducing' the category of RtD and elaborating on its origin. In Section 3.4, we discuss the status quo of RtD discourse and debates in the field of ABE. In Section 3.5, we develop our RtD approach in relation to the discourse. In Section 3.6, we conclude and discuss this chapter.

3.2 History and key theories in Research through Design

Various authors have provided their perspective on the history of the Design Research field, to name a few: Bayazit (2004), Buchanan (2001), Cross (2006a, 2006b), Frankel and Racine (2010), and Langrish (2016). A particularly concise summary is provided in the (online) interview for the 2015 RtD conference by Frayling (in Durrant & Price, 2015). We have combined these historical perspectives and introduce key RtD theories by linking them to the historical overview.

3.2.1 Origins of Design Research

The Design Research field is still relatively young, and has been gaining momentum since the 1960's. Prior, design was mostly regarded as a craft activity (Buchanan, 2001). The origins of Design Research can be traced back to influential works and movements decades or centuries earlier. Buchanan (2001) suggests that modern Design Research may be traced back to the seventeenth century work 'the Dialogues Concerning Two New Sciences' of Galileo Galilei: his work reflects the turn towards theoretical investigation in various fields. Cross (2006a, 2006b) identifies the Modern Movement designers of the 1920's as the roots of Design Research. Designers, such as 'de Stijl' member Theo van Doesburg and Le Corbusier, aimed to produce works of art and design based on objectivity and rationality, instead of merely trusting upon craft and intuition. Their goal was to apply scientific knowledge to support designing (Cross, 2006a). Bayazit (2004) points out that the Modern Movement itself could be traced back to the methodological approach to design education taken by Bauhaus; after Bauhaus closed, staff members 'spread out' and introduced the Bauhaus tradition within various design institutions.

3.2.2 Design as a science

The ambitions to scientize design flourished in the 1960's in the Design Methods Movement (DMM) (Cross, 2006a, 2006b; Langrish, 2016). Note that their ideas have since been criticized (see more in Section 3.2.3), Yet, understanding their theories is still valuable: the DMM provided a first, (overly) simplified understanding of designing. We found that going through the same 'thought process' helped to understand further developments in the discourse. Therefore, we elaborate on the origin and DMM theories in the remainder of this section.

Why change design from a craft to a science? The movement can be understood in the context of several societal developments. First, there was an optimistic zeitgeist in which science and creativity were seen as the driver of technological progress and increasing prosperity (Jonas, 2007b; Langrish, 2016). Science and creativity had resulted in major progress in fields like medicine (e.g., antibiotics) and space travel (e.g., the launch of the U.S.S.R.'s Sputnik) (Bayazit, 2004; Cross, 2006b; Langrish, 2016). Second, societal challenges increased the importance of existing design fields and the emergence of new ones. Post-war shortages asked for new production techniques and approaches in architecture and engineering (Bayazit, 2004), for example to solve the staggering housing shortages. The increasing level of consumerism fuelled the importance of Industrial Design Research. Third, the academicization of design faculties in the 1960's and 1990's fuelled the development of a scientific approach to design and Design Research (Findeli et al., 2008; Groat & Wang, 2013). In the first steps of developing a Design Research field, it is understandable that one looked to the well-established research traditions in the exact sciences.

The 'Conference on Design Methods', held in London in 1962 was the start of the development of a scientific design methodology (Bayazit, 2004; Cross, 2006b, 2006a). The DMM can be understood as the collective work of Bruce Archer, John Chris Jones, Christopher Alexander and Horst Rittel (Langrish, 2016). However, others contributors can be identified, such as Buckminster Fuller and Herbert Simon (Frankel & Racine, 2010; Langrish, 2016). They explored if techniques developed during the war could make design more scientific in fields such as industrial design, architecture and town planning (Langrish, 2016). Specifically, the DMM aimed for design methods which could provide a logical, systematic procedure to develop an 'optimal' design solution; design would become an automated process (Groat & Wang, 2013), a matter of 'diagnosis followed by prescription' (Downton, 2003; Frankel & Racine, 2010; Gedenryd, 1998). The DMM incorporated scientific techniques and methods into the design process and attempted to develop rational criteria for decision making (Bayazit, 2004). Influential works included Archer's (1965) 'systematic methods for designers' (Bayazit, 2004; Frankel & Racine, 2010) and Simon's (1968) 'the science of the artificial' (Bayazit, 2004; Cross, 2006a). Simon called for a design educational reform. His larger aim was to develop an objective, value-neutral, quantifiable and mathematical field of research focused on problem solving (Huppatz, 2015). The design of the artificial – e.g., man-made things, organisations – was to become the research subject of its own field

(Bayazit, 2004); designing was to be aided using capabilities of computers and tools from artificial intelligence and operational research (Simon, 1997).

Various publications provided systematic design process models, which externalize the design process into charts and diagrams (Groat and Wang, 2013). Jones (1963) recognised that design consisted of three sequential phases: (1) analysis, (2) synthesis, and (3) evaluation. Even though the models appear simplified and linear, they did acknowledge the necessity of iteration. The analysis phase might include a (systematic) inquiry on the existing situation (i.e., site- or plan analysis); it might include comparative precedent studies to identify possible means to solve the problem (e.g., toolbox of partial solutions or morphological table). More examples are described in Nijhuis and Bobbink (2012). The analysis phase provides a better understanding of the specific challenges, opportunities and results in the development of design objectives and requirements. Applying the knowledge acquired in the analysis phase, the designer can (intuitively and/or systematically) generate design variants during the synthesis phase. Finally, in the evaluation phase, the design variants are evaluated to the set criteria and the 'optimum' solution is selected. See Figure 3.1 for a scheme of a three-phased systematic design process model.

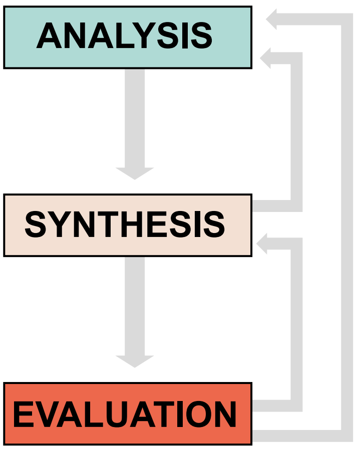


FIG. 3.1 A three-phased systematic design process model

Many variations on- and nuanced interpretation of the systematic design process models have since been developed. For an extensive overview of models we refer to Dubberly (2005). Two notable models are 'the basic design cycle' (Roozenburg & Eekels, 1995) and the 'design process: analysis, synthesis, and evaluation' model (Duerk, 1993).

The former model was presented in the book ‘Product design: fundamentals and methods’ (Roozenburg & Eekels, 1995). A standard work at Industrial Design Engineering faculties which is also used in Architectural education (van Eekhout, 2002). The basic design cycle (1995) specifies both the design process activity and output (see Figure 3.10 on the right). The cycle commences from the desired *function* (input 1) of the to-be-designed artefact (e.g., building, building component, processes, business model). This could be a first idea on its technical-, social-, or economic functions. The *analysis* (activity 1) helps the designer understand the problems and opportunities of the to-be-designed artefact. From the analysis, the designer formulates the *criteria* (output 1) that the to-be-designed artefact should fulfil. In ABE, we often summarize formal requirements in the ‘program of requirements’ (Wamelink, Geraedts, Hobma, & Lousberg, 2009). However, these requirements might also be more intuitive, such as preferences of the designer. The design *synthesis* follows (activity 2). The word ‘synthesis’ refers to the organising, manipulating, combining gathered partial information into a cohesive structure (Kolko, 2010), namely *preliminary design* variant(s) (Roozenburg & Eekels, 1995) (output 2). The design is externalized in various possible forms (e.g., verbally, textually, in sketches, drawings or models). The preliminary design variant is then *simulated* (activity 3) or ‘tested’. The rigor of simulation can vary: the designers can make (intuitive) assumptions on the potential performance of the design variant based on (professional) experience. Yet it is also possible to use scientific research methods (e.g., stakeholder interviews or Life Cycle Assessments) or professional simulation tools (e.g., building climate performance simulation software) to test design variants. Simulation results in *expectations on the characteristics* (output 3) of the designed variant(s). Subsequently, the expected design characteristics are *evaluated* (activity 4). During the evaluation, the expected characteristics are compared to the criteria formulated in output 1. The evaluation shows the *value of the design* variant (output 4). The final activity of the cycle is the *decision* (activity 5). The designers decide if the design variant is either ‘an acceptable design’ (outcome 5) or the designer returns to the synthesis stage to develop a more ‘fit-for-use’ design variant. Another pathway is for the designer to return to the analysis (activity 1) to redetermine the design criteria. Usually, the design cycle will require multiple iterations to develop a satisfactory design (Jager, 2002).

The model of Duerk (1993) challenges the sequential nature of the analysis and synthesis phases and adapts the three-phased systematic design process models. Duerk (1993) expresses that good design variants do not logically follow from the analysis phase. This simultaneously indicates that steps might not happen one after the other. Especially for experienced design practitioners, the design process is not experienced in separate phases (van Dooren et al., 2014). As such, this model illustrates the transition from ‘design as a science’ towards ‘design as a discipline’.

3.2.3 From a science to a discipline

From the 1970's onwards, the scientific design methods and the idea of 'design as a science' were criticized (Bayazit, 2004; Cross, 2006a, 2006b; Rith & Dubberly, 2007). Again, these developments need to be understood in the zeitgeist of that time: belief in science was replaced by distrust (Langrish, 2016); traditional values were rejected; there was a climate of radical political movements and campus protests (Cross, 2006a, 2006b). Notably, amongst the critics were those who originally contributed to the DMM, such as Christopher Alexander and John Chris Jones (Bayazit, 2004; Cross, 2006b; Frankel & Racine, 2010; Langrish, 2016). Critics posed that the simplistic, linear design models were appealing as they attempted to provide a logical understanding of the design process (Buchanan, 1992). However, these models did not reflect or support what happens in design practice (Bayazit, 2004; Cross, 2006b; Gedenryd, 1998).

Rittel contributed to both saving and challenging the design methods field. He introduced the idea of first and second generation design methods (Rittel, 1992): first generation methods had been too simplistic, but reducing complexity was needed in the beginning, supposedly saving the field (Bayazit, 2004; Cross, 1993, 2006b; Langrish, 2016). In the second-generation methods, he argued for (an understanding of) stakeholder participation in the design process. Rittel and Webber (1973) challenged the DMM approach with their 'wicked problems' theory (Frankel & Racine, 2010). They argued that most design problems are wicked problems. The term wicked is not used as 'ethically despicable' but refers to the problem being 'malignant', 'vicious' (like a circle), 'tricky', or 'aggressive' (Rittel & Webber, 1973). Rittel described wicked problems as "that class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing." (Churchman, 1967, p. B141).

This influential theory challenged the applicability of rational, sequential design methods for understanding complex design problems (Buchanan, 1992; Cross, 2006b; Frankel & Racine, 2010; Gedenryd, 1998). Buchanan (1992) aptly explains the difference between the DMM approach and the wicked problems theory: in the linear design models of the DMM, the designer needed to define the variables involved and 'calculate' the solution. This assumes designers can understand, control, and reduce all the variables as is common practice in exact sciences. Proponents of the wicked problems theory argued that (exact) science problems are tame (Cross, 2006b). In contrast, design problems are ill-defined or 'indeterminate' (Buchanan, 1992); a designer cannot define the exact problem due to the complexity of evolving variables and the amount of variables involved. As designers cannot

TOC

realistically determine all the variables a priori, they cannot develop an optimal design variant (Buchanan, 1992; Frankel & Racine, 2010; Rittel & Webber, 1973).

Donald Schön (1983) offered an alternative approach to Design Research in his seminal work 'the Reflective Practitioner'. He explicitly challenged the positivist paradigm at the base of the DMM, applying instead a constructivist paradigm (Bayazit, 2004; Cross, 2006a). Schön based the approach on an analysis of real design processes rather than forcing design processes to fit rational, simplified, and sequential methodologies (Frankel & Racine, 2010). Schön's 'reflective practice' approach was closer to the artistic, intuitive processes which practitioners use when approaching design problems (Cross, 2006a; Schön, 1983). Schön (1983) called for professionals to become aware of their implicit knowledge base and learn from their experience. He introduced three key concepts: 'knowing-in action', 'reflection-on-action' and 'reflection-in-action'. Knowing-in-action refers to the tacit knowledge that is in our actions. A "competent [design] practitioners usually know more than they can say." (Schön, 1983, p. viii). In other words, when a skill has been thoroughly mastered, one might not be able to explain anymore 'how it is done'. Reflection-in-action is to reflect on behaviour during the design activity. Essentially this is a form of 'learning whilst doing'. Reflection-on-action is the evaluation after a design activity is completed. Reflection-in-action and reflection-on-action, can support to make implicit design knowledge explicit. Hence, it can help to generate (scientific) knowledge for the field of Design Research. In chapter 3 of the Reflective Practitioner, Schön (1983) observed an architectural design process in a design studio. From these observations he proposed that the reflective practice in architectural design is a 'conversation with the situation'. He described how the designer 'frames the problem' (i.e., the designer names the problem which they will tackle and names the angle of approach). The designer explores the implications of the setting of the problem and possible solutions in 'moves'. The potential implications of these moves are then reflected on and new frames or moves may be considered (Groat & Wang, 2013). For Schön designing is a complex, and unique process for different designers: each has their own knowledge, personal system of preferences and a specific language of sketching and modelling (Goldhoorn, 1991).

Van Dooren et al. (2014) argued that for experienced practitioners the process does not contain separate steps but is a continuous process based on tacit knowledge and experience. They suggested a framework to help make the individual design process explicit, and so support designers to reflect in- and on action. The framework includes 5 generic elements which each designer uses – to some extend – in their design process. The 5 elements are 'experimenting', 'guiding theme', 'domains', 'laboratory' (or visual language) and 'frame of reference'. Using these elements, the designer can create a map of their design process, results and reasoning.

In line with the train of thought developed by Rittel and Webber's (1973) 'wicked problems theory' and Schön's 'reflective practice', Dorst and Cross (1996) developed their ideas on coevolution of the problem- and solution space. The co-evolution model (see Figure 3.2) proposes that designers determine the design problem as they design the solution. In other words, the problem and solution develop in parallel.

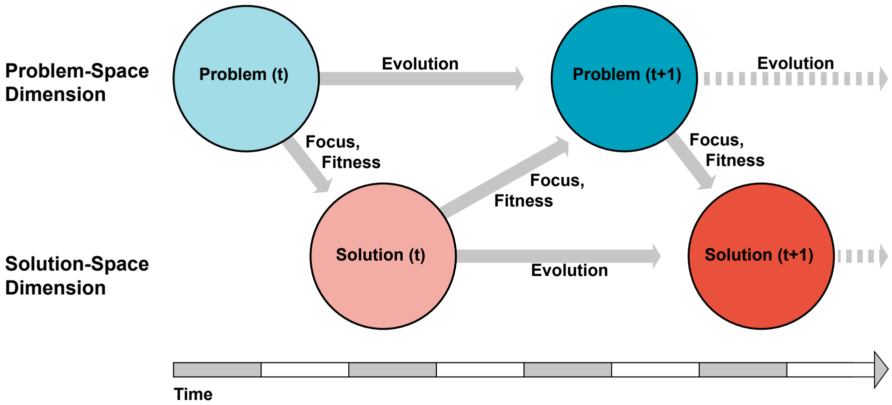


FIG. 3.2 The co-evolution model of the problem-, and solution space of Maher et al. (1996) discussed in Dorst and Cross (1996). Model adapted from Maher et al. (1996). Courtesy © 1996 Springer Science+ Business Media Dordrecht

3.2.4 In debate

The two views in the Design Research field – distinguished by Cross (2006a) as 'design as a science' and 'design as a discipline' – have caused continuing conflict amongst researchers and practitioners (Korhonen, 2011; Langrish, 2016; Soo Meng, 2009). Both schools of thought have yielded Design Research approaches in different design disciplines existing today (Frankel & Racine, 2010). We find approaches based on the DMM, such as Design Science Research (DSR). Such approaches appear to have grounded in the fields of engineering, some branches of industrial design and computer design (Cross, 2006b). On the other hand, we find approaches leaning on the ideas of a 'reflective practice'. In ABE, for example, this 'constructivist view' appears to have been influential (Cross, 2006b). The preference for this approach could be due to the beaux-art legacy of the design discipline (Buchanan, 2001), which emphasises the artistic qualities and uniqueness of the

TOC

architectural designer. Additionally, it could be linked to the increasing indeterminacy of the problem. Jager (2002) argued that architectural design is a scale-level higher than industrial design, increasing the complexity in variables with n-fold (see Figure 3.3). The more indeterminate the problems, the less applicable the systematic design process models (and derived sequential research methods) seem.

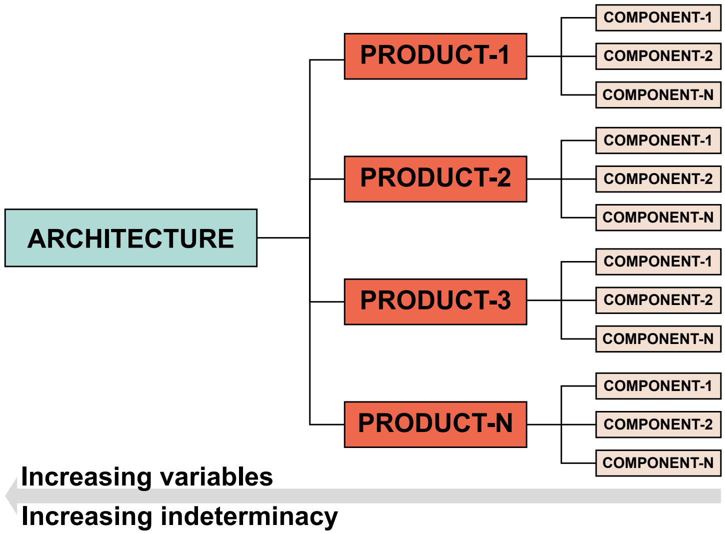


FIG. 3.3 Increasing complexity on architectural level versus product designing. Model adapted from Jager (2002)

Although the different views continue to exist, we can see attempts to move away from or even reconcile the two opposing views. As early as the 1990's, de Jong (1992) aimed to reconcile the language of the design practice with the idiom of science. Dorst (1997) proposed that the constructivist and positivist view were complementary to understand design methodology and suggested a dual-mode approach. Another, example is the work of Soo Meng (2009), who argued that the understanding of Simon, a thought leader of the DMM, was too harsh. According to Soo Meng, Simon was aware of the intuitive, iterative character of design. Both approaches need not be opposing, but could feed each other to enrich further developments of the field.

3.3 Categorization of Design Research: Research through Design and more

The early discussions in Design Research were occupied with determining how to understand design(ing) and its position between science and practice. Another influential debate in the field concerned itself with how to relate design(ing) to research. This includes discourse in which design and research (both as noun and verb) were defined and the similarities and differences between them explored (see e.g., Groat & Wang, 2013; Leatherbarrow, 2013; Stappers & Giaccardi, 2017)). Various scholars have also attempted to categorise different types of research which contain a design component (e.g., Buchanan, 2001; Cross, 1999; Duchhart, 2011; Findeli, 1998; Forlizzi et al., 2009; Frankel & Racine, 2010; Frayling, 1993; Friedman, 2008; Nijhuis & de Vries, 2019; Stappers & Giaccardi, 2017). Buchanan (2001) distinguished clinical, basic and applied research. Frayling (1993) spoke of research for-, through- and into art and design – coining the term RtD. Other authors have introduced prepositions such as 'by', 'in', 'on', and 'about', and still more relationships between design and research can be identified (see Duchhart, 2011, p. 10). RtD is also closely aligned with several other approaches (Chow, 2010; Frankel & Racine, 2010): Findeli used the name Project Grounded Research (PGR) for RtD (e.g., see Findeli et al., 2008). In PGR, research is conducted within the process of a real project. Design Oriented Research seeks to produce new knowledge by involving design activities in the research process (Fallman, 2007). Practice-Led-Research (or Practice-Based-Research) is defined as "research in which the professional and/or creative practices of art, design or architecture play an instrumental part in an inquiry." (Rust, Mottram, & Till, 2007, p. 11).

Even if authors use a similar term, their meaning might differ considerably from author to author (Duchhart, 2011; Frankel & Racine, 2010; Jonas, 2007a). Close reading of each author can clarify the meaning of the different categories, but the large variety does not stimulate clarity in the discourse (Duchhart, 2011). Frankel and Racine (2010) reconciled different frameworks and distinguished: 'Research for Design' (RfD), 'Research about Design' (RaD) and 'Research through Design' (RtD). We adhere to their categories and refer back to Section 3.1 for a more elaborate explanation of each category.

RtD is the category of Design Research which focusses on developing 'generalizable' knowledge through design(ing) (Frankel & Racine, 2010). Jonas (2007a) posed that RtD is the only suitable Design Research approach as the others merely observe or assist the design(ing). As the goal in RtD is to develop knowledge through design(ing), through intervening in reality, we conclude that this approach should play an important role in research within the field of ABE and in the research in this dissertation.

Zimmerman and Forlizzi (2014) identified three places of 'origin' for the practice of RtD, based on the framework of Koskinen, Zimmerman, Binder, Redström and Wensveen (2011): the interaction research group in the universities of technology in the Netherlands applied a 'lab-style' RtD. In a 'lab setting', designers innovate freely using a blend of methods to develop and evaluate a design and extract knowledge. In Scandinavia designers applied a user-centered design- and participatory approach as a 'field-style' RtD. In the art and design schools of the UK, provocative artifacts were central to a 'showroom-style' RtD: critical designs enforce people to consider and reconsider the status quo. Stappers and Giaccardi (2017) suggested that since its conception RtD has been actively developed by the art and design community in the UK and Scandinavia, the Dutch universities of technology and design academies, and the human-computer interaction (HCI) community in the USA.

3.4 Research through Design in the field of Architecture and the Built Environment

RtD has become more popular and the merits of design(ing) within research is being acknowledged (Chow, 2010; Verbeke, 2008; Zimmerman et al., 2010). Many authors have contributed to developing the RtD approach.

A seminal work in architectural research methods is the work of Groat and Wang (2013). Their chapter on the relation between design and research concluded that designing can yield many research questions for which many research methods could be appropriate. Yet, it is noteworthy that this publication does not further elaborate on the term or approach to RtD. "WAYS to study and research urban, architectural and technical design" by de Jong and van der Voordt (2002) initially aimed to provide a text book on research methodology for students of these fields, focusing on RtD. The resulting work shows a rich landscape of views and approaches, but the positioning of these approaches is largely left to the reader. More and more RtD designer-researchers reported on their RtD studies, publishing their innovations, reflections and generated knowledge (e.g., see the proceedings of the Biennial Research through Design conference (2013), (2015), (2017), and (2019)). These publications provide a wide range of examples for RtDs, including for the field of ABE.

There is no doubt that discourse on RtD in the field has become, and is becoming, increasingly rich. Yet, we found that the discourse on RtD in the field of ABE remains diverged and fragmented. The emphasis on the uniqueness of RtD approaches is perhaps a reflection of the 'design as a discipline' approach prevalent in the field – which critiqued the idea of common methodologies. Furthermore, we found fragmentation between the theoretical discourse on RtD and more practical approaches, methods and examples: literature does not yet provide clear, practical guidance on how to RtD (Andriessen, 2008; Reeker et al., 2016). Additionally, much of the discourse on RtD originates from other design disciplines. Herein relevant knowledge is not discussed in the context of research in the field of ABE.

3.4.1 Paradigmatic discussions in RtD in Architecture and the Built Environment

When attempting an RtD in ABE, insight is needed in the research paradigm. Research paradigms can be characterized through three aspects (Guba, 1990): their ontology (i.e., what is the "nature of reality"? (Creswell, 2003, p. 21)), epistemology (i.e., what makes an observation valid; "how do we know what we know?" (Creswell, 2003, p. 21)) and methodology (i.e., how do we go about finding knowledge?).

There is no agreed upon paradigm for RtD (Godin & Zahedi, 2014; Markussen et al., 2015): scholars have argued to practice RtD under different paradigms. We find two opposing views which stem from the schism between the 'design as a science' and 'design as a discipline' (Buchanan, 2001). On the one hand, there are scholars who argue to adopt, adapt or learn from an established research paradigm, adhering to more classical 'rules' and methods for research (e.g., Breen, 2002; Groat & Wang, 2013; Herriott, 2019; Lenzholzer, Duchhart, & Koh, 2013; Markussen et al., 2015; Steinø & Markussen, 2011). As discussed in the previous section, design and Design Research have been approached applying a positivist or constructivist paradigm (see also Lenzholzer et al., 2013). There are also scholars who propose to adhere RtD to pragmatism (e.g., Dixon, 2020; Lenzholzer et al., 2013; Melles, 2008; Nijhuis & de Vries, 2019). Often, Schön is said to have a constructivist approach to Design Research. However, his focus on harnessing the knowledge-in-action from practice aligns to the ideas of Action

TOC

Research and the pragmatist paradigm as described by Dewey (Groat & Wang, 2013; Wolfgang Jonas, 2007a; Gavin Melles, 2008). A similar observation is made for the RtD approach – Project Grounded Research – as described by Findeli (Chow, 2010; Findeli, 2015). On the other hand, there are scholars who pose that RtD should be researched 'in its own terms', applying a design paradigm (Buchanan, 2001). In line with the approach of Schön (1983), the idea of 'designerly ways of thinking' was coined by Archer (1979). Cross (2006a) expanded on this idea and introduced the paradigm of 'designerly ways of knowing'. Various authors have since contributed to the methodological development of RtD working from the designerly paradigm (e.g., Jonas, 2018, 2007b, 2007a; Langrish, 2016; Nijhuis & Bobbink, 2012; Nijhuis & de Vries, 2019). However, what this designerly paradigm precisely entails remains less concrete compared to the 'established' paradigms.

The discussions between these two views boils down to how authors relate knowledge of 'traditional' sciences and design practice (Langrish, 2016). Should design(ing) be informed by knowledge generated in and according to the 'rules' of established scientific fields, or does (traditional) science need to learn from design (practice) (Frankel & Racine, 2010). And, to what extend do we distinguish RtD from other scientific traditions of inquiry, or do we seek similarities? The position of authors in the discourse varies and might be understood by their interests and background (Markussen et al., 2015). For example, is their core focus on developing artifacts or knowledge (see Reeker et al., (2016))? The stronger the focus is on the design of the artifact in a complex design context, the more the designerly paradigm might appeal. If designing is a core component of the field – as is the case in ABE – the placement of RtD under established (but foreign) paradigms might be considered blunt. Cross (2006a), for example, warned against researchers from other disciplines coming into the Design Research field using imported methods and approaches which are inappropriate for developing and understanding design(ing). However, if RtD is considered but a sub-approach to an otherwise positivist or constructivist scientific field, the alignment of RtD to the traditional paradigms could be of vital importance to legitimise RtD in that field (see Lenzholzer et al., 2013). Furthermore, it might depend on which knowledge is valued more by the researcher and the field: that of the scientist or the design practitioner (Cross, 2006a)? The discussion has not yet reached its conclusion; subsequently, different lenses and approaches to RtD persist, also within the field or ABE.

3.5 Our approach to RtD: Designerly pragmatism

As there is no agreed upon approach for RtD in the field of ABE, we needed to develop our own approach for this research in relation to the existing RtD theory. From the overview of the history and key theories, we identified 'building blocks' of RtD theory and argumentation. We combined these building blocks – in a logical manner – to develop our understanding and approach to RtD.

Our approach is based on several underlying arguments. First, we pose that we need to move beyond the idea of 'debate' and continue to develop our understanding and concretize the RtD paradigm (supported by e.g., Chow & Jonas, 2009; Forlizzi et al., 2011, 2009; Frankel & Racine, 2010; Godin & Zahedi, 2014; Jonas, 2007b, 2007a; Gavin Melles, 2008; Reeker et al., 2016). Second, in line with the argumentation of Melles (2008) and Markussen et al. (2015), methodological pluralism in RtD should not be accepted without embracing an underlying methodological reasoning and standard. A clear idea on the ontological and epistemological considerations of the applied methods in RtD is vital to conduct a valid RtD. Finally, we are sympathetic to the ideas that different lenses and methods can be complementary both in understanding and undertaking design (Dorst, 1997; Soo Meng, 2009), as well as extracting knowledge from the design(ing) (Groat & Wang, 2013; Gavin Melles, 2008). We find the crux lies in combining systematic research inquiries and design thinking – and appreciating how different modes of thinking can enrich each other (see also Markussen et al. (2015) and Steinø and Markussen (2011)).

In RtD, we find both a research and design component. We consider these as two connected, yet parallel processes which feed each other. Experienced designer-researchers might find that these two processes are very closely intertwined in their RtDs. Yet, we found that conceptually separating these could provide clarity for a beginning designer-researcher, and support understanding of 'what is happening in an RtD'. The design (process) underlies the research: from (parts of) the design(ing) we derive knowledge. The type of research goals and -questions linked to design(ing) can be diverse and span multiple disciplines; therefore, a multitude of methods can be selected to approach the research problem (Groat & Wang, 2013; Nijhuis & de Vries, 2019). A combination of methods could even be required to develop a full, integrated understanding of the design(ing) (Lenzholzer et al., 2013). Effectively, the designer-researcher needs to be quite a 'scientific chameleon'. This pluralistic methodology can only be the outcome of a commitment to pragmatism (Gavin Melles, 2008). RtD has a fundamentally pragmatic nature: the nature of knowledge is situated, contextual, produced in-, and through design(ing) practice (Hauberg, 2011; Melles, 2008; Nijhuis & de Vries, 2019; Schön, 1983); the research is driven by problems and opportunities aimed at application, to modify and improve upon reality (Gavin Melles, 2008; Nijhuis & de Vries, 2019; Zimmerman & Forlizzi, 2014). 'Truth' is found not in true or false, but in how well does it fulfill the aims, criteria or requirements (Nijhuis & Bobbink, 2012). To intervene in reality, strong, interdisciplinary collaboration with stakeholders is needed (Hauberg, 2011; Hensel, 2013; Gavin Melles, 2008; Reeker et al., 2016). This is certainly true for research in ABE in which knowledge is often generated in a practice-academic collaboration. In conclusion, the methodological pluralism and nature of RtD research suggests that RtD designer-researchers are indeed pragmatists. Several authors support there is a legacy of pragmatism in the field of ABE (see e.g., Melles, 2008; Nijhuis & de Vries, 2019).

Can we 'borrow' pragmatism and apply it in RtD as is? Melles (2008) argues an enlarged pragmatist paradigm is necessary to include all the designing disciplines. However, we consider there might also be a need for a pragmatist paradigm specified to RtD. RtD, has a strong design component underlying – and driving – the research (Frayling in Durrant & Price, (2015)). Design(ing), although a form of 'practice', has its specific ways of reasoning (Archer, 1979; Cross, 2006a; Schön, 1987). We question if RtD should be understood from a 'designerly-ways-of-knowing' paradigm alone, but the pragmatic research paradigm might become underlined, influenced and complemented with a 'designerly lens': Hence, we suggest a specified version of pragmatism could be suitable for RtD, namely 'designerly-pragmatism'. Although the basis of this paradigm could apply for RtD in various design disciplines, the emphasis on which reality is researched and which methodologies are preferred will likely vary from design discipline to design discipline.

In the remainder of this section, we will elaborate on designerly-pragmatism by discussing how we understand ontology, epistemology and methodology.

3.5.1 Ontology of designerly pragmatism

"To a pragmatist the mandate of science is not to find truth or reality, the existence of which are perpetually in dispute, but to facilitate human problem-solving" (Powell, 2001, p. 884). What is the nature of reality in RtD following the pragmatist rationale? Simon (1997, p. 55), already noted that the underlying aim of designing is to (support) *transition* from the current reality into a 'preferred one'. Other authors also mentioned different realities in RtD or explicitly discussed the transition between them (see e.g., Gaver, 2012; Godin & Zahedi, 2014; Jonas, 2018, 2007a, 2007b; Leatherbarrow, 2013; Nijhuis & de Vries, 2019; Zimmerman & Forlizzi, 2014): instead of limiting ourselves to 'what is', in RtD, we are concerned with investigating 'what could', 'what should' and 'what might' be. We focus on exploring realities which are not yet there and, so, need to be designed and tested. Furthermore, in RtD, we do not only observe these realities from the outside, but we research whilst also standing within (Frayling, 1993).

The idea of different realities is illustrated well by several scholars. De Jong (1992) suggests that, next to the existing, we can explore three types of future [realities]: the *possible*, the *likely (or probable)* and the *desirable* future. De Jong relates each of these future realities to a work field: discovering possible futures is the work of designers; predicting which futures are likely, is the work of scientists; those who govern society strive for a desirable future. By relating these three futures, we see that 5 possible realities exist (see Figure 3.4). Jonas (2018; 2007b, 2007a) suggests that the designers' reality – iteratively – transitions from 'the true', to 'the ideal', to 'the real'. 'The true' specifies how things are today; 'the ideal' reality deals with how things can be; 'the real' is how things will be tomorrow. Jonas corresponds these three realities to three design activities: (1) analysis, (2) projection, and (3) synthesis. We have summarized this model is Figure 3.5.

TOC

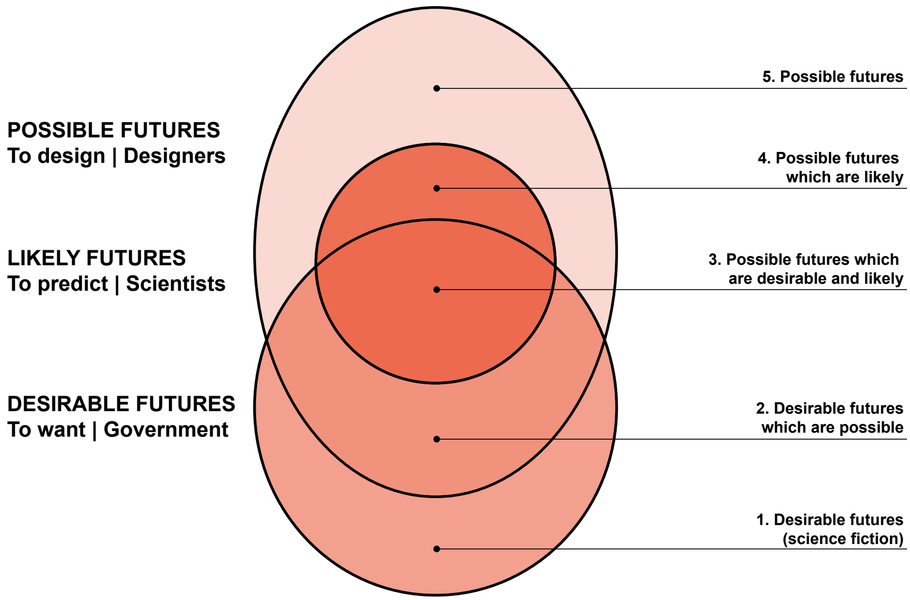


FIG. 3.4 Relationship between possible, likely and desirable futures. Figure adapted from de Jong (1992). Image reprinted by permission of T.M. de Jong.

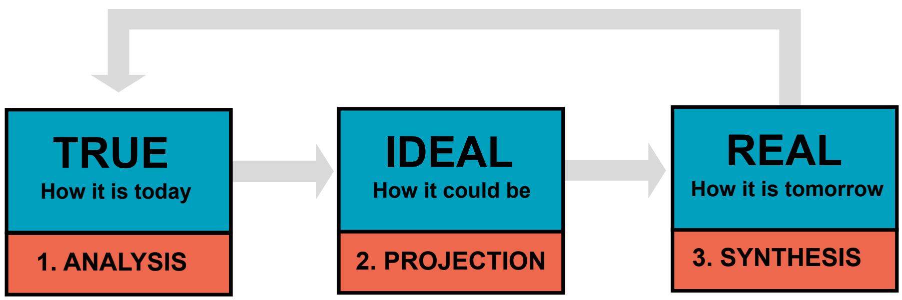


FIG. 3.5 The iterative transition between (1) the true, (2) the ideal and (3) the real in relationship to the design activities: (1) analysis, (2) projection, and (3) synthesis. Figure based on the model of Jonas (2007b, 2007a)

For our research, we developed an ontological model by building on the above-mentioned models (see Figure 3.6). We combine the idea of transition of realities as introduced by Jonas (2018, 2007b, 2007a), but build upon the types of realities as introduced by de Jong (1992) and the three-phased design model of analysis, synthesis and evaluation. In analysis, designer-researchers are concerned with how things are currently, by understanding the problem and opportunities and identifying (partial) solutions in the *existing* built environment. In synthesis, we design *possible* solutions for the built environment: they are concerned with how things could be. During evaluation, we select the most fitting solution. We pose that we are then concerned with how things should be (i.e., the *desirable*) and/or which reality will be most *likely*. This should not be understood as an 'optimally' desirable or 'optimally' likely reality – for all and for always. Rather, desirability and likeliness are in the eye of the beholder. The designer-researcher should be explicit: desirable or likely for whom, when and in what context; how is desirability or likeliness determined; what criteria are used? Consider if, for example, perspectives are conflicting: desirable for one stakeholder might be undesirable for society as a whole. As such we do not seek one 'optimal' desirable and likely reality – but rather explore 'better' or 'worse' realities in and for a particular context.

In the design process, the transition between the different realities is iterative; they exist in parallel. Looking at the research component, depending on what specific knowledge is derived from the design(process), we might research a different reality.

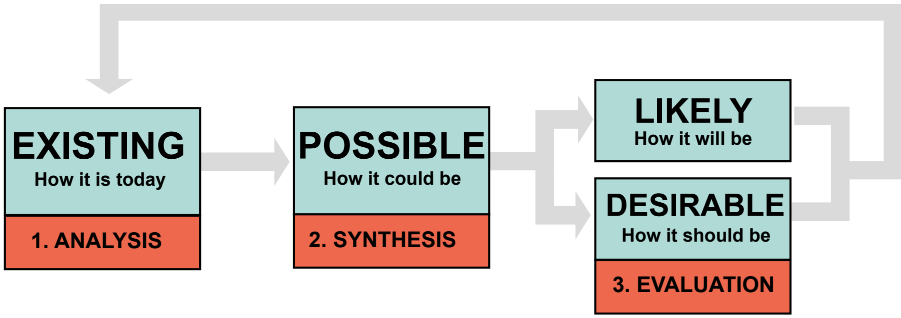


FIG. 3.6 Proposed ontological model for RtD under designerly-pragmatism: a transitional worldview linked to activities in designing

3.5.2 Epistemology of designerly-pragmatism

In RtD, we aim to generate knowledge from design(ing), but how do we know if this knowledge is valid? Common criteria to what makes a rigorous RtD are still lacking (Dalsgaard, 2010; Forlizzi et al., 2011; Markussen et al., 2015). Yet, various criteria have been proposed. Archer (in Cross, 2006b) and Borgdorff (2005) suggest the following criteria for Design Research: (1) it is inquisitive (i.e., it is aimed at extending knowledge); (2) it is informed (i.e., the research is conducted with awareness of precedent research); (3) it is an original investigation; (4) it is purposive: pertinent problems and questions, capable of investigation are addressed; (5) systematic methods are applied to reveal tacit knowledge embodied in designers, designing and the design; (6) it is communicable: results are reported which are testable by others. Although these are valuable criteria to distinguish design practice from an RtD, many of these criteria are generally applicable to research and say little on the rigor of an RtD specifically. Gaver (2012) states that the knowledge developed in an RtD should be understood as provisional, contingent and aspirational; as such, this knowledge should not have to be verifiable and extensible. In line with this reasoning, several contributions emphasize the need of peer review of the generated knowledge and design(ing), especially if the RtD is reflection based (Forlizzi et al., 2011; Hauberg, 2011; Nijhuis & Bobbink, 2012; Nijhuis & de Vries, 2019). On the contrary, authors who argue to align RtD with the established research paradigms imply that RtD should also adopt or adapt the 'normal' criteria of that paradigm to evaluate the validity of generated knowledge.

We propose that the criteria to assess the validity of knowledge generated in an RtD are linked to the design- and research component (see Figure 3.7). We established that the research component in RtD adheres well with the pragmatist paradigm. One could argue that just as in pragmatism, the criteria for assessing validity are adjusted according to the selected research problem and applied method (Lenzholzer et al., 2013). If the researcher applies a quantitative research method, reproducibility, generalizability, validity and reliability become applicable. On the other hand, if a qualitative research method is applied, or if the RtD focusses on highly contextualized case(s), the research should adhere to criteria for qualitative research. This means, in all RtDs, the appropriateness of the methods becomes a vital criterion (Lenzholzer et al., 2013).

We previously argued that the design activities underline and drive the research. Therefore, merely applying the criteria from the established research paradigms might not be enough (see also Markussen et al. (2015)). We pose that independent of the criteria for the research component, criteria for the design component need to be considered as well. Nijhuis and de Vries (2019) refer to purposefulness, reliability, consistency, transparency and usability as criteria for the rigor of the design process. We suggest that criteria do not need to assess the 'rigor' (in terms of quality) of the design(ing), per se. A researcher can learn a great deal from a poor design or design process. The criteria for the design component reflect on the rigor in the argumentation in the design(ing): is it possible to follow the logic, the line of argumentation in the design process (Nijhuis & de Vries, 2019)? Can we retrace and understand what aim is striven for; what means are used, on what basis choices were

TOC

made and why (Bardzell, Bardzell, Dalsgaard, Gross, & Halskov, 2016; Nijhuis & de Vries, 2019)? For this purpose, Findeli (1998), Jonas (2007a) and Godin and Zahedi (2014) pose that we should turn to the criteria 'strength of logic' and 'recoverability' in the design(ing). Strength of logic refers to "the strength of the chain of reasoning" (Biggs & Büchler, 2007, p. 69). Recoverability refers to making the design process "recoverable by anyone interested in subjecting the research to critical scrutiny." (Checkland & Holwell, 1998, p. 18); more specifically, "to make clear to interested observers the thought processes and models which enabled the [design]team to make their interpretations and draw their conclusion." (Checkland & Holwell, 1998, p. 18).

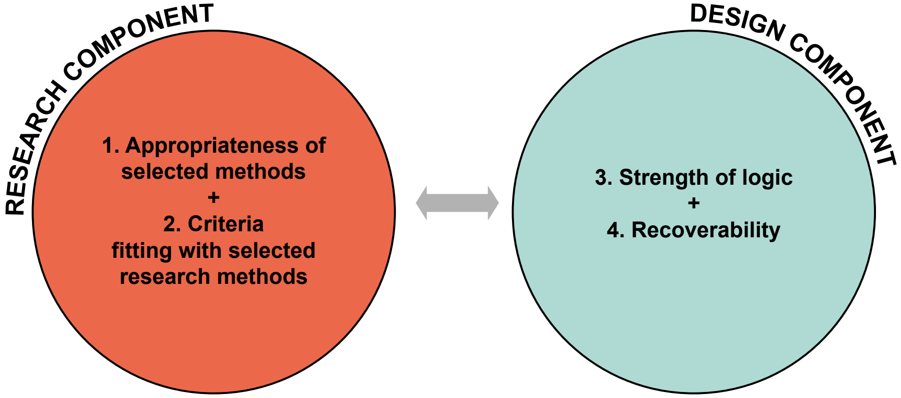


FIG. 3.7 Proposed criteria for evaluating the validity of knowledge generated in an RtD

Practically, the criteria of 'strength of logic' and 'recoverability' mean that understanding and documenting the (choices in the) design process are vital to ensure the knowledge derived from of the design component is valid. We pose that the designing in RtD would therefore benefit from some form of systemization. Here we explicitly do not mean systemizing the design process in the tradition of the DMM. Yet, we stress that the designer-researcher needs to understand the design process: it is key to know which parts of the design(ing) provide input for knowledge generation. Hence, it could be beneficial to (try to) plan the design process. Furthermore, how design(ing) is documented and analyzed is vital in an RtD (Bardzell et al., 2016; Reeker et al., 2016; Zimmerman & Forlizzi, 2014).

3.5.3 Methodology of designerly pragmatism

In this section we elaborate on how we go about finding knowledge – the methodology – for RtDs. First, we elaborate on the research approach, in which we look into the overall set-up of an RtD: the steps of extracting knowledge from design(ing). Second, we discuss suitable research methods: the ‘procedures and activities’ with which we extract knowledge from design(ing). Third, we discuss the design approaches to support systemization of our understanding of the design process.

3.5.4 Research approaches for RtD

The approach for the research component determines how the research is set-up and in what steps knowledge is – systematically – extracted from the design(ing). There are various models which provide procedural steps of an RtD. Figure 3.8 shows the RtD procedure as applied in the Project Grounded Research of Findeli (2015): the model shows how to transition from a design problem to an RtD. The general procedural steps of an RtD are described as well in the models of van Aken and Romme (2009) and Peffers, Tuunanen, Rothenberger and Chatterjee (2007). The latter model consists of 6 steps (see Figure 3.9). First, the design and research *problems are identified*; why it is relevant to address these issues is *motivated*. The design and research goals and planning are determined. Second, following an analysis, the *requirements of the solution* are specified. Third, the *design solution(s) is developed*. Fourth, the developed design is *demonstrated* (i.e., tested, or simulated). Fifth, the demonstrated design is *evaluated*. The model of Peffers et al. (2007) indicates these as different ‘point of entry’ for research. Adding to the points they identified, knowledge can be derived from the evaluation step or from reflection on the entire design process as well. Finally, the derived knowledge is *communicated* through academic papers, practical guidance articles, expositions, etc. Note that these schemes remain quite abstract and could be applied for varies types of RtDs. Each of these steps will require specification to the aims of the specific RtD: how is the designer developing the design solutions; how is the design simulated; what criteria are used in the evaluation? By specifying these steps, the designer-researcher determines the applied research methods; if it will be a more qualitative or quantitative research. We also refer to the work of Breen (2002) for schemes which are specified to different types of RtDs: the types are distinguished based on ‘where’ knowledge is extracted in the design(ing) (i.e., is knowledge extracted from the design or the designing) and how the knowledge is extracted.

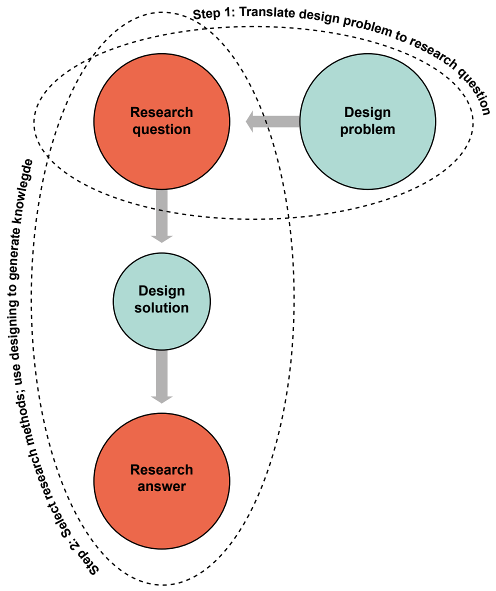


FIG. 3.8 Steps of the Project Grounded Research approach – Figure adapted from Findeli (2015)

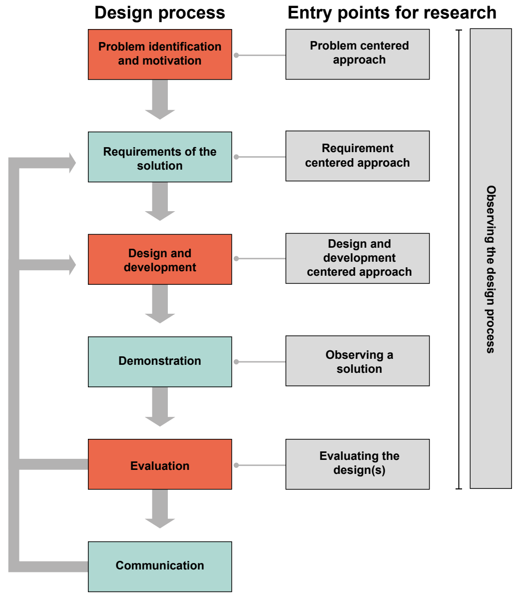


FIG. 3.9 Steps of the design science research process and research entry points – Model adapted from Peffers et al. (2007)

3.5.5 Research methods for RtD

The selected research methods in an RtD determine how knowledge is derived from (steps of) the design(ing). In which we understand methods as the ‘procedures and activities for selecting, collecting, organizing and analyzing data’ (Blaikie, 2010, p. 8). Which methods are preferent for RtD in the field of ABE? We already established that a multitude of methods can be selected to best approach the research problem in an RtD (Groat & Wang, 2013; Melles, 2008; Nijhuis & de Vries, 2019). This can be referred to as methodological pluralism (Creswell, 2003). Pragmatism is also associated with ‘mixed-methods’ (Creswell, 2003). In a mixed methods research, a qualitative and quantitative study are conducted separately. Only in the findings are the results systematically integrated to draw conclusions. Yee (2010) introduced the term ‘pick and mix method’ for RtD: due to the lack of established Design Research methods, designer-researchers need to compose their own method using methods from the social sciences, humanities, and natural sciences (Galloway, 2008). Even though these names might sound similar, they are differences. We suggest to adhere to the terminology stemming from pragmatism, namely methods in RtD are pluralistic. Practically, this means that no method is necessarily preferent or 'of limits'. Yet, the selection of methods – and the order in which they are applied – should be considered carefully (Lenzholzer et al., 2013).

3.5.6 Approaches for the design component in RtD: understanding, planning and documenting design

Although research methods can vary widely between RtDs, all RtDs derive knowledge from design(ing). In an RtD, the designing itself does not have to be a systematic process. Yet, as argued in Section 3.5.2, a 'systematic' understanding of the design and design process is vital for the validity of the knowledge generated in an RtD. In the following paragraphs, we will elaborate on approaches to support this understanding, focusing on planning, documenting and analyzing the design process. The designer-researcher needs to determine what and how knowledge is derived from the design(ing). The designer-researcher should understand what happens (or happened) when designing: what is analyzed; how is the design synthesized, simulated and evaluated; which parts of the design(process) provide the input for knowledge generation? For example, one could derive knowledge by reflecting on a 'completed' design or design process; knowledge might only be extracted from particular steps of the design process, or by analyzing from a particular viewpoint. Compare it to a lab-research, most chemists do not start a lab experiment without knowing exactly what they are testing and hence researching. Even though it sounds logical for a researcher to carefully plan the 'experiment', in RtD 'clarity' of the 'design experiment' in the up-front planning is challenging (if not an illusion). We refer again to the wicked problems theory and co-evolution of problem and solution (Dorst & Cross, 1996; Rittel & Webber, 1973). Langrish (2016) aptly states that the design process is too wonderous to capture in a linear process, to plan, manage and forecast; yet in an RtD we found it beneficial to keep trying. Concretely we suggest to plan 'as best we can' and continuously update the plans as new design and research insights appear.

Although the systematic design models originating from the DMM were found unable to systemize the design process – to make it prescriptive – these models could be helpful to increase understanding of the design(ing). De Souza van der Linden, de Lacerda and Ornaghi de Aguiar (2011) conclude that these models can support structuring the complex design activity, allowing the designer-researcher to detach and critically examine the process. Moreover, they found that these models – due to their simplification – can teach beginning designer-researchers to understand the design activity and help standardize the language needed to communicate on design(ing). For the purpose of understanding and 'planning' the design process different 'systematic design models' could be applied or adapted to fit the design goal of the RtD. For example, the basic design cycle by Roozenburg and Eekels (1995) provides a clear overview of the design activities and outputs per design iteration (Figure 3.10). The steps from the basics design cycle can be 'multiplied' in models which describe different stages of a development process. Which model is most suitable depends on what is designed (e.g., building, product, business model, strategy). For the innovation of a building product, the product innovation phases of Roozenburg and Eekels (1995) can be adopted (or adapted); for the design of a building, the building design and realisation process from Geraedts and Wamelink (2009) and NEN 2634 (Figure 3.10) can be used.

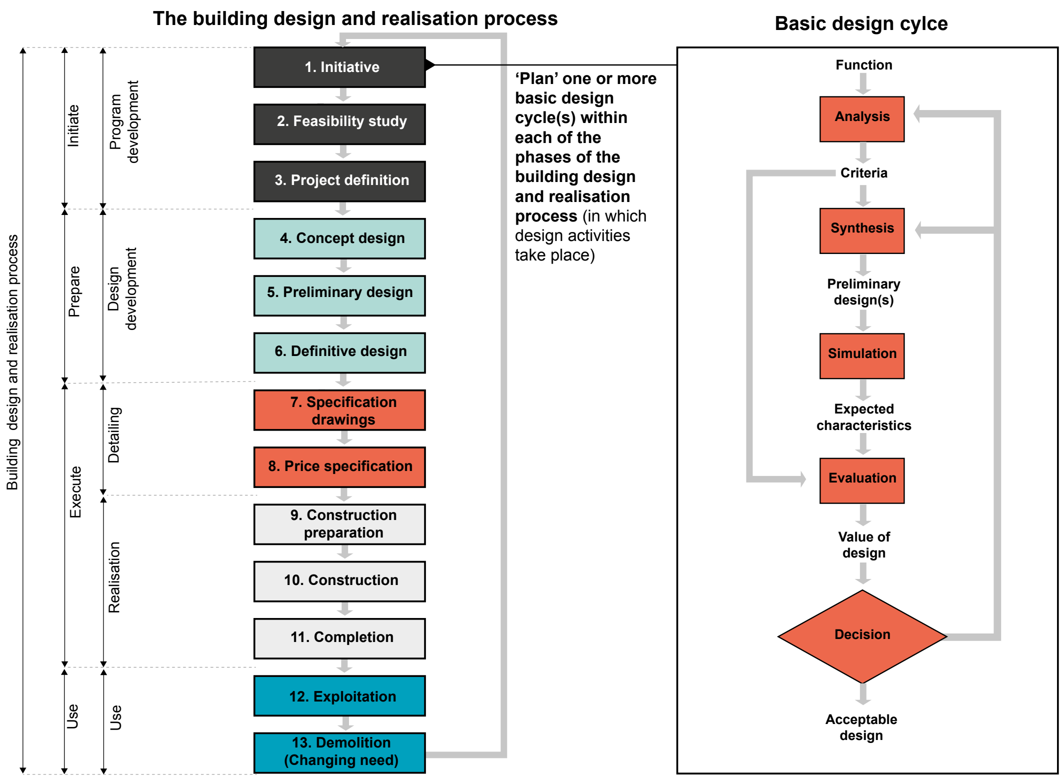


FIG. 3.10 The basic design cycle from Roozenburg and Eekels (1995) multiplied in the building design and realisation process (adapted) from Geraedts and Wamelink (2009) and NEN 2634

Documentation and analysis of the design, design process and the design choices (i.e., logic) is vital in RtD (Bardzell et al., 2016; Nijhuis & de Vries, 2019; Reeker et al., 2016; Zimmerman & Forlizzi, 2014). What and how the design(ing) is documented, might vary depending on the research goals and questions. Bardzell et al. (2016) suggest the documentation can include choices, way-finding, breakthroughs, challenges, and paths not taken. Documentation can occur in different ways, referring to workbooks (Gaver, 2012), annotated portfolios (Gaver, 2012), maps (Dalsgaard, Halskov, & Nielsen, 2008), traceable genealogy (Brandt & Binder, 2007) or using design reflection tools (Bardzell et al., 2016). Different models could be used as a basis for documenting and analyzing the choices in a design process. The design process could be documented following the 'design activities' specified in the basic design cycle by Roozenburg and Eekels (1995) (see Figure 3.10) and the divergence and convergence model by Roozenburg and Eekels (1995) (see Figure 3.11). Combined, these models could support visualization of the evolutionary logic of the design(ing), for example, in a 'map' of the design process. However, if such models are used the designer-researcher "should assume there is a gap between the complexity of practice and the simplicity of a theoretical model." (de Souza van der Linden et al., 2011, p. 11). The design process rarely follows the sequential, linear iterations suggested in these models, it might be difficult to document (and understand) the true design process using these models. An alternative model – to make the process explicit – is the generic elements framework by van Dooren et al. (2014). However, a more 'true documentation' might require further reductive analysis to show the logic behind the design choices. Using a combination of these models could help unveil to the logic in the design process (see also the dual-mode model of Dorst (1997)).

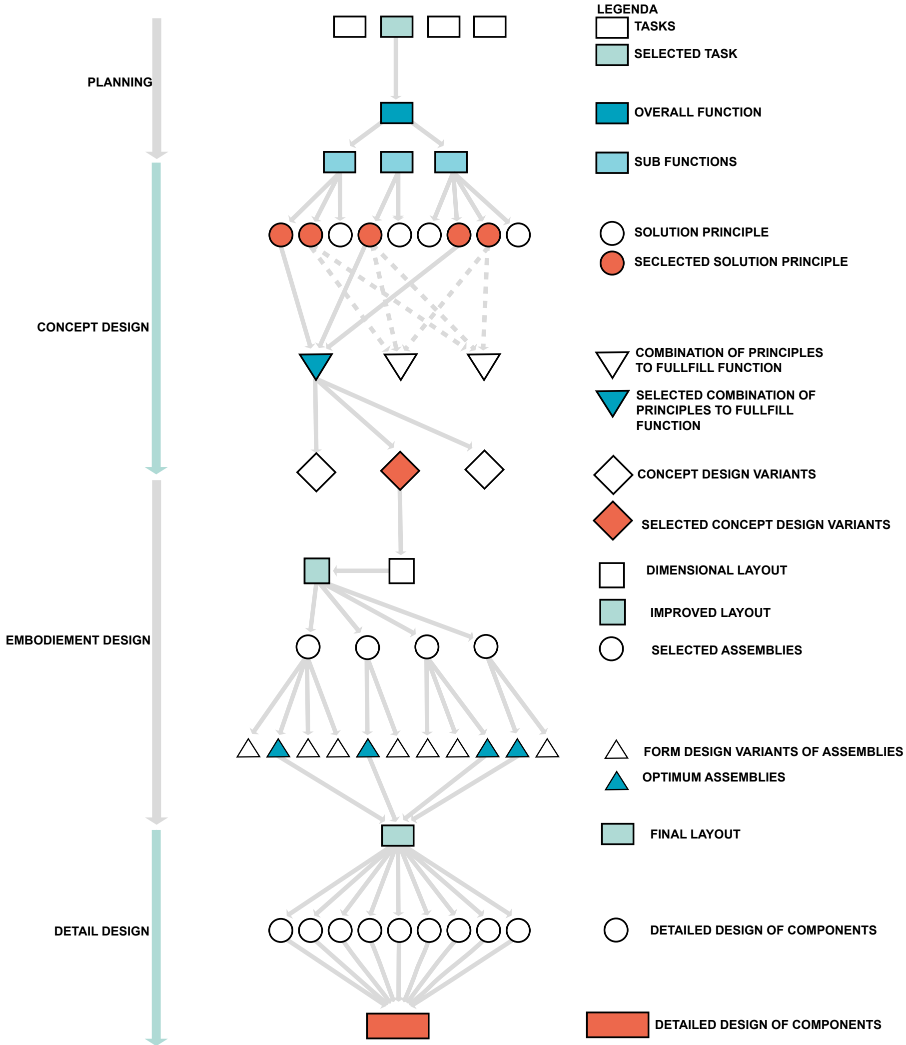


FIG. 3.11 Converging and diverging in the design process. Model adapted from Roozenburg and Eekels (1995). Used with permission of John Wiley & Sons - Books, from Product design: Fundamentals and methods, Roozenburg and Eekels, © 1995; permission conveyed through Copyright Clearance Center, Inc.

3.6 Conclusion and discussion

In this chapter, we provided a historical overview and introduced key theories in Research through Design (RtD). We showed the shift in the methodological debate from ‘design as a science’ to ‘design as a discipline’. We elaborated on the different categories in Design Research and the origin of RtD. We concluded that different lenses and approaches to RtD persist, also within the field or Architecture and the Built Environment (ABE). By providing the historical overview and showing the status quo in the discourse, we aimed to contribute to increasing methodological overview, awareness and cohesion in the discourse on RtD. Using existing theories as building blocks, we developed the RtD approach which we apply in this research: ‘designerly-pragmatism’. We discussed the ontological, epistemological and methodological considerations of our approach. We proposed a transitional understanding of the nature of reality suggesting that – in different stages of design – different realities are explored. We argued that a systematic research approach with appropriate methods should be complemented with a systematic understanding of design(ing) through careful planning, documentation and analysis. For the validity of RtD, the criteria of the research component need to be aligned with the criteria commonly applied for the selected research methods; the design(ing) needs to be ‘recoverable’ and the chain of reasoning needs to be ‘strong in logic’.

The rich research possibilities of RtD – linked to the complexity of the design process – are the strength of RtD. However, it also makes good application challenging, especially to the beginning designer-researcher. Providing methodological overview in this section and showing how we developed our approach in relation to the discourse, might help other designer-researches to develop and to position their RtD approaches. Our approach – which still allows for a wide range of possible RtDs – might also provide a usable approach for other designer-researchers in the field. Although the research in this dissertation already provides a concrete example of our approach, we suggest that more concrete guidance on applying an RtD approach might still be beneficial for beginning designer-researchers. Therefore, we hope that future research will continue to link RtD theory with practice and provide beginning designer-researchers guidance for various ‘types’ of RtDs.

References

Andriessen, D. (2008). Combining design-based research and action research to test management solutions. *Towards Quality Improvement of Action Research: Developing Ethics and Standards*, 125–134. Retrieved from http://www.onderzoekscoach.nl/wp-content/uploads/2012/12/Andriessen-2008-Chapter-9-in-Towards-quality-improvement-of-Action-research.pdf

Archer, B. (1965). *Systematic Method for Designers*. London: The Design Council.

Archer, B. (1979). What ever became of design methodology. *Design Studies*, *1*(1), 17–20.

Bardzell, J., Bardzell, S., Dalsgaard, P., Gross, S., & Halskov, K. (2016). Documenting the research through design process. *DIS 2016 - Proceedings of the 2016 ACM Conference on Designing Interactive Systems: Fuse*, 96–107. https://doi.org/10.1145/2901790.2901859

Bayazit, N. (2004). Investigating Design: A Review of Forty Years of Design Research. *Design Issues*, *20*(1), 16–29. https://doi.org/10.1162/074793604772933739

Biggs, M. A. R., & Büchler, D. (2007). Rigor and practice-based research. *Design Issues*, *23*(3), 62–69. Retrieved from https://www.jstor.org/stable/25224118?seq=8#metadata_info_tab_contents

Blaikie, N. (2010). *Designing social research: The logic of anticipation* (second edi). Cambridge, UK: Polity Press.

Borgdorff, H. (2005). *The debate on research in the arts*. Retrieved from http://www.ahk.nl/lectoraten/onderzoek/ahkL.htm.

Brandt, E., & Binder, T. (2007). Expertimental design research: Genealogy-intervention-argument. *International Association of Societies of Design Research*. Hong Kong.

Breen, J. (2002). Design driven research. In T. M. de Jong & D. J. . van der Voordt (Eds.), *Ways to study and research urban, architectural and technical design*. Delft: DUP Science.

Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design Issues*, *8*(2), 5. https://doi.org/10.2307/1511637

Buchanan, R. (2001). Design research and the new learning. *Design Issues*, *17*(4), 3–23. https://doi.org/10.1162/07479360152681056

Checkland, P., & Holwell, S. (1998). Action Research: Its Nature and Validity. *Systemic Practice and Action Research*, *11*(1), 9–21. https://doi.org/10.1023/A:1022908820784

Chow, R. (2010). What Should be Done with the Different Versions of Research-Through-Design? In C. Mareis, G. Joost, & K. Kimpel (Eds.), *Entwerfen - Wissen - Produzieren* (pp. 1–12). https://doi.org/10.14361/transcript.9783839414637.145

Chow, R., & Jonas, W. (2009). *Beyond Dualisms in Methodology: An Integrative Design Research Medium" MAPS" and some Reflections*. (July 2008), 16–19. Retrieved from http://digitalcommons.shu.ac.uk/drs2008/session10/track_b/2

Churchman, C. . (1967). Wicked problems. *Management Science*, *4*(14), B141–B146. Retrieved from http://www.rocksbackpages.com/Library/SearchLinkRedirect?folder=free-free-for-all

Creswell, J. W. (2003). *Research design: Qualitative, quantitative and mixed methods approaches* (second edi). London: Sage.

Cross, N. (1993). A history of design methodolgy. In M. J. de Vries, N. Cross, & D. P. Grant (Eds.), *Design Methodology and Relationships with Science* (pp. 1–14). https://doi.org/10.1007/978-94-015-8220-9_1

Cross, N. (1999). Design Research: A Disciplined Conversation. *Design Issues*, *15*(2), 5. https://doi.org/10.2307/1511837

Cross, N. (2006a). *Designerly ways of knowing*. https://doi.org/10.1360/zd-2013-43-6-1064

Cross, N. (2006b). Forty years of design research. *Design Studies*, *28*(1), 1–4. https://doi.org/10.1016/j.destud.2006.11.004

Dalsgaard, P. (2010). Research in and through design. *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction - OZCHI '10*, 200. https://doi.org/10.1145/1952222.1952265

Dalsgaard, P., Halskov, K., & Nielsen, R. (2008). Maps for design reflection. *Artifact*, *2*(3–4), 176–189. https://doi.org/10.1080/17493460802526412

de Jong, T. M. (1992). *Kleine methodologie voor ontwerpend onderzoek*. Amsterdam: Boom Meppel.

de Jong, T. M., & van der Voordt, D. J. . (2002). Ways to study and research urban, architectural and technical design. In *Ways to study and research*. Delft: DUP Science.
de Souza van der Linden, J. C., de Lacerda, A. P., & Ornaghi de Aguiar, J. P. (2011). The evolution of design methods. *9th International Conference of the European Academy of Design*, 1–12. https://doi.org/10.2307/4444220
Dixon, B. (2020). *Dewey and Design: A Pragmatist Perspective for Design Research*. Cham: Springer International Publishing.
Dorst, K. (1997). *Describing design: A comparison of paradigms*. Delft: Delft University of Technology.
Dorst, Kees, & Cross, N. (1996). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, *17*(4), 341–361. https://doi.org/10.1016/S0142-694X(01)00009-6
Downton, P. (2003). *Design Research*. Melbourn: RMIT University Press.
Dubberly, H. (2005). *How do you design? A compendium of models*. Retrieved from http://www.dubberly.com/wp-content/uploads/2008/06/ddo_designprocess.pdf
Duchhart, I. (2011). *An annotated bibliography on research-by-design (ontwerpend onderzoek)*. Wageningen and Utrecht: Wageningen University and Deltares.
Duerk, D. (1993). *Architectural programming: Information management of design*. Wiley.
Durrant, A., & Price, J. (2015). Provocation by Sir Christopher Frayling Part 1: Research Through Design Evolution.
Fallman, D. (2007). Why Research-oriented Design Isn ' t. *Knowledge, Technology & Policy*, *20*(3), 193–200.
Findeli, A. (1995). Design History and Design Studies: Methodological, epistemological and pedagogical inquiry. *Design Issues*, *11*(1), 43–65.
Findeli, A. (1998). A quest for credibility: Doctoral education and research in design at the university of montreal. In R. Buchanan, D. Doordan, L. Justice, & V. Margolin (Eds.), *Doctoral Education in Design: Proceedings of the Ohio Conference* (pp. 99–116).
Findeli, A. (2015). La recherche-projet en design et la question de la question de recherche : essai de clarification conceptuelle. *Sciences Du Design*, *1*(1), 57. https://doi.org/10.3917/sdd.001.0045
Findeli, A., Brouillet, D., Martin, S., Moineau, C., & Tarrago, R. (2008). Research through Design and Transdisciplinarity: A Tentative Contribution to the Methodology of Design Research. In Swiss Design Network (Ed.), *Focused: Current Design Research Projects and Methods* (pp. 67–94). Berne, Switzerland.
Forlizzi, J., Koskinen, I., DiSalvo, C., Wensveen, S., & Bardzell, J. (2011). Quality control: A panel on the critique and criticism of design research. *Conference on Human Factors in Computing Systems - Proceedings*, 823–826. https://doi.org/10.1145/1979742.1979497
Forlizzi, J., Stolterman, E., & Zimmerman, J. (2009). From design research to theory: Evidence of a maturing field. *Proceedings of the 3rd Conference of the International Association of Societies of Design Research (IASDR'09): Rigor and Relevance in Design*, (October 2015), 2889–2898. https://doi.org/10.1016/j.biopsych.2008.07.017
Frankel, L., & Racine, M. (2010). The complex field of research: for design, through design, and about design. In E. Durling, D., Bousbaci, R., Chen, L, Gauthier, P., Poldma, T., Roworth-Stokes, S. and Stolterman (Ed.), *Design and Complexity - DRS International Conference 2010*. Retrieved from https://dl.designresearchsociety.org/drs-conference-papers/drs2010/researchpapers/43
Frayling, C. (1993). Research in art and design. *RoyalCollege of Art Research Papers*, *1*(1).
Friedman, K. (2008). Research into , by and for design. *Journal of Visual Arts Practice*, *7*(2), 153–160. https://doi.org/10.1386/jvap.7.2.153/1
Galloway, A. (2008). *A brief history of the future of urban computing and locative media*. Carleton University, Ontario, Canada.
Gaver, W. (2012). What should we expect from research through design? *CHI'12: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 937–946. https://doi.org/10.1145/2207676.2208538
Gedenryd, H. (1998). *How Designers work: Making Sense of Authentic cognitive Activity*.
Geraedts, R., & Wamelink, H. (2009). Het bouwproces. In H. Wamelink, R. Geraedts, F. Hobma, & L. Lousberg (Eds.), *Inleiding Bouwmanagement* (pp. 1–34). Delft: VSSD.
Godin, D., & Zahedi, M. (2014). Aspects of research through design : A literature review. In A. Lim, Y., Niedderer, K., Redström, J., Stolterman, E. and Valtonen (Ed.), *Design's Big Debates - DRS International Conference 2014* (pp. 1667–1680). Retrieved from https://dl.designresearchsociety.org/drs-conference-papers/drs2014/researchpapers/85

Goldhoorn, B. (1991). Het atelier, analyse van een onderwijsmethode. *Archis*, *3*, 49–51.
Groat, L. N., & Wang, D. (2013). *Architectural research methods* (second edi). Hoboken, NJ: John Wiley & Sons, Inc.
Guba, E. . (1990). *The paradigm dialog*. Thousand Oaks: SAGE Publications, Inc.
Hauberg, J. (2011). Research by Design - a research strategy. *AE... Revista Lusófona de Architectura e Educacao*, (5), 46–56.
Hensel, M. U. (2013). Introduction to design innovation for the built environment – research by design and the renovation of practice. In M. U. Hensel (Ed.), *Design Innovation for the Built Environment: Research by Design and the Renovation of Practice* (pp. 1–4). https://doi.org/10.4324/9780203129746
Herriott, R. (2019). What Kind Of Research Is Research Through Design. *IASDR: International Association of Societies of Design Research Conference*, 1–11.
Huppatz, D. J. (2015). Revisiting Herbert Simon's "Science of Design." *Design Issues*, *31*(2).
Jager, A. (2002). Industrial design methods. In T. M. de Jong & D. J. M. van der Voordt (Eds.), *Ways to study and research* (p. 367). Delft: DUP Science.
Jonas, W. (2018). Systems design thinking: theoretical, methodological and methodical considerations. A German narrative. In P. H. Jones & K. Kijima (Eds.), *Systemic design methods: theory, methods and practice* (pp. 89–118). Tokyo: Springer Japan KK.
Jonas, Wolfgang. (2007a). Design Research and its meaning to the methodological development of the discipline. In R. Michel (Ed.), *Design Research Now* (pp. 187–206). https://doi.org/10.1007/978-3-7643-8472-2_11
Jonas, Wolfgang. (2007b). Research through DESIGN through research: A cybernetic model of designing design foundations. *Kybernetes*, *36*(9–10), 1362–1380. https://doi.org/10.1108/03684920710827355
Jones, J. C. (1963). A Method of systematic design. In J. C. Jones & D. G. Thornely (Eds.), *Conference on Design Methods* (pp. 53–73). New York: The Macmillan Company.
Kolko, J. (2010). Abductive Thinking and Sensemaking: The Drivers of Design Synthesis. *Design Issues*, *26*(1), 15–28. https://doi.org/https://doi.org/10.1162/desi.2010.26.1.15
Korhonen, J. M. (2011). The unpublished notebooks of J. M. Korhonen: Theories of design - is design problem-solving? Retrieved December 29, 2018, from https://jmkorhonen.net/2011/04/29/theories-of-design-is-design-problem-solving/
Koskinen, I., Zimmerman, J., Binder, T., Redström, J., & Wensveen, S. (2011). *Design Research Through Practice From the Lab, Field, and Showroom*. Waltham: Morgan Kaufmann Publishers, Inc.
Langrish, J. Z. (2016). *The Design Methods Movement: From Optimism to Darwinism*. 1–13. Retrieved from https://static1.squarespace.com/static/55ca3eafe4b05bb65abd54ff/t/574f0971859fd01f18ec63c1/1464797554420/222+Langrish.pdf
Leatherbarrow, D. (2013). The project of design research. In M. U. Hensel (Ed.), *Design Innovation for the Built Environment: Research by Design and the Renovation of Practice* (pp. 5–14). New York: Taylor & Francis.
Lenzholzer, S., Duchhart, I., & Koh, J. (2013). "Research through designing" in landscape architecture. *Landscape and Urban Planning*, *113*, 120–127. https://doi.org/10.1016/j.landurbplan.2013.02.003
Lousberg, L. H. M. J., & van Stijn, A. (2023). Positioning interventionist research methods. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods*. Taylor & Francis.
Maher, M.L., Poon, J., Boulanger, S. (1996). Formalising Design Exploration as Co-Evolution. In: Gero, J.S., Sudweeks, F. (eds) *Advances in Formal Design Methods for CAD. IFIP — The International Federation for Information Processing*. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-34925-1_1
Markussen, T., Krogh, P. G., & Bang, A. L. (2015). On What Grounds ? An intra-disciplinary account of evaluation in research through design. *IASDR 2015 Congress*, 1–16. Brisbane, Australia: Queensland University of Technology.
Meijers, A., van Eijk, D., Hummels, C., Rapp, C., Schrijver, L., Teunissen, J., … van Kersen, J. (2015). *Call NWO creative industries: Research through design*. Den Haag: NWO, NRPO SIA & STW.
Melles, G. (2008). The Academization of Design and its Consequences for the Visual, Textual and Artefactual Produc-tion of Practice-based Research. In Swiss Design Network (Ed.), *Focused: Current Design Research Projects and Methods*. Berne, Switzerland.
Melles, Gavin. (2008). an Enlarged Pragmatist Inquiry Paradigm for Methodological Pluralism in Academic Design Research. *Artifact*, *2*(1), 3–11. https://doi.org/10.1080/17493460802276786

Nijhuis, S., & Bobbink, I. (2012). Design-related research in landscape architecture. *Journal of Design Research*, *10*(4), 239–257. https://doi.org/10.1504/JDR.2012.051172

Nijhuis, S., & de Vries, J. (2019). Design as research in landscape architecture. *Landscape Journal*, *38*(1–2), 87–103. https://doi.org/10.3368/lj.38.1-2.87

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A Design Science Research Methodology for Information Systems Research. *Journal of Management Information Systems*, *24*(3), 45–77. https://doi.org/10.2753/MIS0742-1222240302

Powell, T. C. (2001). Competitive advantage: logical and philosophical considerations. *Strategic Management Journal*, *22*(9), 875–888. https://doi.org/10.1002/smj.173

Proceedings of the 2nd Biennial Research Through Design Conference: 21st century makers and materialities. (2015). Cambridge, UK.

Proceedings of the 3rd Biennial Research Through Design Conference: New Disciplines of Making – Shared Knowledge in Doing. (2017). Edinburgh, UK: University of Edinburgh and Edinburgh Napier University.

Proceedings of the 4th Biennial Research Through Design Conference: Method and Critique. (2019). Delft and Rotterdam, The Netherlands: Delft University of Technology.

Reeker, L. F., Langen, P. H. G. van, & Brazier, F. M. T. (2016). *Lessons Learned from Research through Design An empirical research towards practical guidelines for Research through Design.* (manuscript). Retrieved from http://repository.tudelft.nl/islandora/object/uuid:4df597d5-ec4e-4acc-8dce-ed6a654f52a5/datastream/OBJ1/download

Rith, C., & Dubberly, H. (2007). Why Horst W. J. Rittel Matters. *Design Issues*, *23*(1), 72–91. https://doi.org/10.1162/desi.2007.23.1.72

Rittel, H. (1992). *On the planning crisis: Systems analysis of the “First and Second Generations.”* Berkeley: Institute of Urban & Regional Development, University of California.

Rittel, H., & Webber, M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169.

Roozenburg, N. F. M., & Eekels, J. (1995). *Product design: Fundamentals and methods.* Chichester: Wiley.

Rust, C., Mottram, J., & Till, J. (2007). *Review Report: AHRC Research Review Practice-Led Research in Art, Design and Architecture.* UK: Arts & Humanties Research Council, Sheffield Hallam University, Nottingham Trent University and The University of Sheffield.

Schon, D. A. (1983). *The reflective practitioner: How professionals think in action.* London: Maurice Temple Smith Ltd.

Schon, D. A. (1987). *Educating the Reflective Practitioner.* San Francisco, CA: Jossey-Bass.

Simon, H. A. (1997). The sciences of the artificial, (third edition). In *Computers & Mathematics with Applications* (Vol. 33). https://doi.org/10.1016/S0898-1221(97)82941-0

Soo Meng, J. C. (2009). Donald Schön, Herbert Simon and The Sciences of the Artificial. *Design Studies*, *30*(1), 60–68. https://doi.org/10.1016/j.destud.2008.09.001

Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In M. Soegaard & R. Friis-Dam (Eds.), *The Encyclopedia of Human-Computer Interaction.* Retrieved from https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design

Steinø, N., & Markussen, T. (2011). Design Research between Design and Research. *When Architects and Designers Write, Draw, Build? A PHD. Symposium of the Nordic Association of Architectural Research.* Aarhus School of Architecture.

van Aken, J. E., & Romme, G. (2009). Reinventing the future: Adding design science to the repertoire of organization and management studies. *Organisation Management Journal*, *6*(1), 5–12. https://doi.org/10.1057/omj.2009.1

van Dooren, E., Boshuizen, E., van Merriënboer, J., Asselbergs, T., & van Dorst, M. (2014). Making explicit in design education: Generic elements in the design process. *International Journal of Technology and Design Education*, *24*(1), 53–71. https://doi.org/10.1007/s10798-013-9246-8

van Eekhout, M. (2002). Methodology of component development. In T. M. de Jong & D. J. . van der Voordt (Eds.), *Ways to study and research urban, architectural and technical design.* Delft: DUP Science.

Verbeke, J. (2008). Developing Architectural Research through Design - Experiences with Research Training Sessions. *Conference Architectural Inquiries*, 1–11. Göteburg.

Wallace, J., Yee, J., & Durrant, A. (2013). *Proceedings of the 1st Biennial Research Through Design Conference: Praxis and Poetics.* Newcastle upon Tyne: Northumbria University,.

Wamelink, H., Geraedts, R., Hobma, F., & Lousberg, L. (2009). *Inleiding Bouwmanagement.* Delft: VSSD.

Yee, J. S. R. (2010). Methodological innovation in practice-based design doctorates. *Journal of Research Practice*, *6*(2), 1–23. Retrieved from https://files.eric.ed.gov/fulltext/EJ935247.pdf
Zimmerman, J., & Forlizzi, J. (2014). Research through design in HCI. In J. S. Olson & W. A. Kellogg (Eds.), *Ways of Knowing in HCI* (pp. 167–190). https://doi.org/10.1007/978-1-4939-0378-8_6
Zimmerman, J., Forlizzi, J., & Evenson, S. (2007). Research through design as a method for interaction design research in HCI. *SIGCHI Conference on Human Factors in Computing Systems*. San Jose, USA.
Zimmerman, J., Stolterman, E., & Forlizzi, J. (2010). An Analysis and Critique of Research through Design: towards a formalization of a research approach. *DIS 2010 - Proceedings of the 8th ACM Conference on Designing Interactive Systems*, 310–319. Aarhus, Denmark.

4 Towards a circular built environment

An integral design tool for circular building components

Chapter published in its entirety in 2018 in Smart and Sustainable Built Environment, 9(4), 635–653. https://doi.org/10.1108/SASBE-05-2019-0063

A van Stijn[1,2] and V.H. Gruis [1,2]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL Delft, The Netherlands.

[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), building 027W, Kattenburgerstraat 5, 1018 JA Amsterdam, The Netherlands.

ABSTRACT

Purpose – The transition to a *Circular Economy* (CE) in the built environment is key to achieve a resource-effective society. The built environment can be made more circular by applying circular building components. This paper presents a design tool that can support industry in developing circular building components.
Design/methodology/approach – The tool was developed and tested in 5 steps. In step 1, we analysed existing circular design frameworks to identify gaps and develop requirements for the design tool (step 2), In step 3, we derived circular design parameters and options from existing frameworks. In step 4, we combined and specified these to develop the *'Circular Building Components Generator*' (CBC-Generator). In step 5, the CBC-Generator was applied in the development of an exemplary component: *The Circular Kitchen* (CIK), and tested in a student workshop.
Findings – The CBC-Generator is a three-tiered design tool, consisting of a technical, industrial and business model generator. These generators are 'parameter based'; they consist of a parameter-option matrix and design canvasses. Different variants for circular components can be synthesised by filling the canvasses through systematically 'mixing and matching' design options.

Research limitations/implications – The developed tool does not yet support establishing causal links between 'parameter-options' and identification of the most circular design variant.
Practical implications – The CBC-generator provides an important step to support the building industry in developing and implementing circular building components in the built environment.
Originality/value – Whilst existing tools and frameworks are not comprehensive, nor specifically developed for designing circular building components, the CBC-generator successfully supports the integral design of circular building components: (1) it provides all the design parameters which should be considered; (2) it provides extensive design options per parameter; (3) it supports systematic synthesis of design options to a cohesive and comprehensive circular design.

KEYWORDS circular economy; design tool; building components, circular kitchen

4.1 Introduction

Many authors (e.g., Bocken, de Pauw, Bakker and van der Grinten (2016); Ellen MacArthur Foundation (2013); Ness and Xing (2017)) point out that the linear economy of 'take-make-use-dispose' leads to increasing pressure on natural resources, environmental pollution, carbon emissions and waste generation. The *Circular Economy* (CE) proposes a more resource-effective model by decoupling economic growth from resource consumption. The model originates from several schools of thought, including *industrial ecology* (IE) (Ayres & Ayres, 2002; Graedel & Allenby, 2003), *regenerative design* (Lyle, 1994), *the performance economy* (Stahel, 2006), *biomimicry* (Benyus, 1997), and *cradle-to-cradle* (C2C) (McDonough & Braungart, 2002). (Ellen MacArthur Foundation, 2013; Mendoza, Sharmina, Gallego-Schmid, Heyes, & Azapagic, 2017) The CE model can be summarised in the following three principles: "(1) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimise resource yields by circulating products, components, and materials at their highest utility at all times in both technical and biological cycles; (3) foster system effectiveness by revealing and designing out negative externalities." (Ellen MacArthur Foundation, 2013)

The building sector consumes 40% of global natural resources, produces 40% of global waste and 33% of emissions (Ness & Xing, 2017). Due to its high impact, the transition to a circular built environment is key to achieve a resource-effective and sustainable society. Within the building sector, the focus is currently on dealing with waste, or recycling. *Recycling* is mentioned as the 'outer technological cycle' in the CE model as presented by the Ellen MacArthur Foundation (2013). However, a main principle of the CE is to first make optimal use of the 'inner technological cycles' such as *maintain, reuse,* and *remanufacture*, and thus to prevent waste. Buildings consist of many components such as climate installations, kitchens, and facades which could be replaced by 'circular building components' during the natural maintenance and retrofit moments. Thus, we can gradually make the building stock more circular.

Developing such circular components has immediate urgency: the European Union – as set out in the EPBD – stimulates improving the operational energy-efficiency of buildings through retrofitting. Although such retrofits will help to reduce the operational impact of the built environment, they can significantly add to the embodied impact (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013; Pomponi & Moncaster, 2016). By developing circular building components for such retrofits – such as circular façades, roofs, climate installations, and kitchens – we can reduce operational energy in a resource-effective way.

To develop and implement circular building components, professionals would benefit from a specific tool which can support choices concerning the technical design, composition of the supply chain and financial engineering. Indeed, many circular design frameworks and tools have been developed. However, these are fragmented: they fail to integrate all relevant disciplines and often exclude relevant design choices and options. Furthermore, most are not developed specifically for use in the built environment, let alone for building components in particular. Therefore, in this article we present a tool to support the design of circular building components in an integral manner.

4.2 Method

An iterative, stepwise approach was used to develop and test the circular design tool (see Figure 4.1). In step 1, we analysed existing circular design frameworks to identify gaps and – in step 2 – develop requirements for the design tool. In step 3, through a systematic literature review, we identified circular design parameters and options in existing design frameworks. In step 4, we combined and specified these into the *Circular Building Components Generator* (CBC-Generator). In step 5, we applied the CBC-generator in the development of an exemplary circular building component with industry partners: The Circular Kitchen (CIK); we tested the developed tool during a student workshop. Finally, we reflect upon the resulting tool and identify opportunities for further development. The rest of the article is structured following these steps.

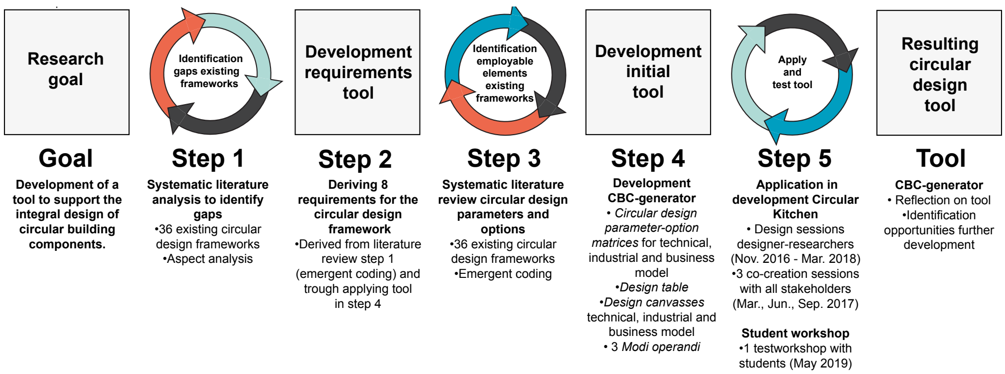


FIG. 4.1 Tool development method (Adapted from Geissdoerfer, Bocken and Hultink (2016), Bocken, Allwood, Willey and King (2011), and Leising, Quist and Bocken (2018)

4.3 Step 1: Literature review of existing circular design frameworks

In this section, we analyse existing circular design frameworks to identify their shortcomings and to derive requirements for the tool in the following step.

4.3.1 Literature review and analysis

De Koeijer, Wever and Henseler (2017) summarise two main types of circular design tools and models: generative and evaluative. The distinction is made on the basis of their applicability in the front-end or back-end of the product development process (Bocken, Farracho, Bosworth, & Kemp, 2014; Bovea & Pérez-Belis, 2012;

de Koeijer et al., 2017; Fitzgerald, Herrmann, Sandborn, & Schmidt, 2005; Telenko, Seepersad, & Webber, 2008). Generative tools offer the initial (front-end) support in synthesis of design variant(s) and, therefore, are the focus of this paper. Existing generative circular design frameworks were identified through literature review, including peer-reviewed, conference and professional sources. The frameworks were identified through Web of Science and Google Search engines using the following keywords: ‘circular economy’ and ‘design’ or ‘supply chain’ or ‘business model’ and ‘framework’, ‘method’ or ‘tool’. We only included frameworks which support the design of a circular technical, industrial and/or business model and support the synthesis of a design proposal. This resulted in 36 frameworks to be included in the review. We analysed these frameworks on three aspects. First, we analysed the *discipline* (D) for which the framework offers design support, distinguishing the technical model (design), industrial model (supply chain management) and business model (marketing and finance). Second, we analysed the *level* (L) for which the framework offers design support. The CE can be designed at macro (country, region and urban area), meso (buildings, networks), and micro (company, (building) product) level (Geng, Fu, Sarkis, & Xue, 2012; Pomponi & Moncaster, 2017). Finally, we analysed the *type of support* (T) offered in the model: for example, if the framework provides step-by-step guidance and/or includes design canvasses. The results of the analysis can be found in Tables 4.1-2.

4.3.2 Gaps in existing circular design frameworks

Several gaps were identified. First, there is a paucity of frameworks which are developed for the ‘meso’ scale or buildings. The exceptions are the design frameworks developed by Geldermans (2016) and Leising et al. (2018), which address the building level. Second, most authors recognise the need for a systems-, and integral approach. Yet, very few provide such frameworks. Good examples of integrated frameworks are Bakker et al. (2014), Bocken et al. (2016), Mendoza et al. (2017) and Moreno, De los Rios, Rowe and Charnley (2016).

Third, there is a missing link between more comprehensive yet ‘abstract’, academic frameworks (e.g., Bocken et al., 2016; Leising et al., 2018; Scheepens, Vogtländer, & Brezet, 2016) and frameworks which offer very concrete design options. Finally, industrial parameters are insufficiently considered in most frameworks. For example, parameters such as *mode of transport*, and *location of activities* are omitted or only briefly mentioned, whilst these can have a significant environmental impact.

TABLE 4.1 Aspect analysis of existing circular design frameworks

Name framework	Source	L			D			T							
		Level			Discipline			Type of support							
		L1	L2	L3	D1	D2	D3	T1	T2	T3	T4	T5	T6	T7	T8
		Macro level	Meso level	Micro level	Technical model	Industrial model	Business model	Guidelines or criteria	Step-by-step guide	Design canvas	Design architypes	Design strategies	Design parameters	Design options	Case examples
The value hill	(Achterberg et al., 2016)	.	.	x	.	.	x	.	x	~	.	x	.	.	x
Framework for sust. business model innovation	(Antikainen and Valkokari, 2016)	~	~	x	.	.	x	.	.	x	.	.	x	.	.
Products that last - framework	(Bakker et al., 2014)	.	.	x	x	~	x	.	x	.	x	x	.	.	x
Product req., guidelines and businessm. for CE	(Balkenende and Bakker, 2015)	.	.	x	x	.	x	x	.	.	.	.	.	.	~
Circular design framework	(Bocken et al., 2016)	.	.	x	x	~	x	.	.	.	x	x	.	.	x
Circular design guide	(Ellen MacArthur Foundation and IDEO, 2017)	.	.	x	x	~	x	.	x	x	.	~	.	.	x
ReSOLVE framework	(Ellen MacArthur Foundation, 2015)	.	.	x	x	.	x	.	.	.	.	~	x	.	x
New framework on circular design	(Ellen MacArthur Foundation, 2013)	.	x	x	.	x	x	.	~	.	.	.	x	.	~
Circular economy toolkit	(Evans and Bocken, 2014) (Evans and Bocken, 2013)	.	.	x	x	.	x	.	.	.	.	x	.	x	x
10 steps to create a circular business model	(Fischer and Achterberg, 2016)	.	.	x	.	~	x	.	x	.	.	.	x	.	x
Design for demand	(Forum for the Future and Novelis, n.d.)	.	.	x	x	.	x	.	x	x	x	~	.	.	.
Circular business model toolkit	(Forum for the Future and Unilever, n.d.)	.	.	x	~	.	x	.	.	.	x	.	.	.	x
Circular building matrix and new-stepped strategy	(Geldermans, 2016)	.	x	x	x	.	.	.	x	x	.	~	x	~	.
Circular design checklist	(Gerritsen, 2015)	.	.	x	x	.	.	x	.	.	.	x	.	x	.
Design framework	(Gispen, n.d.)	.	.	x	x	x	.	x	.	.	.	.	x	~	.
Speedcycle	(Goldsworthy, 2017)	.	.	x	x	.	.	.	.	.	x	.	x	.	.
C3 Business model canvas	(Hofmann, et al., 2017)	.	.	x	.	.	x	.	.	x	.	.	x	.	.
Guided choices towards a circular business model	(Joustra et al., 2013)	.	.	x	~	~	x	.	x	.	.	x	x	~	x
Collaboration tool for CE in the building sector	(Leising et.al, 2018)	.	x	.	~	x	~	x	x	.	~	.	x	.	~
Circular business model canvas	(Lewandowski, 2016)	.	.	x	.	.	x	.	.	x	.	.	x	.	.

>>>

TOC

TABLE 4.1 Aspect analysis of existing circular design frameworks

Name framework	Source	L Level			D Discipline			T Type of support							
		L1 Macro level	L2 Meso level	L3 Micro level	D1 Technical model	D2 Industrial model	D3 Business model	T1 Guidelines or criteria	T2 Step-by-step guide	T3 Design canvas	T4 Design architypes	T5 Design strategies	T6 Design parameters	T7 Design options	T8 Case examples
CE Business model options, patterns and design strategies	(Lüdeke-Freund et al., 2018)	.	.	x	~	x	x	.	.	.	x	x	.	x	.
Business cycle canvas	(Mentink, 2014)	.	.	x	.	~	x	.	.	x	x	~	x	.	.
Multiple loop life-cycle design frame	(Mestre and Cooper, 2017)	.	.	x	x	.	.	.	.	x	.	x	.	x	.
BECE framework	(Mendoza et al., 2017) and (Heyes, et al., 2018)	.	.	x	x	~	x	~	x	~	.	.	.	.	.
Circular design framework	(Moreno et al., 2016)	.	.	x	x	.	x	.	.	.	x	x	.	.	.
Circular business model framework	(Nussholz, 2017)	.	.	x	.	.	x	.	.	x	.	.	x	.	.
Circular strategies embedded in the business model canvas	(Nußholz, 2017)	.	.	x	.	.	x	.	.	x	.	.	x	.	.
Sustainability qualifying criteria for circular BM	(De Pádua Pieroni et al., 2018)	.	~	x	.	.	x	x	.	.	.	.	.	.	.
Design framework	(Poppelaars, 2014)	.	.	x	x	.	.	x	.	.	.	~	.	x	.
Circular transition framework for business model innovation towards a CE	(Scheepens et al., 2016)	x	x	x	x	x	x	.	.	x	.	.	x	.	.
Sustainable business model canvas	(Sempels, 2014)	.	.	x	.	.	x	.	.	x	.	.	x	.	~
Design tools for a circular economy	(The Great Recovery and RSA, 2013)	.	.	x	x	~	~	.	.	.	x	.	.	.	~
Closing the loop by design: a practical guide	(Toxopeus et al., 2018)	.	.	x	x	.	.	.	.	.	.	x	.	.	.
Circular pathfinder	(van Dam et al., 2017)	.	.	x	x	.	~	.	.	.	.	x	x	.	x
Circular design framework	(van den Berg and Bakker, 2015)	.	.	x	x	.	.	x	.	.	.	x	.	x	.
Circulab board	(WIITHAA, n.d.)	.	.	x	.	.	x	.	.	x	.	.	x	.	.

x Framework includes this aspect
~ Framework includes this aspect in part
. Framework does not include this aspect

TABLE 4.2 Summary of existing circular design frameworks

Source	Summary framework
(Achterberg et al., 2016)	Canvas on which activities, partners and products are placed based on the lifecycle phase of a product. Designers can select from several circular design, supply chain, and business model strategies to develop their design.
(Antikainen and Valkokari, 2016)	Business model canvas extended with the parameters 'business ecosystem' and 'sustainability impact'.
(Bakker et al., 2014)	Framework links circular business model archetypes and circular design strategies, offering some examples.
(Balkenende and Bakker, 2015)	A set of circular product requirements, design guidelines and supporting business model considerations.
(Bocken et al., 2016)	Framework links circular business model archetypes and circular design strategies, offering some examples.
(Ellen MacArthur Foundation and IDEO, 2017)	An website with a wide variety of design methods (activities or workshops), design canvasses, circular design strategies and circular case examples to aid designers in developing and realizing a circular technical and business model.
(Ellen MacArthur Foundation, 2015)	Framework which translates the three principles of the CE into 6 business actions which can support development of circular technical and business models: (1) Regenerate, (2) Share, (3) Optimise, (4) Loop, (5) Virtualise, and (6) Exchange.
(Ellen MacArthur Foundation, 2013)	A concise framework introducing parameters to consider when developing a circular supply chain: (1) the wasted resource flows, (2) value creation potential, (3) possible barriers, and (4) execution.
(Evans and Bocken, 2014) (Evans and Bocken, 2013)	Website which offers circular technical and business model strategies per lifecycle phase of the product; concrete examples are provided to illustrate strategies.
(Fischer and Achterberg, 2016)	A practical, 10 stepped, circular-business-model design framework.
(Forum for the Future and Novelis, n.d.)	A website which takes users in 5 steps through the design process: (1) introduction of CE, (2) materials, (3) solutions (introducing 6 design strategies), (4) strategies (proposing 3 design-business model architypes), (5) 'design brief generator'.
(Forum for the Future and Unilever, n.d.)	Toolkit based on 'circular-', and 'enabling' business model' architypes; the toolkit provides examples of the architypes.
(Geldermans, 2016)	Framework in which the building is unravelled into system elements within a 'Building inventory matrix', and circular re-loop potential is mapped. The accompanying 'New-stepped strategy' provides circular design strategies.
(Gerritsen, 2015)	An extensive checklist, containing technical design criteria with specified design options.
(Gispen, n.d.)	A framework for circular products design, containing technical and industrial model parameters and (some) design options.
(Goldsworthy, 2017)	The speedcycle supports design for different speeds within a products lifecycle, based on 4 parameters: (1) material, (2) production, (3) use and (4) recovery. Several archetypes, are introduced as examples.
(Hofmann, et al., 2017)	Business model canvas which situates (1) the economic dimension (8 components of the business model canvas), within the (2) social dimension (key stakeholders), within the (3) ecological dimension (i.e., environmental inputs, output, impact).
(Joustra et al., 2013)	A practical guide to develop a circular business model, including 5 steps: (1) introduction in CE, (2) review of partners, (3) product (re)design, (4) service (re)design and (5) business model calculation.

>>>

TABLE 4.2 Summary of existing circular design frameworks

Source	Summary framework
(Leising et.al, 2018)	The tool describes 5 phases for forming a circular supply-chain collaboration for the realization of a circular building project; each step specifies several strategies and the expected outcome.
(Lewandowski, 2016)	Business model canvas extended with the parameters 'take-back systems' and 'adoption factors'.
(Lüdeke-Freund et al., 2018)	Circular business model design options, 6 business model architypes and supporting circular design strategies.
(Mentink, 2014)	Business model canvas adapted to fit the 'Butterfly diagram' of EMF (2013), allowing the alignment of business models in the entire supply chain.
(Mestre and Cooper, 2017)	A multiple-loop, life-cycle framework to support circular product design. The framework links the lifecycle phases with design strategies to: (1) slow the loop, (2) close the loop, (3) bio-inspired loops and (4) bio-based loops.
(Mendoza et al., 2017) and (Heyes, et al., 2018)	The BECE framework offers a 10-step, circular guide for business innovations: it links business model planning – through back-casting and the business model canvas – with (eco)design using the ReSOLVE checklist.
(Moreno et al., 2016)	A framework which links business model archetypes and circular design strategies (from a DfX inventory). The framework includes 5 (abstract) design guidelines.
(Nussholz, 2017)	Business model canvas which systematically integrates lifecycle value management: the 9 building blocks of the business model canvas are offset to three circular lifecycle points (i.e., resource recovery, prolong lifespan, and end-of-life).
(Nußholz, 2017)	Business model canvas thought from the 'applied circular strategy' of each business model parameter.
(De Pádua Pieroni et al., 2018)	Qualifying criteria which can serve as a checklist in the development of circular business models.
(Poppelaars, 2014)	An extensive list of guidelines for circular product design, containing various design options.
(Scheepens et al., 2016)	A design canvas which considers different system levels, stakeholder networks, value capturing, effects of regulatory drivers and the four life-cycle stages of products: production, marketing, operation and end-of life.
(Sempels, 2014)	Business model canvas which adds the parameters (1) mental grasp, (2) drivers of productivity, (3) positive and negative externalities. The added parameters focused on assessing and enabling.
(The Great Recovery and RSA, 2013)	The tool offers 4 main circular archetypes which describe the technical, industrial and business model; the tool is complemented with examples and experiences from disassembly and design workshops.
(Toxopeus et al., 2018)	Web-based tool with coherent set of design guidelines, customised to the level of expertise of designer; strategies are supported with illustrations and examples.
(van Dam et al., 2017)	An online guide that asks a maximum of ten product-related questions (based on design parameters), after which it recommends circular design strategies and case examples.
(van den Berg and Bakker, 2015)	An product design framework with extensive circular design strategies and options.
(WIITHAA, n.d.)	Business model canvas game specifying the parameters to circular economy terms (e.g., natural and technical key resources). Positive and negative impacts are added as parameters.

4.4 Step 2: Requirements for the design tool for circular building components

In addition to identifying gaps, we derived 8 requirements for the circular design tool from the analysis of existing circular design frameworks. These requirements were identified through emergent coding (Dahlsrud, 2008; Haney, Russell, & Bebell, 2004; Kirchherr, Reike, & Hekkert, 2017): each time we encountered a new requirement in a framework, it was added to the list. The list of requirements was refined through evaluating initial versions of the tool in the design of the CIK.

Most frameworks (e.g., Bocken et al., 2016; Scheepens et al., 2016; Mendoza et al., 2017; Lüdeke-Freund, Gold, & Bocken, 2018), state that design for circularity requires an approach which ensures circularity is achieved within and beyond the designs' life cycle. On the one hand, a *systems approach* (requirement 1) is required in which the building component is regarded from within its wider system environment. A systems approach ensures no undesirable rebound effects are caused or environmental burdens shifted from one system or system level to the next. On the other hand, an *integral approach* (requirement 2) is needed to ensure that the design in one discipline is in coherence with those in other disciplines. For example, a business model which is based on sales of expensive repair parts, will not incentivise repair of a building component, even though it could technically be engineered for easy repair. In an integral design the technical, business and industrial model should be developed in cohesion with each other. Our analysis of existing frameworks also indicated that a design tool has to include *the relevant circular design parameters* (requirement 3) and *provide various practical design options* to each design parameter (requirement 4). Furthermore, the design framework should be specific enough for designing in the built environment. The framework needs to *relate the scale levels present in buildings* (requirement 5): each material, part and component has its own lifecycle, yet interacts with the whole of the building system (Pomponi & Moncaster, 2017). Furthermore, the average life span of buildings and its components is long, compared to consumer products. Hence, the framework should also *include approaches which are oriented towards longer lifespans* (requirement 6). And the building industry has its own manufacturing techniques, materialisation, supply chain, and financial arrangements. The *strategies or options included in the framework should build onto these* (requirement 7). Finally, a design process is characterized by an exponential information growth curve (Ullman, 2010). Hence, the framework should *accommodate the different stages of a design process* (requirement 8).

TOC

These 8 requirements were taken into account in the development of the design tool for circular building components. In the description of the developed tool we will mention how we fulfil these requirements.

4.5 Step 3: Deriving design parameters from existing circular design frameworks

Through systematic analysis of the 36 existing design frameworks, we identified the design choices – or *design parameters* – which need to be considered when developing a circular technical, industrial and business model. Furthermore, we identified which *design options* were proposed per design parameter. A coding framework – consisting of design parameters and options – was developed to analyse the existing frameworks. A first coding frame was developed deductively, based upon prior knowledge on the topic and on initial review of the frameworks (step 1). Coding dimensions were added inductively through iterative reading of the existing frameworks (i.e., emergent coding (Dahlsrud, 2008; Haney et al., 2004; Kirchherr et al., 2017)). In other words, each time we found an additional design parameter or design option, it was added to the coding frame. We considered that a framework included a design parameter or option if it was an essential element of the design frame, or if it was mentioned or described in the supporting text of the design frame. The results of this analysis are included in Appendix A.1.

4.6 Step 4: Developing a design tool for circular building components

Through combining and specifying the design parameters and options identified in step 3, we constructed our design tool for circular building components: *'the Circular Building Components Generator'* (CBC-Generator). The CBC-Generator is a three-tiered design tool, consisting of a technical, industrial and business model generator. Together, these generators support the integral design of circular building components (requirement 2). For each generator, the relevant *design parameters* and an extensive list of *design options* – as identified in step 3 – are listed in a matrix (requirements 3 and 4). These design options serve as the 'building blocks' to create a design. Additional design options specific for the built environment have been included through brainstorming (requirement 6 and 7). The matrices have been included in Appendix A.1; each matrix is complemented with a design table and design canvas to support the synthesis of design options to a complete and comprehensive circular design.

4.6.1 The parameter-option matrices

The technical model matrix includes the following parameters:

1. What types of ***materials*** are used in the building component throughout its life? Materials include resources, water, and nutrient flows; materials are further subdivided into *biological and technological materials.*
2. What type of ***energy*** is needed in the use-phase of the building component?
3. How is the *systems' architecture* of the technical model built up? In other words, how does the building unravel into components, subcomponents, parts and materials (i.e., *system elements*)?
4. What is the ***amount*** of each system element? We measure in [number of pieces] for (sub)components and parts, [m^3] or [kg] for material, and [kWh] for energy.
5. In how much - and how many – ***time(s)*** *is* a system element made, used and remade? Here we consider the amount of *lifecycles* (or re-loops) made. Furthermore, we consider the *expected lifespan* (functional, economic, or technical) per loop.
6. What is the ***lifecycle stage*** for each system element? The lifecycle stage describes the adoption stage of a system element.
7. What is the applied ***circular design strategy*** per system element? The various design strategies have been subdivided into three categories: 'strategies to narrow, slow and close resource loops' (Bocken, et al. 2016). Designing to 'narrow resource loops' aims to reduce resource use, or achieve resource efficiency. Designing to 'slow resource loops' aims to slow down the flow of resources through extension or intensification of the utilization period of the designed artefact. When a design is made to 'close resource loops', it is designed so all used materials are recycled or biodegraded at the end of life.

The industrial model matrix includes the following parameters:

1. Who are the ***key partners*** in the supply chain (or value network)?
2. What are the ***key activities*** carried out by the partners, including their 'linear' *activities, re-loop activities* and all *(re-)production processes*?
3. What are the ***key resources*** needed in the supply chain? These includes the *facility* in which (re)activities and (re)processes take place and the *system elements* (e.g., (sub)components, parts, materials) which move through the supply chain. The system elements should correspond to the system elements identified in the technical model.
4. Which ***transport*** occurs in the supply chain? The transport includes the *mode of transport* and the *distance*.
5. What ***energy*** is needed in the make and remake phase (i.e., (re)production) of the building component?

The following parameters are included in the business model matrix:

1. Who are the ***key partners*** in the business model? These partners should correspond to the partners identified in the industrial model.
2. Who are the ***customer segments*** in the business model? We consider the sub-parameters *owner* (i.e., who is the owner?) and *customer* (i.e., who is the customer?)
3. What are the ***supply chain relations*** between partners? Who is the *primary partner(s) in the supply chain*: who is/are the leading partner(s)? Who is the *primary contact customer*: is the owner contacted or the user? What is the *kind of customer relationship?* In other words, how is contact made between provider and customer? How is the *collaboration* between partners?
4. What is the ***cost structure*** per partner?
5. How are the ***revenue streams*** per product or service offered? We consider the type of *financial arrangement* (e.g., lease, sale) and *income division* (e.g., per company, over the supply chain) .
6. What is the ***value proposition***? We specify the *product or service proposition* offered to the customer, the *value creation and delivery-*, and *value capturing* per partner. Value creation and delivery clarifies how the product brings value to customers and value capturing how the business model brings value to a partner. Both are needed to align incentives within the supply chain, and it is this alignment that is crucial for the feasibility of the business model.
7. What are the ***channels*** used to reach the customers?
8. What are the ***take-back systems*** in place to ensure the return of key resources for re-looping?
9. What are the ***adoption factors*** which determine how the business model can be implemented within the organisation of a partner, regulations and society?

4.6.2 The design table

The parameter-option matrices are complemented with a design table (see Figure 4.2). This table forms the frame in which options are systematically combined – applying them as building blocks – to form logical combinations for a design.

The horizontal axis of this table lists several categories in which the selected options can be organized, according to how they contribute to achieving circularity. The categories apply the taxonomy of the circular design framework developed by Bocken, et al. (2016): 'narrowing, slowing or closing resource loops'. This categorization is further nuanced with the 9R model - (0) Refuse, (1) Rethink, (2) Reduce, (3) Reuse, (4) Repair, (5) Refurbish, (6) Remanufacture, (7) Repurpose, (8) Recycle and (9) Recover – as developed by Potting et al. (2017). The vertical axis of the design table is used to list the technical, industrial or business model design from its entirety to – more and more – specified per parameter or system element.

				NARROWING LOOPS			SLOWING LOOPS					CLOSING LOOPS	
CATEGORY	#	ITEM(S)		REFUSE	RETHINK	REDUCE	RE-USE	REPAIR	REFURBISH	REMAN.	REPURPOSE	RECYCLE	RECOVER
COMPONENT	1	FILL IN NAME HERE	APPLIED OPTIONS										
			RELOOP CLARIFICATION										
SUB-COMPONENT	1.1	FILL IN NAME HERE	APPLIED OPTIONS										
			RELOOP CLARIFICATION										

FIG. 4.2 Design table for the technical model generator

4.6.3 Design canvasses

The *design canvasses* provide structure for designers to translate the design options to a circular design variant. Three design canvasses were added to the CBC-generator (see Figures 4.3, 4.4 and 4.5); these are partly based on canvasses or frames found in the existing circular design frameworks.

The technical model canvas supports design with *a systems approach* (fulfilling requirement 1). Whilst filling in the canvas, designers are required to distinguish the *system elements* in their design. Several technical model parameters (i.e., *lifespan*, *amount*, and (optional) *applied circular design strategy*) need to be filled in per system element, helping designers to understand the relationship between the different *system elements* (requirement 5). The business-, and industrial model canvasses facilitate the synthesis of a supporting circular business-, and supply chain model: the configuration of the *key partners* and re-loops should be adapted to fit the design proposal; following, the selected design options per parameter can be organised on these canvasses to visualise the circular supply chain and business model. These cyclical canvasses stimulate designers to design for the whole supply chain or value network, rather than consider the view of one company (as is common in linear design tools (Mentink, 2014)). As such, these canvasses help designers strive towards a win-win situation between supply chain partners.

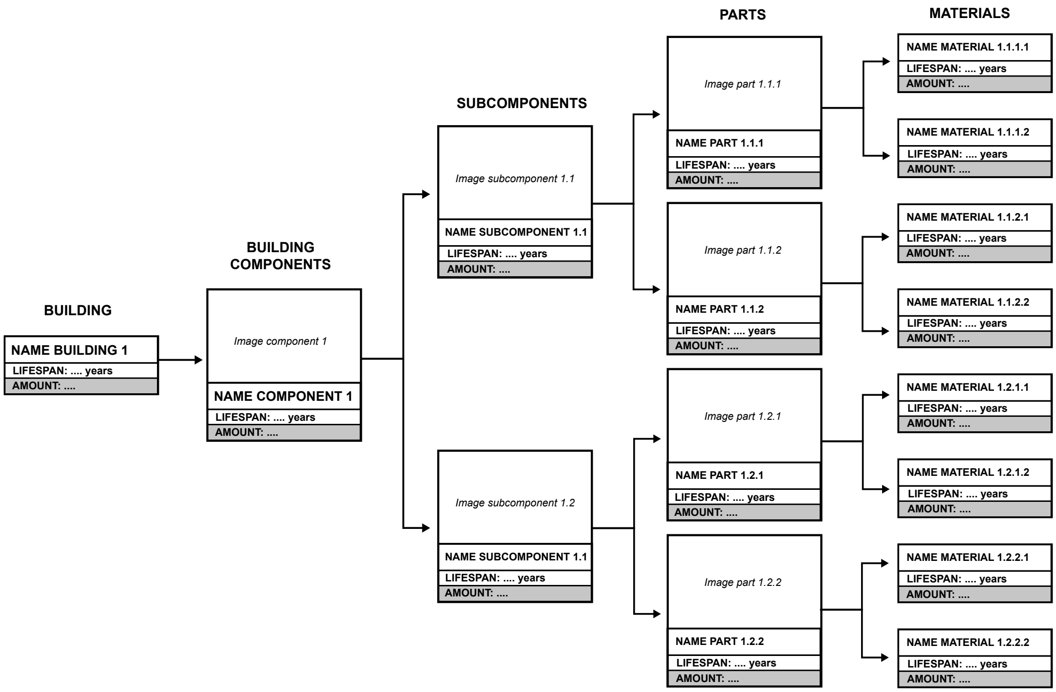


FIG. 4.3 The technical model design canvas, based on the Circular Building Inventory Matrix by Geldermans (2016)

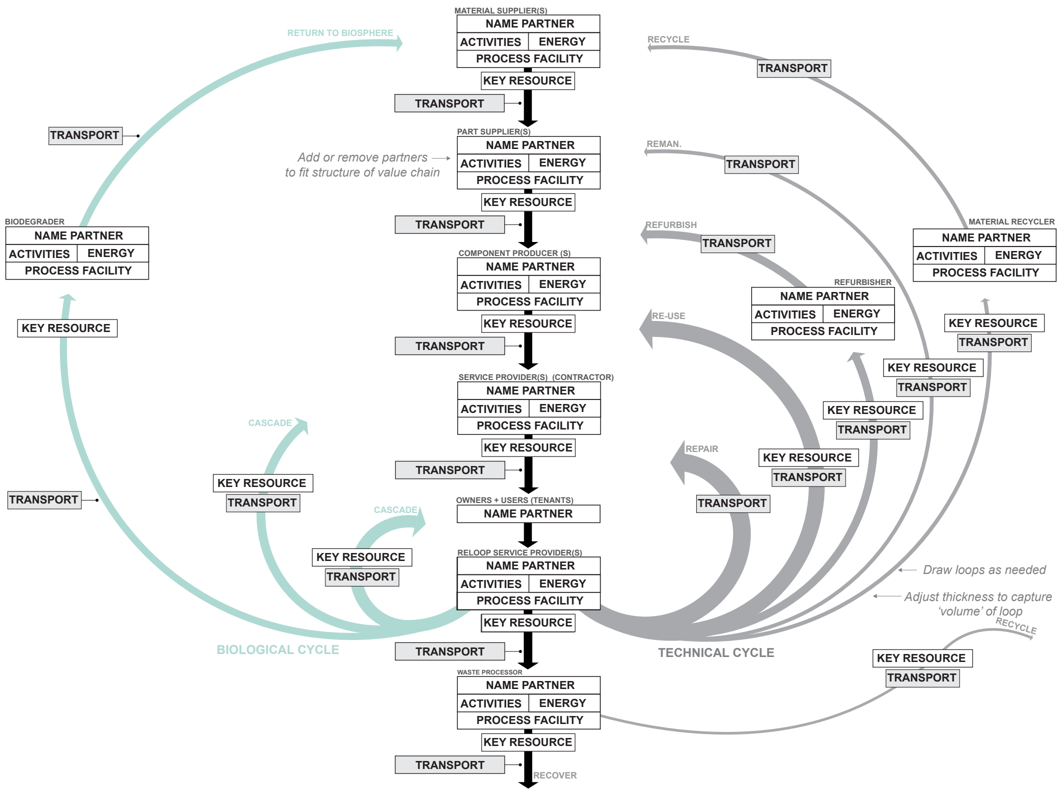


FIG. 4.4 The industrial model design canvas based on the 'Butterfly model' of the Ellen MacArthur Foundation (2013)

4.6.4 Modi operandi: from first idea to detailed circular design proposal

To ensure the tool supports synthesis in different design stages it has three operational pathways: (1) *ideate*, (2) *generate* and (3) *refine*. Each supports synthesis in a different stage of the design process, from ideation, to concept generation, to detailed design (requirement 8). The modi operandi are organised in the design table and canvasses: each surpassing modus operandi requires the designer(s) to fill in more parts of the table and canvas, and with a higher level of detail.

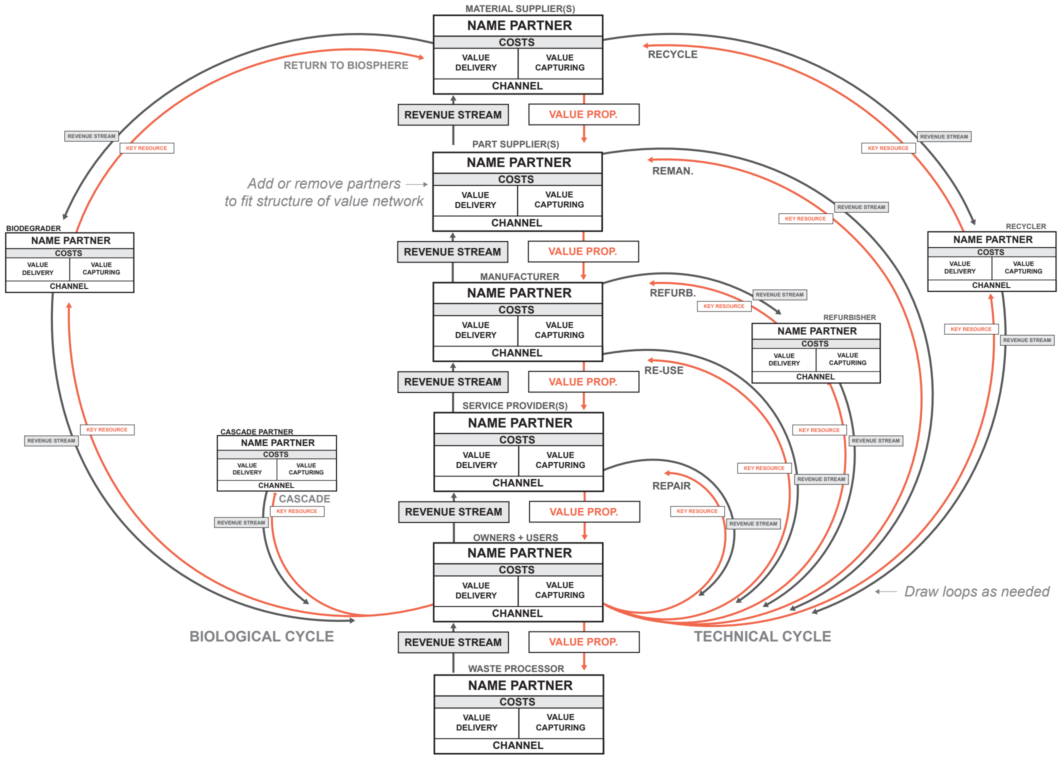


FIG. 4.5 The circular business model design canvas based on the canvas of Mentink (2014)

The first operational pathway, *ideate*, supports the development of first idea(s) for a circular building component design. The design table is filled in by systematically 'mixing and matching' the design options for the different parameters listed in the matrix. A further clarification can be provided on 'how' the design option can be applied in the design. The outcome can be understood as a logical combination of technical, industrial and business model options which could be applied in a design (for an example see Section 4.7.2). The design team is free to start from the technical, industrial or business model generator, based on their preference. However, it is necessary to always use the generators in parallel to achieve an integral circular design. The second operational pathway, *generate*, supports the generation of circular building component concept designs. The combination of design options, as selected in the ideation stage, are applied as building blocks in the design canvasses and translated to a concept design. Additional design options can be selected from the matrices. The third operational pathway, *refine*, supports

TOC

the refinement of a circular building component design. The concept design is further detailed and refined to a comprehensive circular design proposal by completing and detailing all parts of the design table and canvas. The matrices can be consulted for additional options, and alternative options for parts of the design which were considered unfeasible or undesirable.

4.7 Step 5: Testing the CBC-Generator: The Development of the Circular Kitchen

The CBC-Generator has been applied in the development of an exemplary building component: The Circular Kitchen (CIK), and tested during a student workshop.

4.7.1 Applying the framework during the development of the circular kitchen

The CBC-generator has been applied in the development of the Circular Kitchen. The CIK was developed to a proof-of-principle, in co-creation with the TU Delft, AMS-institute, housing associations and industry partners.

The designer-researchers used the CBC-generator to develop design proposals for the CIK. The developed designs would be discussed in the 3 co-creation sessions with all partners; the input from the workshops would feed further development of the design proposal. Developing the CBC-generator and the CIK was an iterative and parallel process: the CBC-generator was applied to support developing the CIK. Simultaneously, by testing the CBC-generator in the development of the CIK, the CBC-generator itself was refined.

We will describe the CBC-generator in the development of the CIK following the three modi operandi ‘ideate’ (4.7.2), ‘generate’ (4.7.3) and ‘refine’ (4.7.4).

TOC

4.7.2 Towards first ideas: ideating a circular building component

Applying the CBC-generator's operational pathway 'ideate', we developed several ideas for circular kitchen design variants. To illustrate how we have used the CBC-generator, we elaborate on the development of one of these ideas: 'The plug-and-play kitchen'. The ideation process started by conceiving an inspirational direction (e.g., requirement, guiding theme, example) for the design variant. In this case, we started from the idea to make a kitchen which has a long life, can be recycled and – subsequently – saves resources. The parameter-option matrices were consulted by systematically looking at each parameter. Design options which helped to achieve the inspirational direction were selected. The technical model matrix was consulted first. Various circular design options to prolong the *lifespan* of the kitchen through reuse, repair, refurbishment, remanufacturing and recycling were selected. Subsequently, we turned to the accompanying business model, which needed to make the long-life design, interesting to the manufacturer. From the business model matrix, the options: 'the manufacturer as *owner*' and '*revenue stream generated through service and updates*' were selected. Then, for the industrial model, options were selected for the various *re-loop activities*, initiated by the manufacturer. The options were organised in the design template, creating a cohesive set of technical, industrial and business model options (see Figure 4.6).

			NARROWING LOOPS		
PLUG-AND-PLAY KITCHEN			REFUSE	RETHINK	REDUCE
GOAL (Check applicable goal)					
TECHNICAL MODEL	The technical design facilitates re-use, repair, refurbishment and remanufacturing through a modular design, separation of the components in support and infill, standardisation, updates and easy de- and re-mountable joints. Recycling is facilitated through separation of parts in biological or technological materials.	OPTIONS TO APPLY			
INDUSTRIAL MODEL	The manufacturer, as owner of the kitchen throughout the life-cycle, initiates the various technical re-loops.	OPTIONS TO APPLY			
BUSINESS MODEL	The business model makes the long-life design interesting to the manufacturer, by placing the ownership of the kitchen with the manufacturer and by generating a revenue stream through service and updates.	OPTIONS TO APPLY			

FIG. 4.6 Design table as filled in during operational pathway ideate

4.7.3 Generating a concept design for the CIK

The combination of options for ‘the plug-and-play kitchen’ – as selected during ideation – were applied as building blocks in the design canvasses to generate a concept design for the CIK (see Figure 4.7). The completed design canvasses are shown in Figures 4.8-10.

The design of the circular kitchen facilitates various re-loops by separating parts based on *lifespan*. The kitchen consists of a docking station in which modules can be easily plugged in and out, allowing for future changes in lay-out. The kitchen modules themselves are also divided in a long-life frame to which ‘module infill’ (e.g., appliances) and ‘style packages’ (e.g., front, countertop, handles) can be easily attached using click-on connections. The high level of modularity and customisability of this design, allowed for additional opportunities in the business model, such as: diversification of *revenue streams* and enlargement of the targeted *customer segments*. The business model parameter-option matrix was reviewed

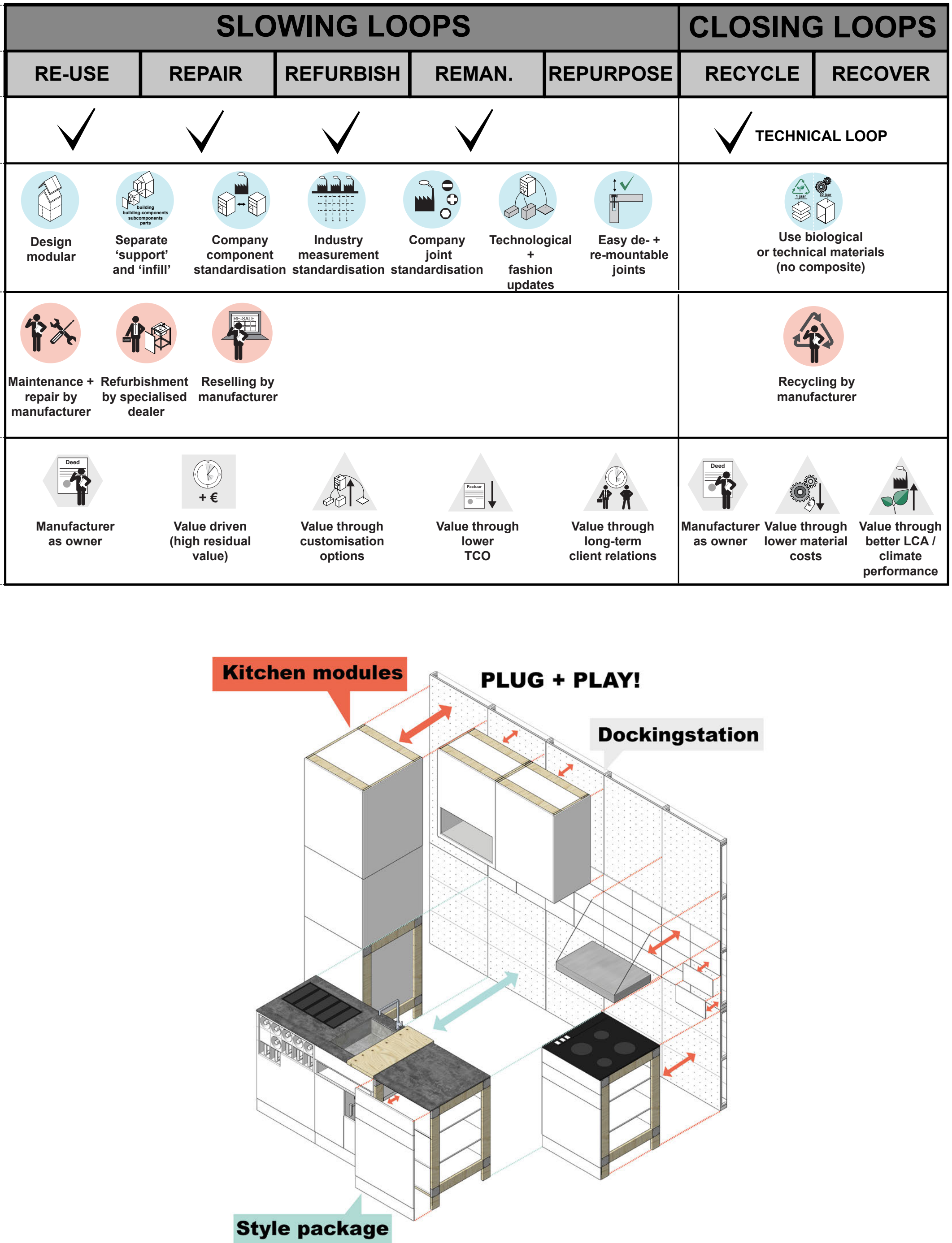


FIG. 4.7 Concept design for the circular kitchen

TOC

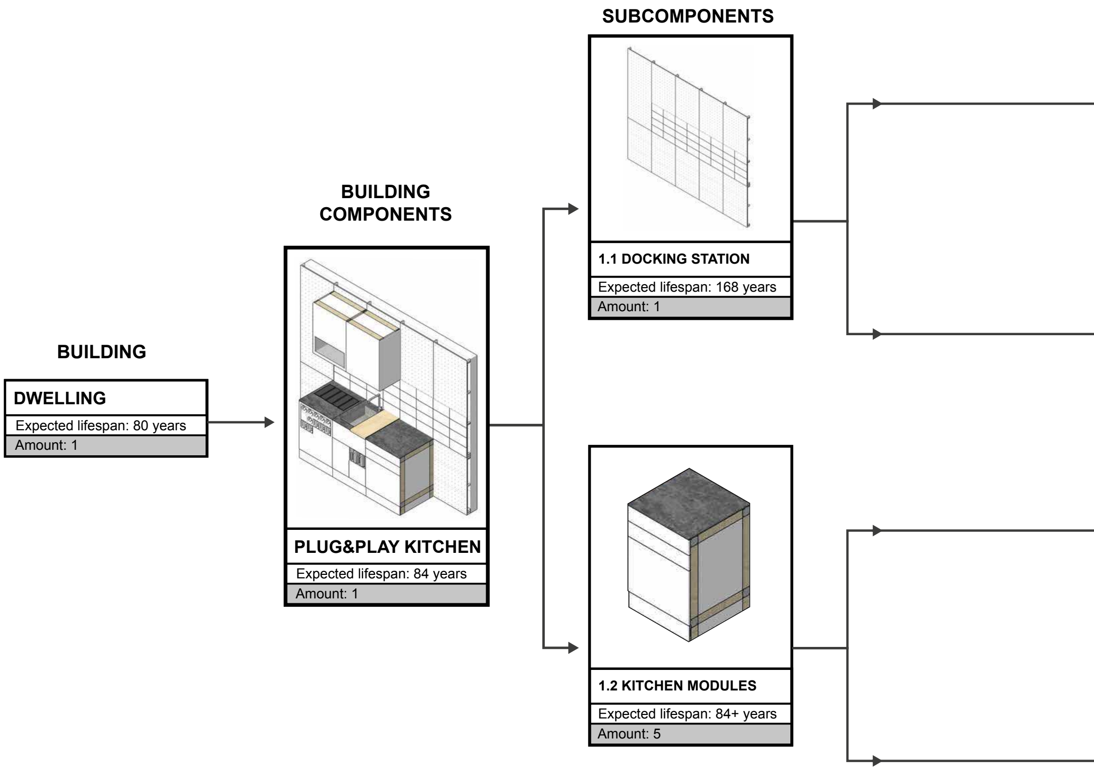
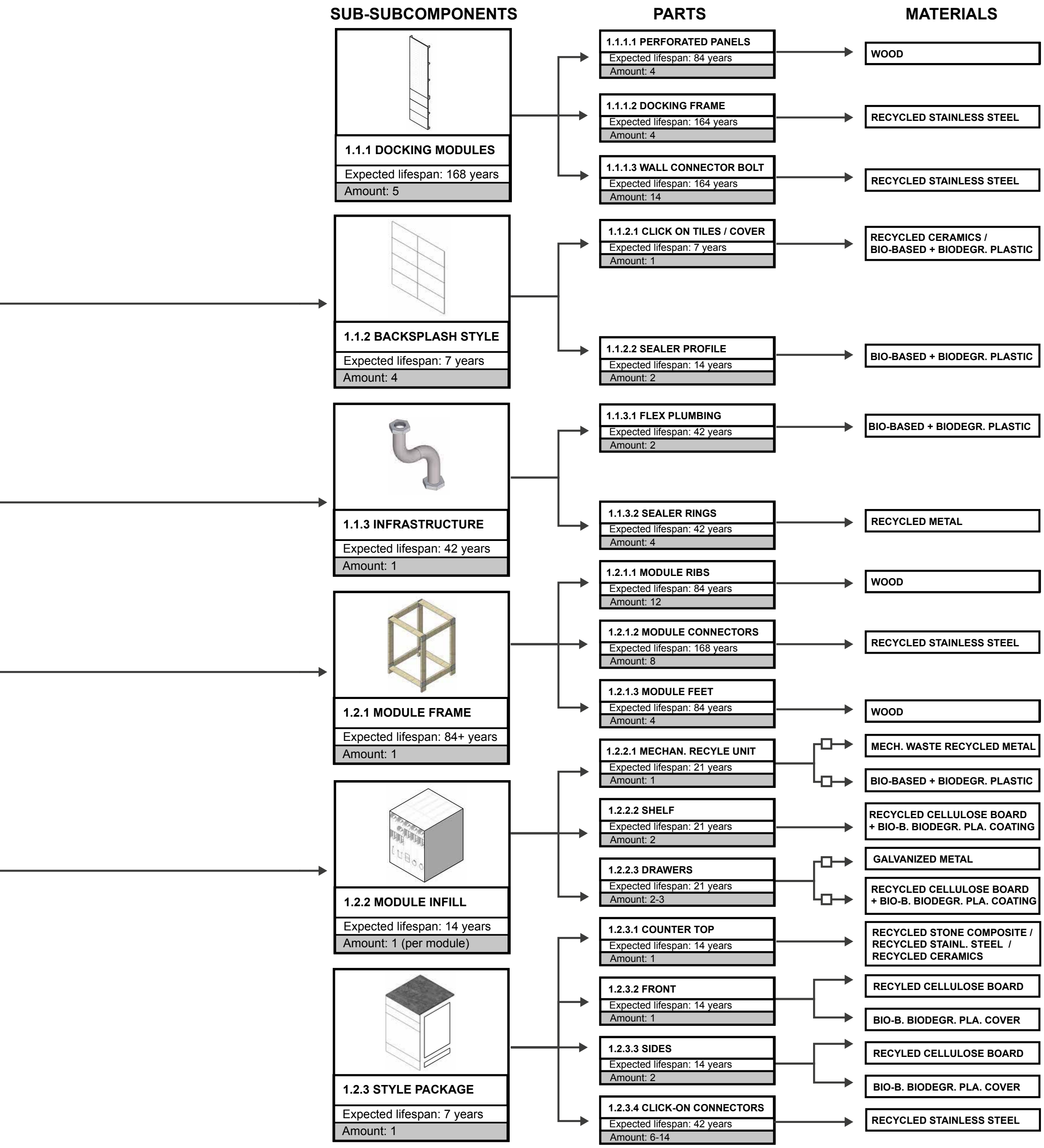


FIG. 4.8 Design canvasses for the circular kitchen's technical model as filled in during the 'generate' and 'refine' operational pathwayst

TOC


SUB-SUBCOMPONENTS
PARTS
MATERIALS
1.1.1 DOCKING MODULES
Expected lifespan: 168 years
Amount: 5
1.1.1.1 PERFORATED PANELS
Expected lifespan: 84 years
Amount: 4
WOOD
1.1.1.2 DOCKING FRAME
Expected lifespan: 164 years
Amount: 4
RECYCLED STAINLESS STEEL
1.1.1.3 WALL CONNECTOR BOLT
Expected lifespan: 164 years
Amount: 14
RECYCLED STAINLESS STEEL
1.1.2 BACKSPLASH STYLE
Expected lifespan: 7 years
Amount: 4
1.1.2.1 CLICK ON TILES / COVER
Expected lifespan: 7 years
Amount: 1
RECYCLED CERAMICS / BIO-BASED + BIODEGR. PLASTIC
1.1.2.2 SEALER PROFILE
Expected lifespan: 14 years
Amount: 2
BIO-BASED + BIODEGR. PLASTIC
1.1.3 INFRASTRUCTURE
Expected lifespan: 42 years
Amount: 1
1.1.3.1 FLEX PLUMBING
Expected lifespan: 42 years
Amount: 2
BIO-BASED + BIODEGR. PLASTIC
1.1.3.2 SEALER RINGS
Expected lifespan: 42 years
Amount: 4
RECYCLED METAL
1.2.1 MODULE FRAME
Expected lifespan: 84+ years
Amount: 1
1.2.1.1 MODULE RIBS
Expected lifespan: 84 years
Amount: 12
WOOD
1.2.1.2 MODULE CONNECTORS
Expected lifespan: 168 years
Amount: 8
RECYCLED STAINLESS STEEL
1.2.1.3 MODULE FEET
Expected lifespan: 84 years
Amount: 4
WOOD
1.2.2 MODULE INFILL
Expected lifespan: 14 years
Amount: 1 (per module)
1.2.2.1 MECHAN. RECYLE UNIT
Expected lifespan: 21 years
Amount: 1
MECH. WASTE RECYCLED METAL
BIO-BASED + BIODEGR. PLASTIC
1.2.2.2 SHELF
Expected lifespan: 21 years
Amount: 2
RECYCLED CELLULOSE BOARD + BIO-B. BIODEGR. PLA. COATING
1.2.2.3 DRAWERS
Expected lifespan: 21 years
Amount: 2-3
GALVANIZED METAL
RECYCLED CELLULOSE BOARD + BIO-B. BIODEGR. PLA. COATING
1.2.3 STYLE PACKAGE
Expected lifespan: 7 years
Amount: 1
1.2.3.1 COUNTER TOP
Expected lifespan: 14 years
Amount: 1
RECYCLED STONE COMPOSITE / RECYCLED STAINL. STEEL / RECYCLED CERAMICS
1.2.3.2 FRONT
Expected lifespan: 14 years
Amount: 1
RECYLED CELLULOSE BOARD
BIO-B. BIODEGR. PLA. COVER
1.2.3.3 SIDES
Expected lifespan: 14 years
Amount: 2
RECYLED CELLULOSE BOARD
BIO-B. BIODEGR. PLA. COVER
1.2.3.4 CLICK-ON CONNECTORS
Expected lifespan: 42 years
Amount: 6-14
RECYCLED STAINLESS STEEL

and additional options were selected and applied in the design. In the business model, the kitchen manufacturer sells the docking station and base modules directly to the housing associations, with a take-back guarantee, maintenance subscription and circular KPI's. This *financial arrangement* offers a clear incentive for the manufacturer to realise a kitchen which is easy to repair and to give a second life, or more. The extra modules and style packages are made available to users through *financial arrangements* such as lease and sale-with-deposit, which motivate returning the product at the end of their use cycle. The industrial model was aligned with the technical and business model. As the repair, reuse, refurbishment, and remanufacturing possibilities increased, the *mode of transport* and/or *location* of these *re-loop activities* became increasingly important to define.

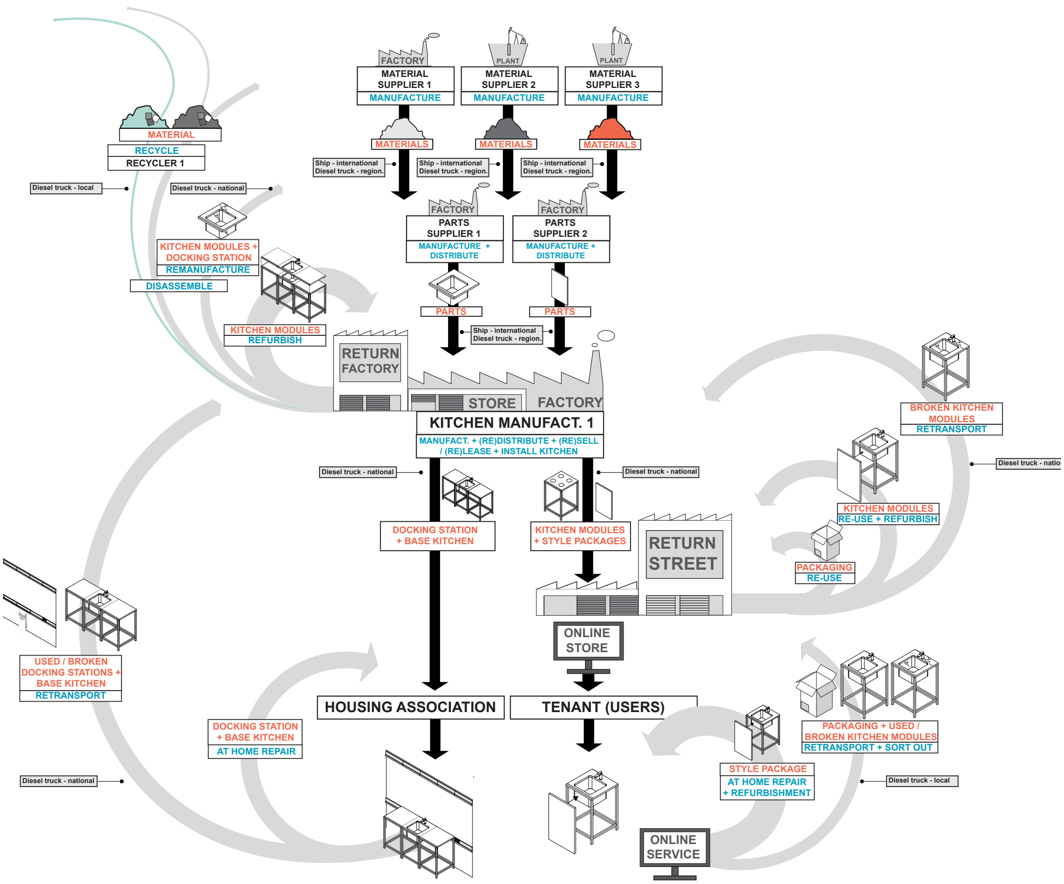


FIG. 4.9 Design canvasses for the circular kitchen's industrial model as filled in during the 'generate' and 'refine' operational pathways

TOC

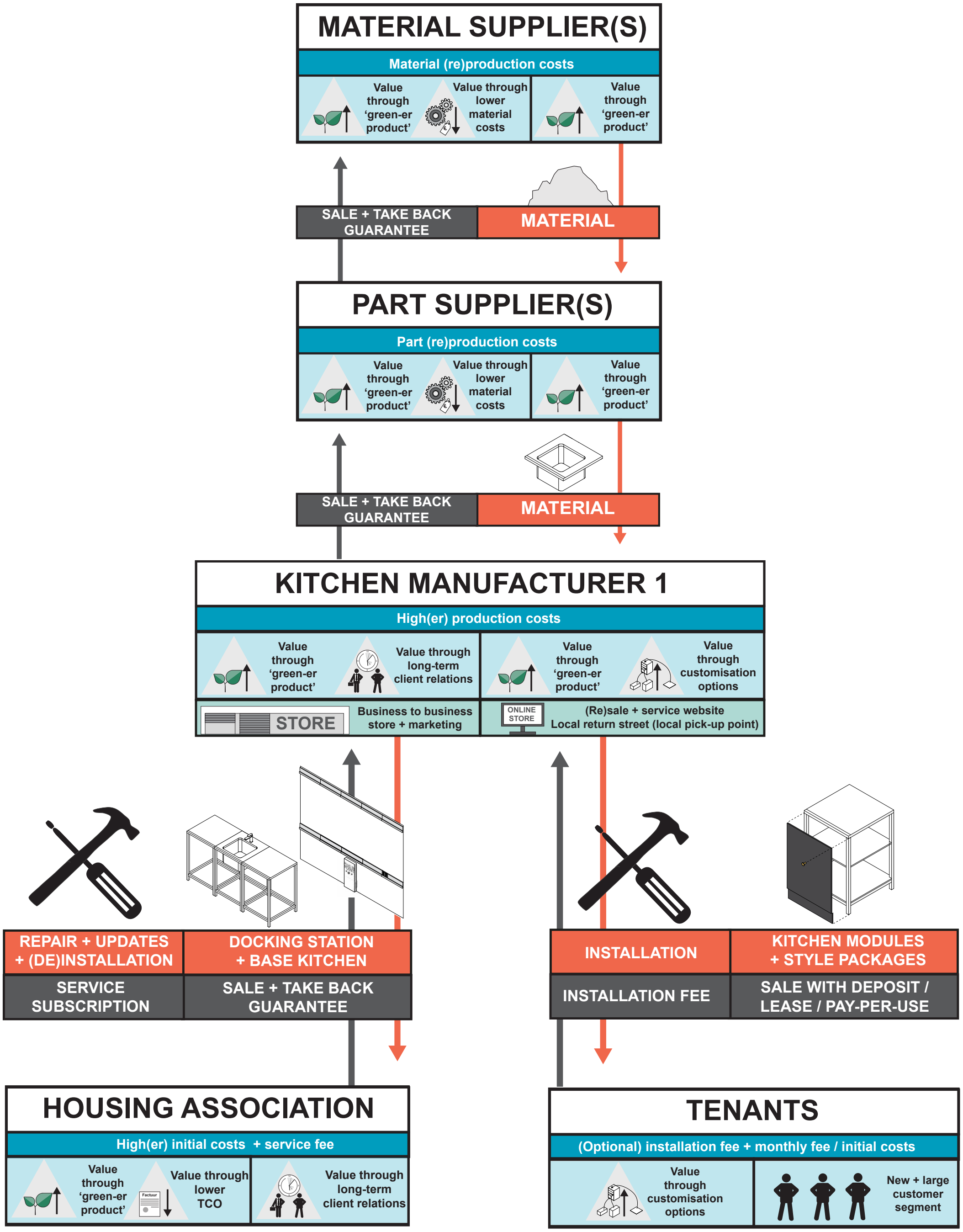


FIG. 4.10 Design canvasses for the circular kitchen's business model as filled in during the 'generate' and 'refine' operational pathways

TOC

As the selected *transport* option relies on fossil fuels, options were selected from the matrix which reduce the *distance* between the user and the *facility* where frequent *re-loop activities* take place. A local 'Return-Street' is introduced in which collected products are sorted to be traded, resold, lightly refurbished or sent back to the kitchen manufacturer. Products that come back to the manufacturer are sorted in their national 'Return-Factory' to be refurbished, remanufactured or recycled.

4.7.4 Refining the CIK

The concept design of the plug-and-play kitchen was refined to a full design proposal in two co-creation sessions with the involved partners. The design canvasses were – iteratively – completed and further detailed: the parameter-option matrices were reviewed to select additional options to complete parts of the canvasses which were previously left underdeveloped. Options, which were dismissed by the group, were reviewed with the parameter-option matrix and alternative options were selected. For example, to increase longevity, the material of the kitchen module frames was initially metal. For reasons of feasibility and poor environmental performance this material was dismissed. Alternative options were reviewed in the matrix and a (technological-looped) wood was selected.

4.7.5 Testing the framework during a student workshop

The CBC-generator was also tested during a design workshop: 14 students from the HAN University of Applied Sciences participated in the workshop. The students had a multidisciplinary background with a majority studying industrial design. The goal of the workshop was to develop design variants of three circular appliances – as part of the circular kitchen.

Several weeks prior to the workshop, the students were given a lecture on circular design and the CBC-generator was introduced. After the lecture, the students were provided with an earlier version of the CBC-generator (as published in van Stijn and Gruis, (2018)). However, they were free to use or prepare other tools for the workshop as well.

The design workshop itself was split in two parts. In the first part, the students made technical design variants for a circular extraction hood, electric cooking hub, and oven. The students were divided into 4 groups and were given 20 minutes per appliance. Afterwards, each group would present their design variants. In the second part of the workshop, the students developed a circular business model for the appliances. The students were, again, divided into 4 groups. Each group was provided with a *financial arrangement* (e.g., lease, pay-per-use, rent, ownership) as a starting point. After one hour, each group would present their business model. After the workshop, the students were asked if they had used the CBC-generator, and why or why not?

We found that for the first workshop the students had developed their own playing cards. Rather than using the options from the parameter-option matrix, they had translated circular design options to ‘what it would mean’ for their appliance. The students indicated that the design options of the CBC-generator remained far too abstract and needed more explanation and specification to their design context. For example, what does ‘*separate the design based on lifespan*’ mean in a circular kitchen appliance? A group who had worked with the *design table* – to ‘mix and match’ design options – concluded it provided structure during the design process. For the second part of the workshop, the students had developed their own *design canvas* to provide structure in ideating the business model. Note that the earlier version of the CBC-generator did not yet provide the design canvasses. Furthermore, the students limited the ideation to several parameters, such as *key partners*, *financial arrangement* and *value proposition.* See Figure 4.11 for pictures of the tools used during the workshops.

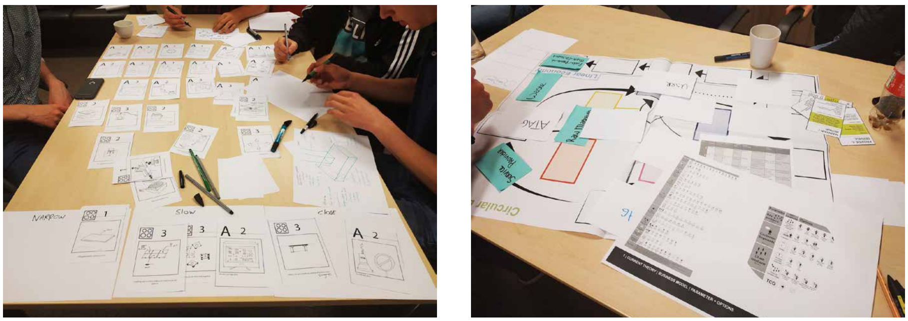


FIG. 4.11 The playing cards translating the design options to the technical model and the design canvas aiding circular business model ideation

From the workshop we derived the following conclusions. First, the CBC-generator could benefit from illustrated playing cards for each design option. These cards can provide an explanation and room on the card where the designer can – ad hoc – translate the option to their design context. Second, we found that the *design table and canvasses* are necessary in the CBC-generator to give structure and help designers translate the design options to a cohesive circular design variant.

4.8 Conclusion and discussion

In this article, we have presented an integral design tool for circular building components (CBC-generator), based on analysis and synthesis of (elements from) previously published generative frameworks for circular solutions. The example of the CIK shows that the CBC-generator can support integral synthesis of circular building components in different stages of the design. It supports designers as follows: (1) it provides designers all the design parameters which should be considered when making a circular design; (2) it gives designers an extensive list of circular design options for each parameter; (3) the CBC-generator supports the synthesis of a cohesive and comprehensive circular design through the design table in which selected design options can be systematically mixed and matched and through the design canvas in which design options can be translated to a design variant. As such, the CBC-generator makes an important step towards supporting industry in developing circular building components and, through the potential implementation of such components, towards creating a circular economy in the built environment.

Yet, some limitations should be noted as well. First, the framework analysis focused on frameworks explicitly related to the CE. CE-precedent design frameworks – such as eco-design, C2C, Design-for-X, biomimicry, and sustainable business model design tools – we not explicitly part of the scope of the analysis. Although these precedents are often at the base of circular design frameworks, further review could provide additional insights and design options. Second, user acceptance is key for the success of circular building components. Preferably, the user(perspective) should be included throughout the co-creation of circular building components. Further research could focus on the user perspective on, and user acceptance of, circular building components. Third, being a generative design tool, the CBC-generator only provides support in the synthesis and not in the assessment of the most circular design. For example, if it is more ‘circular’ to upgrade or recycle a building component, does not become evident in the framework. An appropriate choice for a circular assessment method – and the indicators considered – is vital to ensure circularity of the design: the assessment method determines on which metrics design variants are selected and optimized. Scheepens et al. (2016), propose that the environmental assessment of circularity should include quantitative assessment of material consumption, environmental impact and the value of the designed artefact. Bradley, Jawahir, Badurdeen and Rouch (2018) suggest that the financial assessment of circularity could consist of an analysis of the ‘Total Cost of Ownership (TCO)’. Future research could focus on how to integrate ex-ante evaluation methods in the CBC-generator. Finally, the CBC-generator does not show any causal link yet between different options nor between the technical, industrial, and business models. For example, if for the parameter *transport energy,* the option fossil fuel is selected, then the parameter *distance* should not offer any long(er) distance options such as global, continental, and national. The long transport with fossil fuels would likely have such a negative impact on the environmental performance that the process had better be performed locally, or not at all. The lack of advice on what makes 'logical combinations' of design options makes it difficult to guarantee the circularity of the design. Comprehensive, integral and systemic circularity of the outcome could be ensured in several ways. First, designers should design the technical, industrial and business model in parallel, using the design canvasses and (ultimately) considering all design parameters. Second, the design should be made in co-creation with all key partners: their knowledge and interest is needed to achieve a circular design. Third, a CE-expert who joins design sessions can indicate potentially (ill)logical combinations of design options. Fourth, circularity can be guaranteed by evaluating design variants with the above-mentioned circular assessment method throughout the design process. Finally, assessment results of 'what are logical design combinations' could be integrated into a (web-)programmed version of the CBC-generator to ease the use of the tool by non-skilled circular designers.

Acknowledgements

This research has been carried out as part of the 'Circular Building Components' project and has received funding from the Delft University of Technology and Amsterdam Institute for Advanced Metropolitan Solutions (AMS). Research has continued in the project Circular Kitchen (CIK), carried out by Delft University of Technology and Chalmers University of Technology. The CIK receives funding from the EIT Climate-KIC and AMS-institute.

Addendum: Further development of the CBC-generator

Following on the research presented in this chapter, the CBC-generator has been further developed and tested together with researchers from Chalmers University of Technology. The CBC-generator was used as a basis to develop a card-based game: 'Cards for Circularity'.

In a study led by Giliam Dokter, the card game was used to research the application of design tools to support circular design thinking in practice. Together, we carried out an interactive survey and design workshop with 12 design experts using the cards. We derived 4 key learnings that can support the development of circular design tools and the advancement of CE in practice. (1) Stakeholders are not always willing to commit to a circular design. Designers need tools to educate and convince stakeholders on the value and feasibility of circular design. (2) Circular design remains highly conceptual and theoretic. Tools providing feasible examples are needed. (3) The interconnectedness of parameters was found challenging as well as the need to consider the entire life cycle of the design. Advancing CE in practice requires circular design methods that help to contextualize the design process and reduce complexity. (4) A wide range of CE definitions is in use, hindering collaboration. Tools are needed that align definitions of CE and support collaboration of stakeholders throughout the design process and the design's lifecycle. This research has been published in: Dokter, G., van Stijn, A., Thuvander, L., & Rahe, U. (2020). Cards for circularity: Towards circular design in practice. *IOP Conf. Series: Earth and Environmental Science, 588*(042043), 1–8.

The cards have been used and tested further in educational and practice setting. We also tested them in the development of the circular building components presented in this dissertation. Figure 4.12 shows a workshop in which the stakeholders applied the cards to develop a supply-chain model for the circular dwelling extension. Through the efforts of Giliam Dokter the cards have since been developed into an online game (see Figure 4.13) which is available via https://giliam.shinyapps.io/10_CircularityCards/

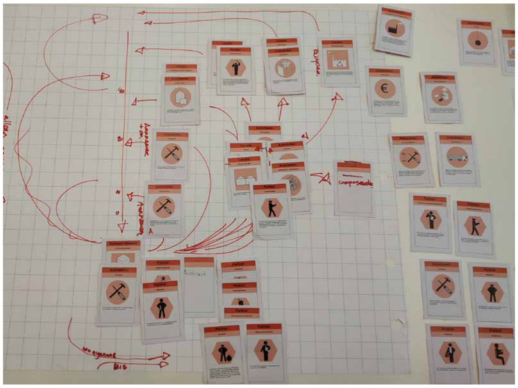


FIG. 4.12 Cards for circularity used during the design of a circular supply-chain model

TOC

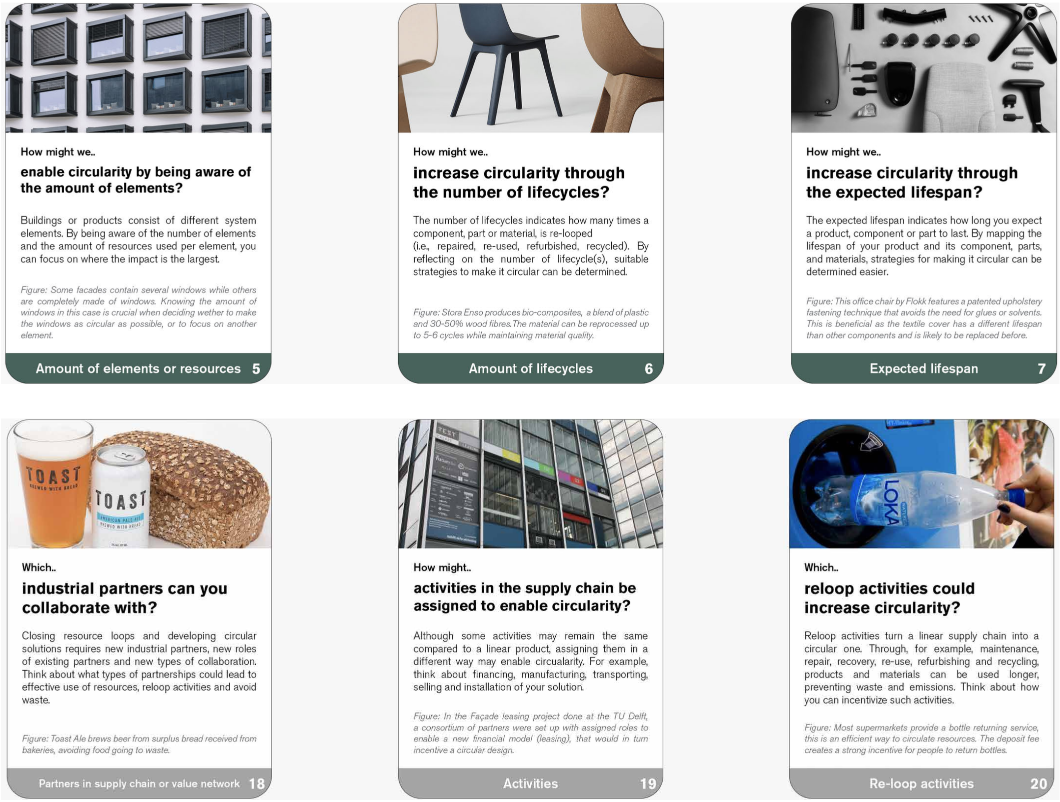


FIG. 4.13 Cards for circularity online game (figure by Giliam Dokter)

References

Achterberg, E., Hinfelaar, J., & Bocken, N. (2016). *Master circular business with the value hill*. Retrieved from https://www.circle-economy.com/wp-content/uploads/2016/09/finance-white-paper-20160923.pdf

Antikainen, M., & Valkokari, K. (2016). A framework for sustainable circular business model innovation. *Technology Innovation Management Review*, *6*(7), 5–12. https://doi.org/http://timreview.ca/article/1000

Ayres, R. U., & Ayres, L. W. (2002). *A Handbook of Industrial Ecology*. Northampton, MA.: Edward Elgar Publishing.

Bakker, Conny, den Hollander, M., van Hinte, E., & Zijlstra, Y. (2014). *Products That Last*. Delft: TU Delft Library & Marcel den Hollander IDRC.

Balkenende, R., & Bakker, C. A. (2015). Developments and challenges in design for sustainability of electronics. In R. Curran, N. Wognum, M. Borsato, J. Stjepandić, & W. J. C. Verhagen (Eds.), *Transdisciplinary Lifecycle Analysis of Systems: Proceedings of the 22nd ISPE Inc. International Conference on Concurrent Engineering*. https://doi.org/10.3233/978-1-61499-544-9-3

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*. New York: William Morrow.
Bocken, N. M. P., Allwood, J. M., Willey, A. R., & King, J. M. H. (2011). Development of an eco-ideation tool to identify stepwise greenhouse gas emissions reduction options for consumer goods. *Journal of Cleaner Production*, *19*(12), 1279–1287. https://doi.org/10.1016/j.jclepro.2011.04.009
Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124
Bocken, N. M. P., Farracho, M., Bosworth, R., & Kemp, R. (2014). The front-end of eco-innovation for eco-innovative small and medium sized companies. *Journal of Engineering and Technology Management*, *31*(1), 43–57. https://doi.org/10.1016/j.jengtecman.2013.10.004
Bovea, M. D., & Pérez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production*, *20*(1), 61–71. https://doi.org/10.1016/j.jclepro.2011.07.012
Bradley, R., Jawahir, I. S., Badurdeen, F., & Rouch, K. (2018). A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation. *Resources, Conservation and Recycling*, *135*, 141–149. https://doi.org/10.1016/j.resconrec.2018.01.017
Dahlsrud, A. (2008). How corporate social responsibility is defined: an analysis of 37 definitions. *Corporate Social Responsibility and Environmental Management*, *15*, 1–13. https://doi.org/https://doi.org/10.1002/csr.132
de Koeijer, B., Wever, R. and, & Henseler, J. (2017). Realizing product-packaging combinations in circular systems: shaping the research agenda. *Packaging Technology and Science*, *30*, 443–460.
Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition
Ellen MacArthur Foundation. (2015). *Growth within: a circular economy vision for a competitive europe*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf
Ellen MacArthur Foundation, & IDEO. (2017). The circular design guide. Retrieved August 27, 2018, from https://www.circulardesignguide.com/
Evans, J., & Bocken, N. M. P. (2013). Circular Economy Toolkit. Retrieved August 22, 2018, from http://circulareconomytoolkit.org/
Evans, J. L., & Bocken, N. M. P. (2014). A tool for manufacturers to find opportunity in the circular economy: www.circulareconomytoolkit.org. In R. Setchi, R. J. Howlett, M. Naim, & H. Seinz (Eds.), *KES Transactions on Sustainable Design and Manufacturing I* (pp. 303–320). England, UK: Future Technology Press.
Fischer, A., & Achterberg, E. (2016). *Create a financeable circular business in 10 steps*. The Netherlands: Circle Economy & Sustainable Finance Lab.
Fitzgerald, D. P., Herrmann, J. W., Sandborn, P. A., & Schmidt, L. C. (2005). Beyond tools: a design for environment process. *International Journal of Performability Engineering*, *1*(2), 105–120. Retrieved from http://www.enme.umd.edu/ESCML/Papers/beyond.pdf
Forum for the Future, & Novelis. (n.d.). Design for Demand. Retrieved August 28, 2018, from http://designfordemand.forumforthefuture.org/
Forum for the Future, & Unilever. (n.d.). Circular business models. https://doi.org/10.1007/978-3-319-71791-3
Geissdoerfer, M., Bocken, N. M. ., & Hultink, E. J. (2016). Design thinking to enhance the sustainable business modelling process - A workshop based on a value mapping process. *Journal of Cleaner Production*, *135*, 1218–1232. https://doi.org/10.1016/j.jclepro.2016.07.020
Geldermans, R. J. (2016). Design for change and circularity - Accommodating circular material & product flows in construction. *Energy Procedia*, *96*, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153
Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: An evaluation and critical analysis. *Journal of Cleaner Production*, *23*(1), 216–224. https://doi.org/10.1016/j.jclepro.2011.07.005
Gerritsen, M. (2015). *Circular Design Checklist*. The Netherlands: Reversed Concepts.
Gispen. (n.d.). Design framework. Retrieved August 24, 2018, from https://www.gispen.com/nl/circulaire-economie/het-ontwerpproces-circulaire-economie

Goldsworthy, K. (2017). The Speedcycle: A design-led framework for fast and slow circular fashion lifecycles. *The Design Journal*, *20*(sup1), S1960–S1970. https://doi.org/10.1080/14606925.2017.1352714
Graedel, T. E., & Allenby, B. R. (2003). *Industrial ecology*. Prentice Hall.
Haney, W. M., Russell, M., & Bebell, D. (2004). Drawing on education: Using drawings to document schooling. *Harvard Educational Review*, *74*(3). https://doi.org/10.17763/haer.74.3.w0817u84w7452011
Heyes, G., Sharmina, M., Mendoza, J. M. F., Gallego-Schmid, A., & Azapagic, A. (2018). Developing and implementing circular economy business models in service-oriented technology companies. *Journal of Cleaner Production*, *177*, 621–632. https://doi.org/10.1016/j.jclepro.2017.12.168
Hofmann, F., Marwede, M., F, N., & D, K. (2017). Circular added value: Business model design in the circular economy. In C. Bakker & R. Mugge (Eds.), *PLATE Product Lifetimes And The Environment 2017* (pp. 171–177). https://doi.org/10.3233/978-1-61499-820-4-171
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026
Joustra, D. J., de Jong, E., & Engelaer, F. (2013). *Guided choices towards a circular business model*. Retrieved from http://www.opai.eu/uploads/Guided_Choices_towards_a_Circular_Business_Model_pdf11.pdf
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
Leising, E., Quist, J., & Bocken, N. (2018). Circular economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010
Lewandowski, M. (2016). Designing the business models for circular economy - Towards the conceptual framework. *Sustainability*, *8*(43), 1–28. https://doi.org/10.3390/su8010043
Lüdeke-Freund, F., Gold, S., & Bocken, N. M. P. (2018). A review and typology of circular economy business model patterns. *Journal of Industrial and Production Engineering*, *23*(1). https://doi.org/10.1111/jiec.12763
Lyle, J. T. (1994). *Regenerative design for sustainable development*. John Wiley.
McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. New York: North Point Press.
Mendoza, J. M. F., Sharmina, M., Gallego-Schmid, A., Heyes, G., & Azapagic, A. (2017). Integrating backcasting and eco-design for the circular economy: The BECE framework. *Journal of Industrial Ecology*, *21*(3), 526–544. https://doi.org/10.1111/jiec.12590
Mentink, B. (2014). Circular Business Model Innovation: A process framework and a tool for business model innovation in a circular economy. Delft University of Technology & Leiden University.
Mestre, A., & Cooper, T. (2017). Circular product design: A multiple loops life cycle design approach for the circular economy. *The Design Journal*, *20*(sup1), S1620–S1635. https://doi.org/10.1080/14606925.2017.1352686
Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability*, *8*(937), 1–15. https://doi.org/10.3390/su8090937
Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586
Nußholz, J. (2017a). Circular Business Model Framework : Mapping value creation architectures along the product lifecycle. In C. A. Bakker & R. Mugge (Eds.), *PLATE Product Lifetimes And The Environment 2017*. Delft: IOS press.
Nußholz, J. (2017b). Circular business models: Defining a concept and framing an emerging research field. *Sustainability*, *9*(1810), 2–16. https://doi.org/10.3390/su9101810
Pádua, M. De, Pigosso, D. C. A., & Mcaloone, T. C. (2018). Sustainable qualifying criteria for designing circular business models. *Procedia CIRP*, *69*(May), 799–804. https://doi.org/10.1016/j.procir.2017.11.014
Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, *181*, 687–700. https://doi.org/10.1016/J.JENVMAN.2016.08.036
Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Poppelaars, F. (2014). Designing for a circular economy: The conceptual design of a circular mobile device. Delft University of Technology.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075

Sempels, C. (2014). Implementing a circular and performance economy through business model innovation. In Ellen MacArthur Foundation (Ed.), *A new dynamics: Effective business in a circular economy*. Cowes, UK: Ellen MacArthur Foundation.

Stahel, W. R. (2006). *The performance economy*. Palgrave Macmillan.

Telenko, C., Seepersad, C. C., & Webber, M. E. (2008). A compilation of design for environment principles and guidelines. *DETC/CIE 2008, ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, (June 2014), 1–13. https://doi.org/10.1115/DETC2008-49651

The Great Recovery, & RSA. (2013). *Investigating the role of design in the circular economy*. UK: The Great Recovery & RSA.

Toxopeus, M. E., van den Hout, N. B., & van Diepen, B. G. D. (2018). Supporting product development with a practical tool for applying the strategy of resource circulation. *Procedia CIRP*, *69*, 680–685. https://doi.org/10.1016/j.procir.2017.11.033

Ullman, D. G. (2010). *The Mechanical Design Process*. New York: McGraw-Hill.

Van Dam, S. S., Bakker, C. A., De Pauw, I., & Van Der Grinten, B. (2017). The circular pathfinder: development and evaluation of a practice-based tool for selecting circular design strategies. *PLATE Product Lifetimes And The Environment 2017*, 102–107. https://doi.org/10.3233/978-1-61499-820-4-102

van den Berg, M. R., & Bakker, C. A. (2015). A product design framework for a circular economy. *PLATE Product Lifetimes And The Environment 2015*, 365–379. Nottingham: Nottingham Trent University.

van Stijn, A., & Gruis, V. H. (2018). Towards a circular economy in the built environment: An integral design framework for circular building components. *Smart and Sustainable Built Environment (SASBE) 2018*. Sydney.

WIITHAA. (n.d.). Tools - Circulab board, the business game to activate your circular business model. Retrieved August 27, 2018, from https://circulab.eu/tools/#board

5 A Circular Economy Life Cycle Assessment (CE-LCA) model for building components

Chapter published in its entirety in 2021 in Resources, Conservation and Recycling, 174(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.10568

A van Stijn[1,2], L C Malabi Eberhardt[3], B Wouterszoon Jansen[1,2] and A Meijer[1]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL Delft, The Netherlands.

[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), building 027W, Kattenburgerstraat 5, 1018 JA Amsterdam, The Netherlands.

[3] Department of the Built Environment, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen SV, Denmark.

ABSTRACT The transition towards a Circular Economy (CE) in the built environment is vital to reduce resource consumption, emissions and waste generation. To support the development of circular building components, assessment metrics are needed. Previous work identified Life Cycle Assessment (LCA) as an important method to analyse the environmental performance in a CE context. However, questions arise about how to model and calculate circular buildings components. We develop an LCA model for circular building components in four steps. First, we elaborate on the CE principles and LCA standards to identify requirements and gaps. Second, we adapt LCA standards and propose the 'Circular Economy Life Cycle Assessment' (CE-LCA) model. Third, we test the model by assessing an exemplary building component: the Circular Kitchen (CIK). Finally, we evaluate the CE-LCA model with 44 experts. In the CE-LCA model, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include these cycles, dividing the impacts using a circular allocation approach. The case of the CIK shows that the CE-LCA model supports an ex-ante assessment of circular building components in theoretical context; it makes an important step to support the transition to a circular built environment.

KEYWORDS Circular Economy (CE), assessment method, Life Cycle Assessment (LCA), multi-cycling, allocation, building component

5.1 Introduction

The building sector is said to consume 40% of global resources, and to generate 33% of all emissions and 40% of waste globally (Ness & Xing, 2017). The concept of the Circular Economy (CE) – originating from several schools of thought and popularised by the Ellen MacArthur Foundation (2013) – proposes an alternative to the linear economy of 'take-make-use and dispose'. The CE aims to enable economic growth without an ever-growing pressure on the environment (Pomponi & Moncaster, 2017). We understand CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing and narrowing material and energy loops." (Geissdoerfer, Savaget, Bocken, & Hultink, 2017 p. 759) Narrowing loops is reducing resource use (i.e., increasing efficiency); slowing loops means prolonging the use of (building) components, parts and materials by extending lifespans and introducing multiple cycles; closing loops is to (re)cycle materials from End-of-Life (EoL) back to production (Bocken, de Pauw, Bakker, & van der Grinten, 2016). The cycles in the CE can be divided into biological and technical material cycles (Ellen MacArthur Foundation, 2013). Value Retention Processes (VRPs) – also called R-imperatives – are key in realising the cycles in a CE (Potting, Hekkert, Worrell, & Hanemaaijer, 2017; Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Examples of VRPs are reduce, repair, reuse, and recycle; we refer to the framework of Wouterszoon Jansen et al. (2020).

As the building sector has the highest share in resource consumption, emissions and waste generation of all industries (Ness & Xing, 2017), the transition towards a CE in the built environment is vital to create a more sustainable society. The built environment can be made more circular by integrating CE principles in building components. These components can be placed in new buildings and in existing buildings during maintenance and renovation to gradually make the existing stock more circular. To integrate CE principles in building components, integral changes in their designs, supply chains, and business models are needed (Bocken et al., 2016; Ellen MacArthur Foundation, 2013; Hart, Adams, Giesekam, Tingley, & Pomponi, 2019; van Stijn, Eberhardt, Wouterszoon Jansen, & Meijer, 2020; van Stijn & Gruis, 2020; Wouterszoon Jansen et al., 2020). Yet, there are many possible design alternatives for (more) circular building components (van Stijn & Gruis, 2020). A roof which is constructed with non-virgin materials, or modular, or bio-based and biodegradable could be considered more circular in its own respect. To transition to the 'most' circular built environment, we need to assess which designs result in the most environmentally-circular building components; so, an assessment method is needed.

In previous research, two methods are often identified to support assessment of environmental performance in the CE: in a Material Flow Analysis (MFA), mass balances are calculated over time to identify the state and changes of material flows within a defined system (Corona, Shen, Reike, Rosales Carreón, & Worrell, 2019). MFA can be used to analyse quality of resource flows (e.g., virgin, renewable, recycled) and the resource consumption of building components in a CE (Elia, Gnoni, & Tornese, 2017; Pomponi & Moncaster, 2017). Life Cycle Assessment (LCA) is the best-defined method to analyse environmental impacts, and can be applied in a CE context (Pomponi & Moncaster, 2017; Scheepens, Vogtländer, & Brezet, 2016). The focus in this paper is on applying LCA to assess environmental impacts in circular building components.

In LCA, the environmental impacts of a building (component) are assessed along (parts of) its life cycle. However, conventional LCA studies focus on analyzing the impact of a building for a single service life (cycle) (M. Z. Hauschild, Rosenbaum, & Olsen, 2018; Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020; Suhariyanto, Wahab, & Rahman, 2017). Whereas in a CE, within the building (component) lifecycle, parts and materials – potentially – have different and multiple (use) cycles (Malabi Eberhardt et al., 2020; van Stijn et al., 2020; van Stijn & Gruis, 2020; Wouterszoon Jansen et al., 2020). Methodological questions arise: how to apply LCA in circular building components with multiple cycles?

Approaches to multiple cycles in LCA are discussed in standards (EN 15804, 2012; EN 15978, 2011; ISO 14040, 2006; ISO 14044, 2006), and have been compared for short-lived products (e.g., Allacker et al., 2017; van der Harst et al., 2016), for reuse of building components (see De Wolf, Hoxha, & Fivet, 2020)) and in a circular built environment context (see Malabi Eberhardt et al. (2020)). Allacker et al. (2017)

TOC

compared 11 allocation approaches. Only the ‘Linearly Degressive’ (LD) approach included all cycles of the product system within the product assessment. Ultimately, Allacker et al. (2017) preferred to (only) include the previous and subsequent cycle of the product within the assessment as they found predicting all cycles challenging. On the other hand, Malabi Eberhardt et al. (2020) suggested the LD approach incentivises narrowing, slowing and closing cycles both now (i.e., downstream) and in the future (i.e., upstream). They built upon the LD approach, presenting the CE LD approach. De Wolf et al. (2020) posed that the allocation approaches they compared – including LD – did not assess reuse of building components accurately, concluding that further development is needed.

These studies focused on allocation, concluding with recommendations and/or (optimized) allocation formulas. Studies addressing CE adoption in building LCA remain sparse (Hossain & Ng, 2018). Comprehensive and practical guidance to apply LCA in circular building components remains lacking. Doing such an LCA, we touch upon multiple methodological questions: how to set the system boundary and model the system; how to apply an allocation approach which shares impacts between all cycles; how to address system uncertainties? In turn, it influences how to define the object of the assessment, period of assessment, functional unit, stages of assessment, modelling of the Life Cycle Inventory (LCI), calculations of environmental impacts (LCIA), and sensitivity analysis. Consequently, adaptations to LCA standards for building products and buildings – such as EN 15978 (2011) and EN 15804 (2012) – are needed.

We built upon the aforementioned allocation studies; we depart from the application perspective by exploring how these abovementioned methodological questions can be addressed in multi-cycle LCAs – and testing the (dis)advantages. By adapting existing building LCA standards, we aim to propose a model to apply LCA in the development of circular building components.

5.2 Method

An iterative, stepwise approach was used to develop the model (see Figure 5.1). In step 1, we elaborated on key principles of CE in building components and analysed how existing LCA standards deal with these; we identified potential gaps in theory and current standards, and defined requirements for LCA of circular building

TOC

components. In step 2, we built on the existing LCA standards, proposing the CE-LCA model for building components. In step 3, we tested the CE-LCA model by applying it in the assessment of an exemplary circular component: the Circular Kitchen (CIK). In step 4, we evaluated the model with experts. Iterations of refinement, test and evaluation were continued until the model fulfilled the requirements and the evaluation step yielded no new remarks by the experts. This paper is structured following these steps – presenting the final iteration of the CE-LCA model.

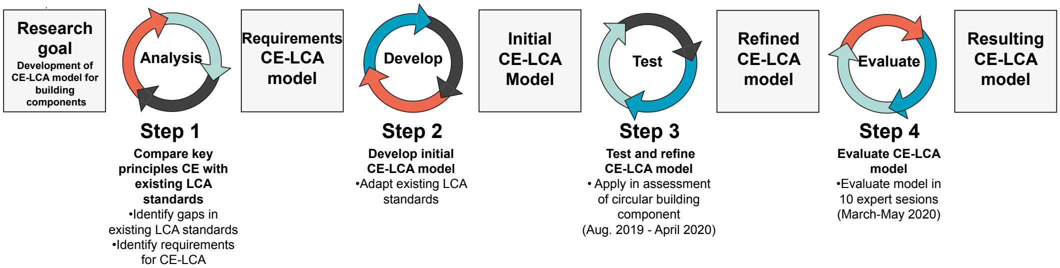


FIG. 5.1 Iterative approach for developing, testing and evaluating the CE-LCA model based on Peffers et al. (2007)

5.3 Key principles, gaps and requirements for LCA of circular building components

5.3.1 Integrate multiple levels in LCA: building component as a composite of parts and materials

To cycle building components at their highest utility and value, we should consider the building components as a composite of parts and materials, each with their own – optimised – lifespan. Duffy coined the concept of 'shearing layers', which was later elaborated on by Brand (1994): a building consists of 'layers' with their own lifespan which could be changed independently. Similarly, building components could be regarded as a composite of parts and materials with different lifespans. Per building component more levels (e.g., sub-components, resources) or fewer could be identified.

To increase the overall lifespan of building components, parts and materials might be exchanged at a different rate (Bocken et al., 2016; Wouterszoon Jansen et al., 2020). Alternatively, parts or materials might have longer lifespans than the building component. Consider a façade with a 30-year lifespan and brick finishing with a 75-year lifespan. Commonly bricks are laid using mortar making them hard to separate and reuse after 30 years. If during design the 'layers' were differentiated based on lifespan, alternative finishing materials and – equally important – joining-techniques could have been considered to prevent premature disposal.

Current European LCA standards focus on building (EN 15978, 2011) and building product (EN 15804, 2012) assessment. An intermediate link – on building component level – is missing (Lützkendorf, 2019). In the EN 15978 (2011), the building is considered as a composite of components, parts and materials with different lifespans. Yet, different levels of the building system are commonly not integrated into a single LCA. How multiple levels are 'connected' can influence the lifespans and cycles of each element in the system; optimising these is a key principle to keep elements cycling at their highest utility and value. Therefore, a multi-level LCA is required in CE-context. For a building component LCA, this means including underlying levels such as parts and materials; as the building component is installed in a building, the cohesion with the building level should be considered.

5.3.2 Consider the interplay of different lifespans

Understanding the interplay of different types of lifespan is vital to slow and close loops optimally. For example, Geraedts et al. (2009, p. 298) distinguish technical, functional and economic lifespan. The technical lifespan is defined as "the maximum period during which it can physically [perform]" (Cooper, 1994, p. 5). The economic lifespan is the period in which the benefits outweigh the costs (Geraedts et al., 2009). The functional lifespan can be influenced by regulations and changing user needs, including the function or appearance of the building component (Geraedts et al., 2009; Méquignon & Ait Haddou, 2014). By analysing the interplay of different lifespans – in the entire building component system – the *leading lifespan* can be identified. This is 'the weakest' link determining the obsolescence – and replacement rate – of (parts of) the system.

Assumptions on lifespan in LCAs are complex; how they are made varies. When applying LCA, Reference Service Lifespans (RSL) of buildings types are provided in national standards (e.g., Stichting Bouwkwaliteit (2019, p. 37)). Building products and materials RSL may be found in reference lists which could be based on argued assumptions by the producer (Stichting Bouwkwaliteit, 2019, p. 13) or calculated by balancing the technical, functional, aesthetic and economic lifespan (e.g., Aagaard, Brandt, Aggerholm and Haugbølle (2013)). For newly-designed circular components, an estimated Service Life (SL) needs to be determined. ISO 15686 (2011) provides the standard for SL planning for buildings – including for 'innovative' components. It includes the 'factor method' in which the 'Estimated SL' of the component is calculated by multiplying its RSL by a number of factors that affect the technical lifespan (e.g., 'material quality' or 'work execution level'). However, no functional or economic lifespan factors are included. Previous work concluded that buildings or components are replaced more frequently than assumed (Barras & Clark, 1996; Seo & Hwang, 2001; Slaughter, 2001) indicating that the functional or economic lifespan was shorter than expected. Junnila & Horvath (2003) argue that the influence of obsolescence is insufficiently considered in LCA. In CE-LCA, the interplay of the technical, functional and economic lifespan should be considered for all elements of the building component system.

5.3.3 Integrate VRPs in LCA system boundary

To slow and close cycles optimally, each element of the building component system might have multiple and different use cycles, requiring different VRPs. These cycles can be 'open-' or 'closed loops': In recycling theory, closed loops refer to recycling for the same quality or use (Huysveld, Hubo, Ragaert, & Dewulf, 2019). However, in circular supply chains, closed cycles may refer to VRPs realised by the industry(partners) involved in the original production (French & LaForge, 2006; Genovese, Acquaye, Figueroa, & Lenny Koh, 2017). Additionally, VRPs can take place 'inside' the assessed building component, or 'outside'. For example, windows can be refurbished and re-installed in the same façade, or they can be re-installed elsewhere.

Guidelines for dealing with multiple cycles (also named 'multifunctionality' or 'secondary functions') can be found in LCA standards (EN 15804, 2012; EN 15978, 2011; ISO 14040, 2006; ISO 14044, 2006). The ISO 14044 (2006) includes a hierarchical procedure explained well by Bjørn et al. (2018, p. 90): dividing impacts between cycles – i.e., allocation – should be avoided by (1) dividing the processes between the cycles and 'cutting off' the processes of secondary cycles. If this is not possible, then (2) 'system expansion' should be applied: multiple cycles are included in the system boundary (e.g., through displacement or avoidance of impacts). If system expansion is not possible, (3) allocation should be used. The European building LCA standards – EN 15804 (2012) and EN 15978 (2011)

– handle multifunctionality by combining approaches. Impacts from production, use and waste disposal (module A-C) are calculated using the 'cut-off' allocation approach; the system boundary is extended to include reuse, recycling and recovery potential of building products and materials in one subsequent cycle. The net benefits and burdens are reported separately in the informational module D.

In a CE-LCA, the abovementioned approach is problematic for two reasons. First, it is difficult to standardize crediting of reuse, recycling or recovery benefits (de Valk & Quik, 2017; Delem & Wastiels, 2019; Malabi Eberhardt et al., 2020; Wastiels, Delem, & van Dessel, 2013). Second, cycles prior to the SL of the assessed building component or after one subsequent cycle remain invisible: they are not included in the scope of the assessment. In CE-LCA, the VRPs for all cycles in the building component system should be included in the system boundary of the assessment; these include VRPs inside and outside the assessed building component.

5.4 Towards a circular economy life cycle assessment model

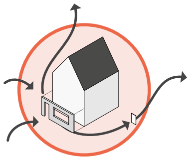
We built upon EN 15804 (2012) and EN 15978 (2011) to develop a Circular Economy Life Cycle Assessment (CE-LCA) model for building components which fulfils the requirements identified in Section 5.3. We explore how the methodological questions mentioned in the introduction can be addressed. We present the CE-LCA model following the LCA phases (adjusted from ISO 14040 (2006)): (1) goal and scope definition, (2) CE Life Cycle Inventory (CE-LCI), (3) CE Life Cycle Impact Assessment (CE-LCIA), and (4) interpretation of results.

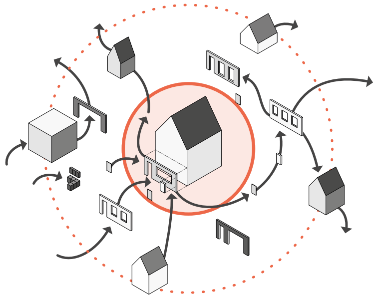
5.4.1 Goal and scope definition

In phase 1, the goal and scope of the CE-LCA is defined, addressing the object of assessment, functional unit, and system boundary.

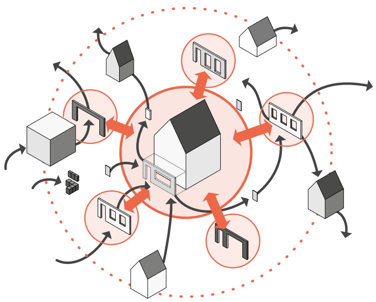
5.4.1.1 Object of assessment in CE-LCA

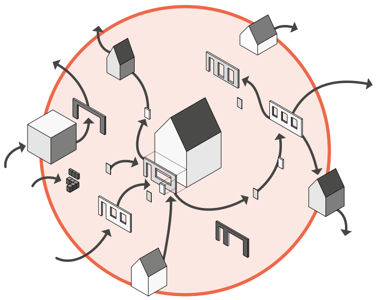
In current standards, the object of assessment is ‘the building (component) during its SL, including reuse and recycling potential’; previous cycles and cycles after one future cycle are not considered. If we consider all cycles, the object becomes ‘the entire building component system including all use cycles’. This might be useful to assess the impacts of entire circular systems. Yet, it hinders comparability of individual building components as impacts of multiple uses are integrated into one assessment. In CE-LCA the purpose is to assess a building component within a circular system. Herein we distinguish two possible objects of assessments. Consider, a kitchen with fronts which can be reused once. A possible object of assessment could be to determine the environmental impacts of an *average* kitchen within the circular system. We then assume that half of the fronts are made with virgin material and half with second-hand material. Such analysis is relevant to determine Environmental Product Declarations (EPD) of standardized designs, to assess a Product-Service System (PSS) or for LCAs in early-stage design. However, in some cases, we need to determine the impact of a *specific* kitchen within the circular system. For example, if we apply a kitchen with second-hand fronts in a building, we should only declare impacts of second-hand fronts. Such analysis is relevant in the context of LCAs for building projects. See Figure 5.2 for an overview.





Object of assessment:	**Building component for a single service life, including re-use or recycle potential**	***Specific* building component in a circular system**
Usable for assessing:	**Linear or non multi-cycling building components**	**Circular building components in a building project**





Object of assessment:	***Average* building component in a circular system**	**A circular building component system**
Usable for assessing:	**Circular building component EPDs, PSS, mass-produced building components, early-stage designs**	**Circular systems**

FIG. 5.2 Overview four ‘objects of assessment’ in CE-LCAs for building components

5.4.1.2 Functional unit in CE-LCA

The functional unit (FU) of a CE-LCA for building components follows the template: "the use of an *average/specific what, quality,* in a circular system over a period of *x years*". The template adapts the EN standards and follows Suhariyanto et al. (2017) who concluded that the FU of a multi-cycle LCA should be based on function or activity.

5.4.1.3 System boundary in CE-LCA

In EN 15978 (2011), the life cycle of a building (component) – and system boundary of the LCA – is described in modules A, B, C, and D. We have adapted this framework, applying elements of the butterfly model of the Ellen MacArthur Foundation (2013) and the VRP framework of Wouterszoon Jansen et al. (2020). We extended the system boundary to include all use cycles on all levels of the building component lifecycle. We identify four modules and 45 life cycle stages in a CE-LCA (see Figure 5.3). Module CE-A 'Production, construction and pre-use' commences with the extraction and supply of the virgin materials and ends with the installation of the assessed building component in the building. If non-virgin material is applied in the building component, module CE-A also includes all the previous use cycles of this material. Module CE-B is the use of the building component. Module CE-C reports all following VRPs of the building component, parts and materials. Module CE-D reports on the final disposal of the material back into the bio and techno sphere.

5.4.1.4 Reference study period

In the LCA standards, the Reference Study Period (RSP) is aligned with the SL of the building (e.g., 60, 75, 100 years). At t=0 the building (component) is constructed. At the end of the RSP, the building (component) is (assumed to be) demolished and materials are reused, recycled or disposed. This approach increases comparability. In CE-LCA, the RSP – and what happens when – is more precarious to determine. We assume that at t=0 the building component is constructed and taken into use. Yet, materials and parts could have been produced and cycled prior to this moment (t<0); and they might cycle long after the assumed SL of the building component has ended. To be able to assess if 'loops are slowed', the (functional, economic and technical) lifespans for the building component, parts and materials need to be reported exact. Therefore, the RSP should be determined by the longest, leading lifespan within the assessed building component. To ensure comparability, the impact may be calculated back to an impact/time unit (e.g., impact per x year(s)).

5.4.2 Circular Economy Life Cycle Inventory

In phase 2 of the CE-LCA, the CE-LCI is made in accordance with the system boundary described in Section 5.4.1. See a model flowchart in Figure 5.3. Building components need to be inventoried as a composite of (e.g.,) parts and materials. Materials with different use cycles within their lifecycle and different lifespans should be distinguished; all VRPs and use cycles are inventoried. Processes occurring 'inside' the assessed building component are included in the 'foreground system'; processes occurring 'outside' are part of the 'extended foreground system'. Note that in the CE-LCIA (Section 5.4.3), impacts are allocated at the material level. So, processes taking place on part or building component levels (i.e., lifecycle stages CE-A.3.2 to CE-C.3.6) should be divided (e.g., based on mass) over and modelled on the associated material level. For example, a kitchen front (consisting of a coated board) is reused. Then a fraction of the processes of the reuse cycle is included in the lifecycle of the board material and the remaining fraction in the lifecycle of the coating material.

5.4.3 Circular Economy Life Cycle Impact Assessment

In phase 3, 'the CE-LCIA', the environmental impacts are calculated from the CE-LCI.

5.4.3.1 Allocation approach for CE-LCIA

When calculating the impacts, dividing burdens between cycles is a leading consideration. As discussed in Section 5.3.3, there are many different allocation approaches and the approach applied in EN 15978 (2011) and EN 15804 (2012) is less suitable for CE-LCA as all cycles should be included.

Alternative approaches can be found in previous works on 'multi-cycle LCA' (mLCA) and research on allocation. In the mLCA method by CE Delft, IVAM and Rebel (2016), multiple subsequent cycles are included through the avoidance of future primary production in the form of an 'up-front credit'. Already introduced in the introduction, the LD (Allacker et al., 2017) or CE LD (Malabi Eberhardt et al., 2020) approach allocates impacts between cycles: the largest share of initial production and disposal impacts is allocated to the cycle where they occur, namely the first and last, respectively. The share of impacts allocated to following or previous cycles reduces linearly. The impacts of VRPs are divided evenly between cycles.

Different approaches could have merit in different instances. For short-cycling parts and materials when reuse and recycling avoids primary production of the same 'thing', applying the same processes, an equal distribution of impacts between all cycles could be reasonable (and simple). A condition is that quality or value should be retained throughout cycles. For example, for kitchens in which cabinets are reused twice, we could assume that for every cabinet only one-third of material is virgin. On the other hand, CE LD allocation is preferable when the building component, part or material is cascaded into something else (i.e., the value between cycles is not the same). In such instances, equal distribution between all cycles is undesirable and it becomes necessary to distinguish which cycle a building component, part or material is in. Furthermore, CE LD is more suitable for long-cycling parts and materials, when it becomes less certain if, and what, impacts are avoided in the future.

In the CE-LCIA, the fraction of impact of the building component system allocated to the assessed building component is captured with parameter 'allocation fraction' (Af). In appendix B.1, we explain how to determine Af using an equal distribution or CE LD approach.

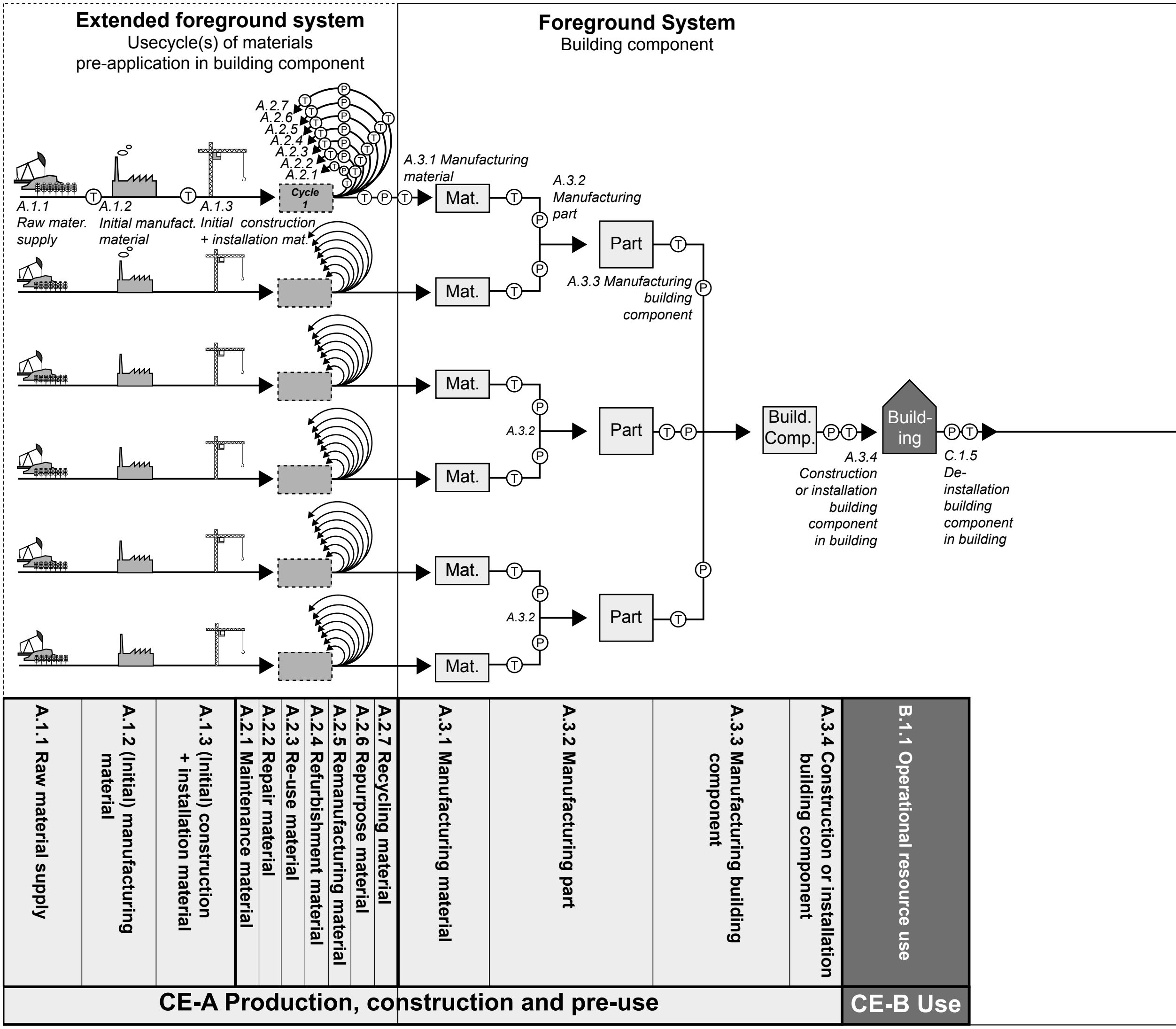
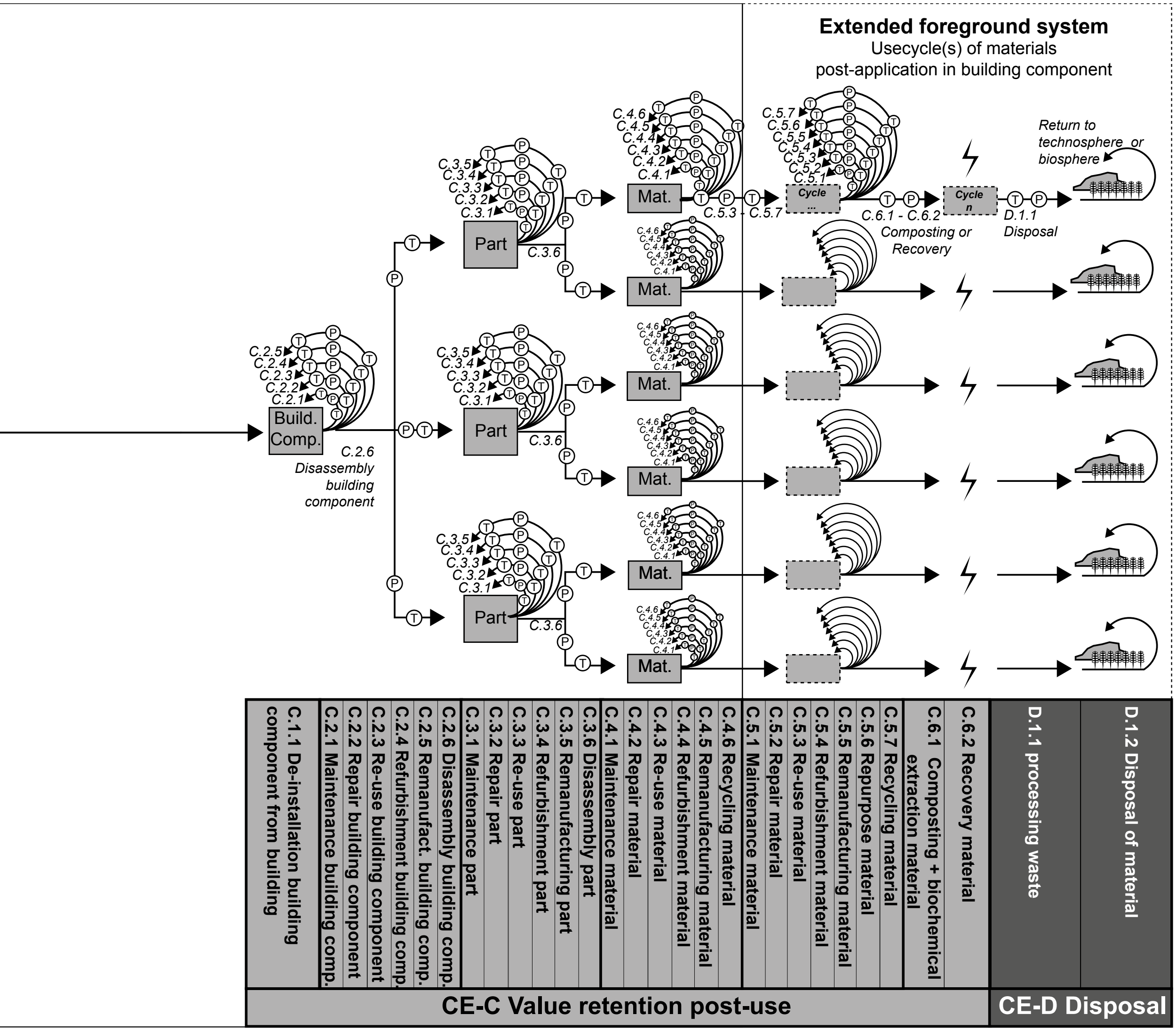


FIG. 5.3 CE-LCI Model


Extended foreground system
Usecycle(s) of materials
post-application in building component
Return to technosphere or biosphere
Build. Comp.
C.2.6 Disassembly building component
Part
C.3.6
Mat.
C.5.3 - C.5.7
Cycle ...
C.6.1 - C.6.2
Composting or Recovery
Cycle n
D.1.1 Disposal
C.1.1 De-installation building component from building
C.2.1 Maintenance building comp.
C.2.2 Repair building component
C.2.3 Re-use building component
C.2.4 Refurbishment building comp.
C.2.5 Remanufact. building comp.
C.2.6 Disassembly building comp.
C.3.1 Maintenance part
C.3.2 Repair part
C.3.3 Re-use part
C.3.4 Refurbishment part
C.3.5 Remanufacturing part
C.3.6 Disassembly part
C.4.1 Maintenance material
C.4.2 Repair material
C.4.3 Re-use material
C.4.4 Refurbishment material
C.4.5 Remanufacturing material
C.4.6 Recycling material
C.5.1 Maintenance material
C.5.2 Repair material
C.5.3 Re-use material
C.5.4 Refurbishment material
C.5.5 Remanufacturing material
C.5.6 Repurpose material
C.5.7 Recycling material
C.6.1 Composting + biochemical extraction material
C.6.2 Recovery material
D.1.1 processing waste
D.1.2 Disposal of material
CE-C Value retention post-use
CE-D Disposal

5.4.3.2 Impact calculation

The impact calculation follows the hierarchy of the CE-LCI model: in a series of sums, the impacts on each building component system level are added to determine the impact of the assessed building component.

The total impact of a building component is calculated using equation 5.1:

$$\mathrm{I}_{building\ \ component,x} = \sum_{k=1}^{n_1} I_{part,\ k}$$
$$= I_{part,1} + I_{part,2} + I_{part,3} + \ldots + I_{part,n_1-2} + I_{part,n_1-1} + I_{part,n_1} \tag{5.1}$$

which is the sum of the impacts of all its parts, where n_1 is the number of parts in this building component. Likewise, the impact of a part is the sum of the impacts of all the materials, where n_2 is the number of materials with different use cycles and a different lifespan. The impact of a part can be calculated using equation 5.2:

$$\mathrm{I}_{part,y} = \sum_{l=1}^{n_2} I_{material,\ l}$$
$$= I_{material,1} + I_{material,2} + I_{material,3} + \ldots + I_{material,n_2-2} + I_{material,n_2-1} + I_{material,n_2} \tag{5.2}$$

To calculate the impact of a material $(I_{material,z})$ for all the life cycle stages within that materials life cycle, allocated to the assessed building component during the RSP, we use equation 5.3:

$$I_{material,z} = \sum_{m=1}^{n_3} P_{life\ \ cycle\ \ stage,m} \cdot Af_{life\ \ cycle\ \ stage,\ m} \cdot AI_{life\ \ cycle\ \ stage,m} \cdot R_{\ life\ \ cycle\ \ stage,m} \tag{5.3}$$

where n_3 is the number of *different* life cycle stages (as defined in 5.4.1.3) for this material. *P* represents the probability of a life cycle stage to occur. Integrating a chance could be relevant for VRPs when assessing an *average* building component in a circular system. For example, in an EPD of a mass-produced circular façade, repair of parts might only occur for x% of the building components. The allocation fraction

(Af) is the fraction of impact of a life cycle stage which is allocated to the material in the use cycle of the assessed building component. AI represents the *absolute* environmental impacts (i.e., before allocation) from completing a life cycle stage once. For example, to determine how much impact of a future remanufacturing cycle is allocated to the assessed building component, we need to know the *absolute* impact of the remanufacturing cycle. This is a sum of *absolute* impacts of the material, transport, process and energy in this life cycle stage as described in equation 5.4:

$$AI_{lifecycle\ stage} = AI_{materials} + AI_{transport} + AI_{process} + AI_{energy} \tag{5.4}$$

In equation 5.3, R is the rate – the number of times – in which a life cycle stage occurs in the RSP and following chain of cycles of the material. To find R for a life cycle stage of a material, relevant R values on each building component level need to be multiplied as shown in equation 5.5:

$$R_{life\ cycle\ stage} = R_{building\ component} \cdot R_{part} \cdot R_{material} \tag{5.5}$$

For example, to determine the remanufacturing-rate for the coating material of a kitchen, the replacement rates of the building component needs to be multiplied with the remanufacturing rate of the to-be-recoated parts. The rate of life cycle stages on different building levels can be determined using different equations. How often the assessed building component is replaced $(R_{building\ component})$ can be calculated by dividing the *RSP* by the leading lifespan $(L_{leading})$ of the building component using equation 5.6:

$$R_{building\ component,\ x} = \frac{RSP}{L_{leading,\ building\ component,x}} \tag{5.6}$$

Reuse takes place when the functional lifespan of a component, part or material is reached prior to its technical lifespan; the R for reuse can be calculated by dividing these. Note that 'one instance' might need to be subtracted, as VRPs often do not take place at installation, end of use or EoL. For example, the R for reuse of a part can be determined using equation 5.7:

TOC

$$R_{reuse,\ part} = \left(\frac{L_{technical,\ part}}{L_{functional,\ part}} - 1 \right) \quad (5.7)$$

Repair, refurbishing and remanufacturing take place when the $L_{leading}$ of the higher system level is longer than that of the lower system level. For example, the R of repair of a part could be calculated as shown in equation 5.8:

$$R_{repair,\ part} = \left(\frac{L_{leading,building\ \ component}}{L_{leading,\ part}} - 1 \right) \quad (5.8)$$

The $L_{leading}$ is determined differently for each VRP: for repair, the $L_{leading}$ is equal to the technical lifespan whilst for refurbishment, the functional lifespan might be leading.

5.4.4 Interpretation of results

In phase 4 of an LCA, we interpret the results from the CE-LCIA. A sensitivity analysis is needed to test the robustness of results and influence of assumptions, methods and data (Junnila & Horvath, 2003). Sensitivity analysis is not always included in building (component) LCAs. Common are sensitivity analysis of variations in grid mix, influence of material selection and lifespans. As CE-LCA includes all cycles on all building component system levels, additional analysis is needed. CE-LCA could be complemented with an LCA following EN 15804 (2012) and EN 15978 (2011) standards and/or the sensitivity of assumptions on the cycles could be tested.

5.4.4.1 Sensitivity of number of cycles for each material applied in the building component

The number of use cycles (N_{cycles}) for all materials applied in the building component is difficult to predict. N_{cycles} influences how much impact is allocated to the assessed building component (through parameter Af). If assumptions are optimistic, impacts might be spread over too many cycles and vice versa. So, the effects of adding or subtracting cycles should be tested. A distinction can be made between (1) known cycles, (2) likely past or future cycles, and (3) uncertain past or future cycles. The uncertainty is larger for cycles far into the future, for future cycles which are yet to be organised, when the partners who manufacture the building component are not involved in past or future cycles, or when materials are not traced through cycles (e.g., material passport). The analysis should focus on testing the most uncertain cycles.

5.4.4.2 Sensitivity of the cycle number in which the material is in when applied in the building component

If Af is determined using the CE LD approach (Malabi Eberhardt et al., 2020), the influence of varying the cycle number (C_{number}) should be tested. The C_{number} influences how much impact is allocated to the assessed building component (represented by parameter Af). For example, the impact allocated to cotton insulation is higher if the cotton had only one previous use cycle (e.g., fast fashion) than if it had three (e.g., as new clothing, second-hand clothing and cleaning cloths). Most relevant is to test materials with uncertain past cycles.

5.4.4.3 Sensitivity of impact of the cycle

The absolute impact of a life cycle stage is determined by the absolute impact of materials $(AI_{materials})$, transport $(AI_{transport})$, energy (AI_{energy}), and processes $(AI_{processes})$ of that life cycle stage. A cycle with a very low absolute impact is a local, direct, reuse cycle whilst (e.g.) remelting material at great distance has a much higher absolute impact. Correctly assuming the absolute impacts of each cycle – some far in the future – is trying. Additional sensitivity analysis could include varying amounts and types of processes, materials, energy and transport per cycle.

5.4.4.4 Sensitivity of varying lifespans

How often life cycle stages take place is expressed in R, which is influenced by the $L_{leading}$ of the material, part, and building component. The effects of varying the technical, functional or economic lifespan, or a combination should be tested. Consider a kitchen door which is reused. If only the technical lifespan varies, the number of reuse cycles increases or reduces – resulting in a similar analysis as varying N_{cycles}. If only the functional lifespan is altered, more or fewer replacements of the door take place and the number of reuse cycles might increase or decrease proportionally. If both lifespans are increased or decreased in parallel, more or fewer (re)placements of the doors take place – whilst maintaining the same number of reuse cycles.

5.4.4.5 Sensitivity of probability of a cycle

P represents the probability that life cycle stages take place. A sensitivity analysis could determine the effect of varying the probability of (in particular) uncertain cycles.

5.5 Testing the CE-LCA model: the case of the circular kitchen

To test (and illustrate) the CE-LCA model, we compared the environmental impacts of two design variants of a Circular Kitchen (CIK) – to a business-as-usual (BAU) kitchen. First, we describe the kitchen variants (5.5.1). Following, we elaborate on the test following the CE-LCA phases: goal and scope definition (5.5.2), CE-LCI (5.5.3), CE-LCIA (5.5.4), and interpretation of the results (5.5.5).

5.5.1 Description of the Circular Kitchen design variants

We developed variants of the CIK in co-creation with Dutch industry partners and social housing associations. The housing associations are a logical primary target group owning 30% of the nation's housing stock; they have a substantial interest in implementing CE principles. Their kitchens are basic, have a similar layout and, usually, no appliances are provided. Therefore, the design variants focussed on redesign of the cabinetry. For each variant, the same countertops options were possible; therefore it was left outside of the scope of this assessment.

Figure 5.4 visualises the technical models of the kitchen variants. The BAU kitchen represents the current practice. It is made of melamine-coated chipboard. Static joints are glued and movable joints are made with metal hinges and drawer slides. The kitchen is replaced every 20 years. The manufacturer sells the BAU kitchen to housing associations. Due to the low cost-price, BAU kitchens are rarely repaired, refurbished, or reused. At EoL, the kitchen is demolished and separated into waste flows. The chipboard is incinerated for energy recovery.

The 'Reclaim! kitchen' is based on substituting virgin materials with non-virgin alternatives. In this design variant, we assumed a similar technical, industrial and business model as the BAU kitchen. We assume the materials are directly reused (i.e., in a secondary use cycle) and have a reduced lifespan of 10 years.

The Plug-and-Play (P&P) kitchen slows and closes loops by combining circular design strategies. It is a modular design, in which parts are separated based on their functional and technical lifespan. The cabinets consist of a construction (frame) with a long lifespan of 80 years. Infill parts, (e.g., drawers and shelves) have a medium lifespan between 20 and 40 years. The finishing parts (e.g., fronts) have shorter use cycles of 20 years. Parts are joint with de- and remountable connections, which facilitate future adjustments and reuse. The kitchen is made from plywood, to allow for a longer technical lifespan and multiple use cycles of parts. The kitchen manufacturer sells the kitchen to housing associations with a take-back guarantee and maintenance subscription. Extra kitchen modules and finishing-updates are offered to tenants through lease and sale-with-deposit contracts. At end of use, returned parts are sorted locally, to be reused or sent back to the kitchen manufacturer where they are sorted to be remanufactured, recycled or recovered.

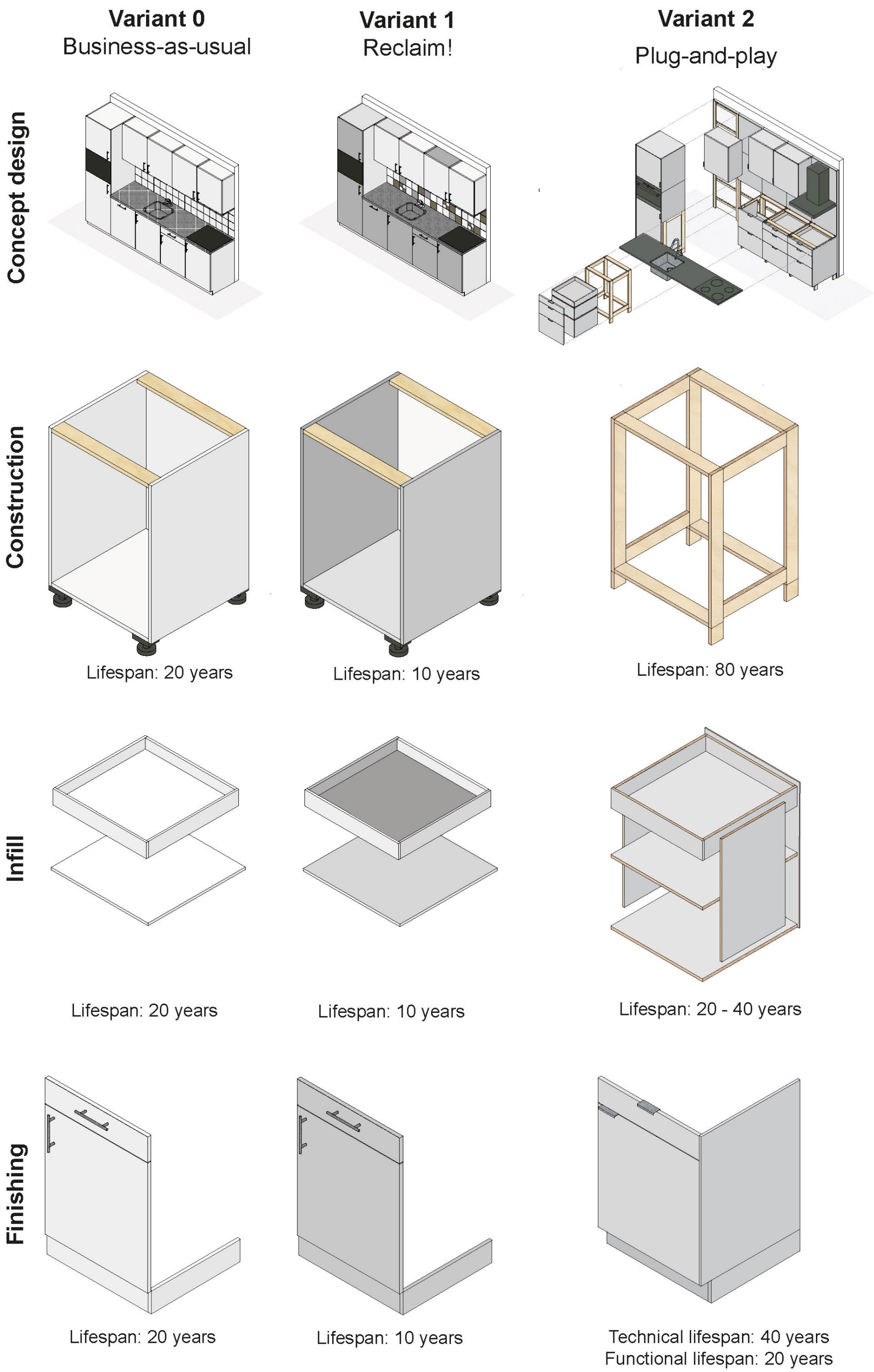


FIG. 5.4 Technical model of the design variants showing materialisation and lifespan

TOC

5.5.2 Test of CE-LCA model: Goal and scope definition

We compared the environmental impacts of different CIK variants, and a BAU variant. The functional unit was '*the use of a specific configuration of a lower kitchen cabinet in a circular system over a period of 80 years'*. The system boundary included life cycle stages CE-A to CE-D (as defined in 5.4.1.3). Yet, none of the variants had processes in stage CE-B and CE-D. In the foreground system, we excluded capital goods.

5.5.3 Test of CE-LCA model: CE-LCI

The CIK design variants were developed to the level of concept or prototype. As these remain 'theoretical' designs for which suppliers and VRP-partners were unknown, estimations were made on transport distances, production, VRPs and disposal processes. We also estimated the number of use cycles, and functional and technical lifespans. The assumptions were based on the expectations on how various circular design strategies could perform (compared to the BAU variant). For example, if directly reused materials were applied in the Reclaim! variant, we expect a lower technical lifespan than in the BAU kitchen. Additionally, the assumptions were based on experience of the housing associations and industry partners involved in the development. Furthermore, assumptions were aligned between variants (e.g., similar distance between manufacturer and user, similar recycling scenarios). For materials recycled in infinite 'open loops', we set N_{cycles} at 10.

The CE-LCI of each design variant has been summarised in a flowchart (see Figures 5.5-7). See Appendix B.2, for the detailed CE-LCI.

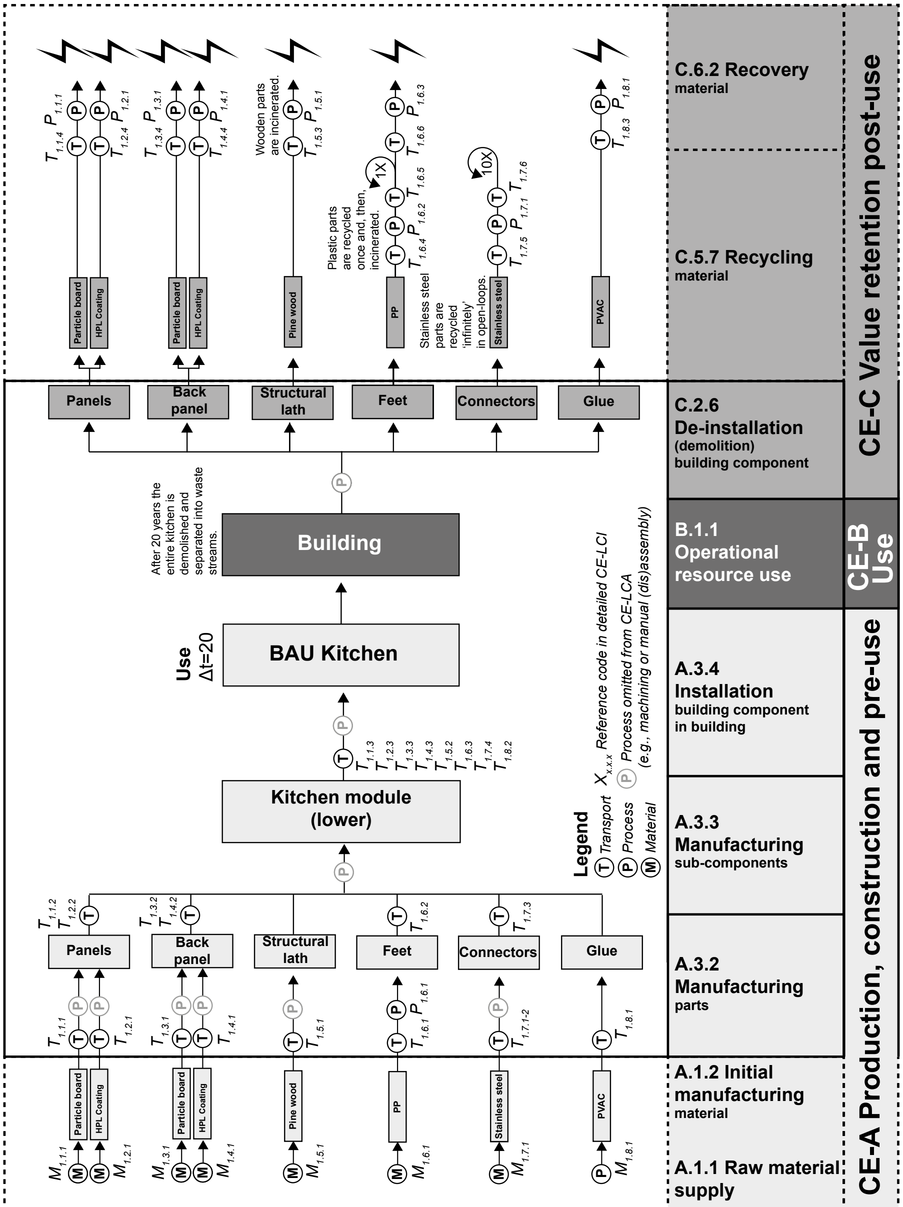


FIG. 5.5 Simplified CE-LCI flowchart of the BAU kitchen

TOC

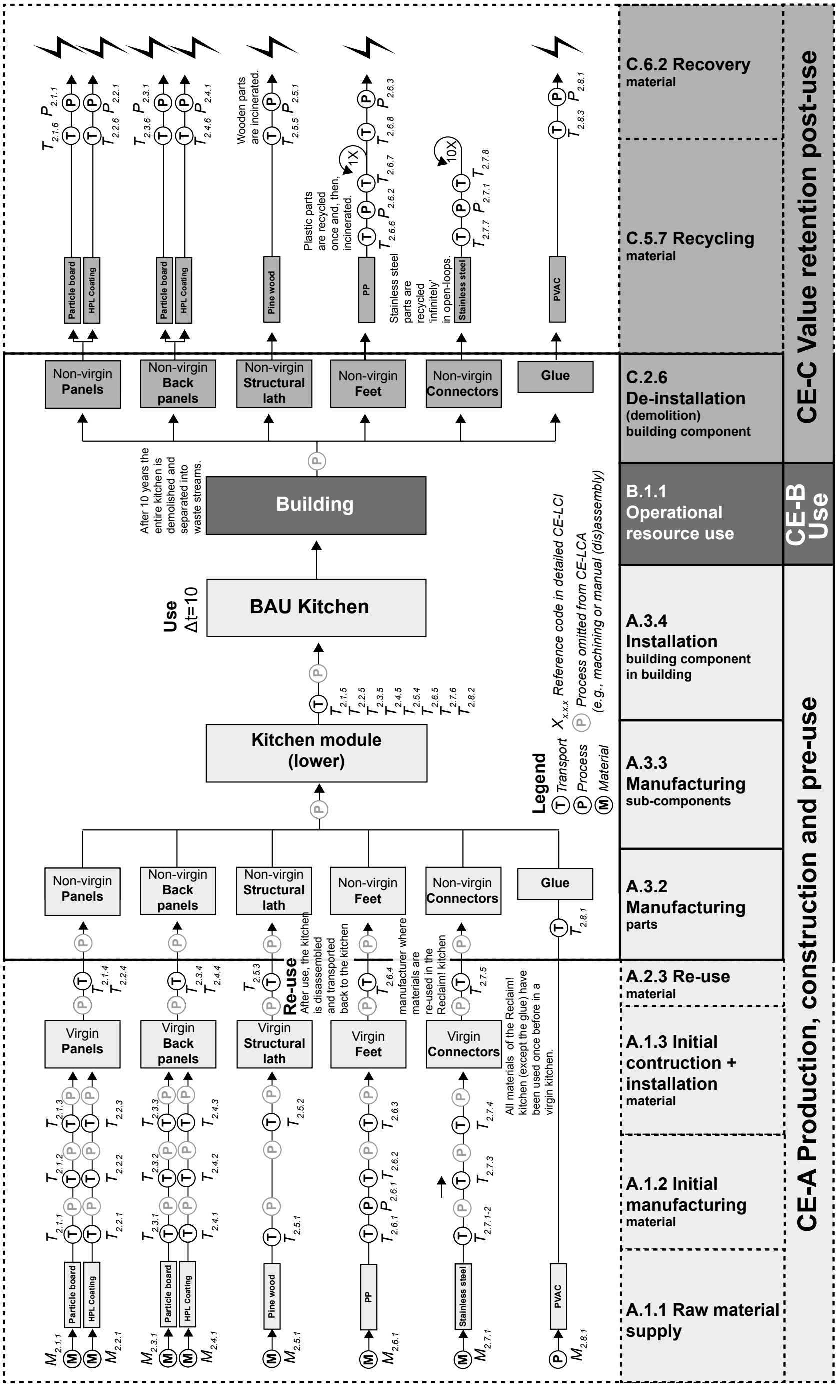


FIG. 5.6 Simplified CE-LCI flowchart of the Reclaim! kitchen

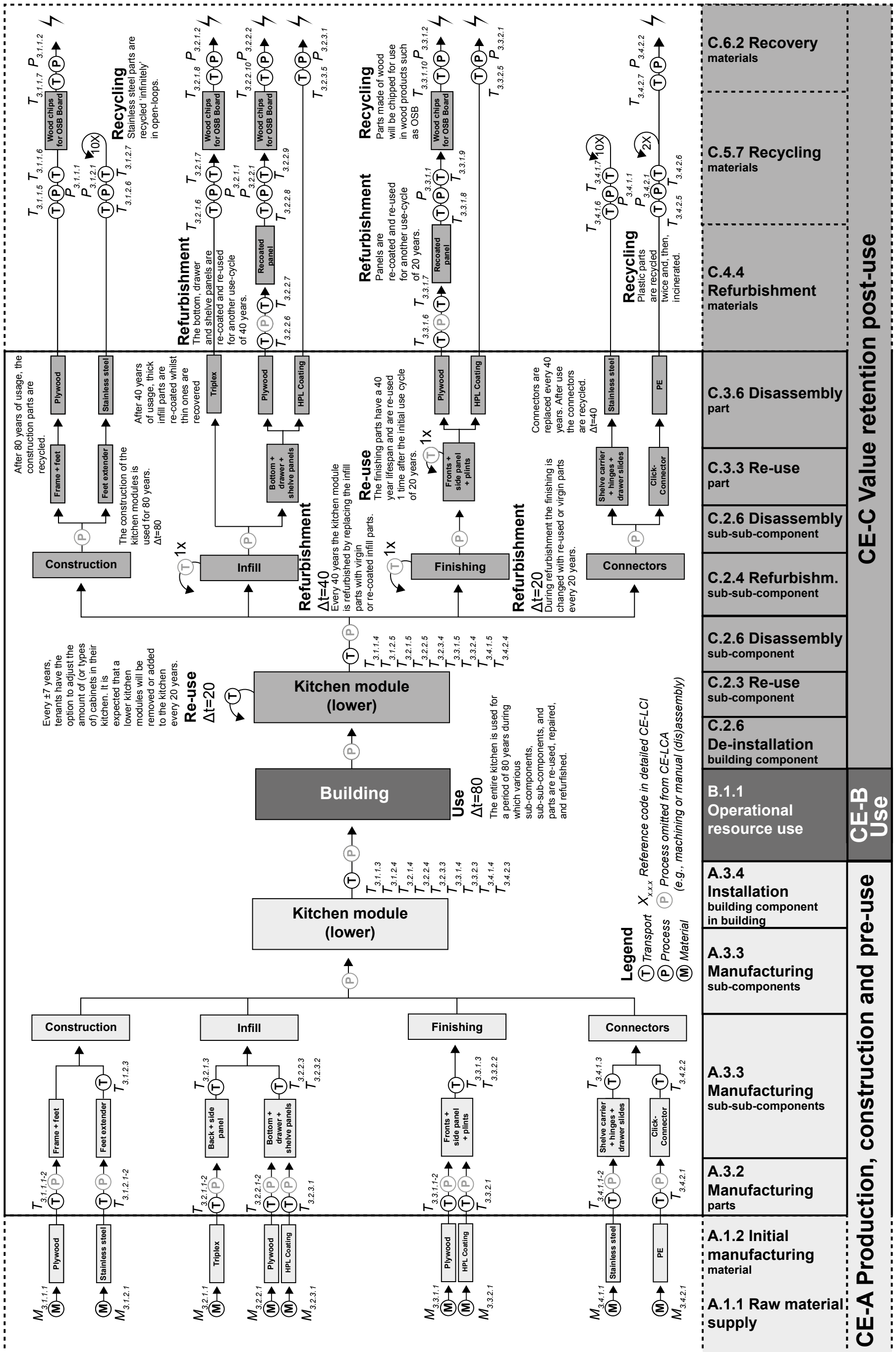


FIG. 5.7 Simplified CE-LCI flowchart of the P&P kitchen

TOC

5.5.4 Test of CE-LCA model: CE-LCIA

The CE-LCIs were modelled in openLCA version 1.9 software; the background system was modelled 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 Centre for Environmental Studies (CML)-IA baseline (Guinée et al., 2001). CML includes 11 environmental, resource-depletion and toxicology midpoint impact categories and is commonly used by the building sector. We excluded biogenic carbon (e.g., in wood) from the impact assessment. As we consider all cycles, it is assumed that carbon uptake equals carbon emission over the lifecycle of the material; we question the fairness to give first cycles a benefit from carbon uptake occurring prior to initial use cycles. Therefore, we applied the '0-0 rule' to biogenic carbon. The CE-LCIA parameters were determined for each material (see Appendix B.3). The value differs between cycles, so we applied the CE LD approach to determine Af . As the object of assessment was a specific configuration of a lower kitchen cabinet, P is set at 1: each inventoried VRP is assumed to occur.

The results of the CE-LCIA are summarised in Table 5.1. The Reclaim! kitchen has a lower environmental impact than the BAU on 6 of the 11 impact categories. P&P realises a significant impact reduction in all indicators in comparison to the BAU case. We refer to Appendix B.4 for further analysis on the impact distribution between 'production and construction pre-use' and 'value retention post-use', allocation of impacts to the kitchen over the RSP, and the distribution of impacts between use cycles of materials applied in the kitchen over time.

TABLE 5.1 CE-LCIA results for the BAU and CIK variants over 80 years

Impact category	Unit	BAU		Reclaim!	P&P	
		Baseline	Baseline	Savings to BAU [%]	Baseline	Savings to BAU [%]
Global warming potential	kg CO2 eq	1,48E+02	1,50E+02	-1%	6,40E+01	57%
Ozone layer depletion potential	kg CFC-11 eq	1,32E-05	1,12E-05	15%	6,92E-06	48%
Photochemical oxidation potential	kg C2H4 eq	5,10E-02	4,71E-02	7%	2,54E-02	50%
Acidification potential	kg SO2 eq	5,99E-01	5,34E-01	11%	2,99E-01	50%
Eutrophication potential	kg PO4--- eq	2,22E-01	1,98E-01	11%	1,05E-01	53%
Abiotic depletion potential for elements	kg Sb eq	1,55E-03	1,24E-03	20%	9,77E-04	37%
Abiotic depletion potential for fossil fuels	MJ	1,81E+03	1,56E+03	14%	7,88E+02	56%
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	8,30E+01	9,37E+01	-13%	3,73E+01	55%
Human toxicity potential	kg 1,4-DB eq	1,82E+02	2,37E+02	-30%	9,11E+01	50%
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	1,70E+05	1,71E+05	-1%	7,62E+04	55%
Terrestrial ecotoxicity potential	kg 1,4-DB eq	4,93E-01	4,94E-01	0%	2,81E-01	43%

Note: The colour shows a gradient between the highest (blue) and lowest (light blue) value per impact category.

5.5.5 Test of CE-LCA model: Interpretations of the results

For the purpose of testing and illustrating the CE-LCA model, we extensively tested the sensitivity of assumptions on cycles. Comparing CE-LCA (using CE LD allocation) to an LCA following the EN 15978 (2011) and EN 15804 (2012) standards was not part of the scope of this study. We refer to Malabi Eberhardt et al. (2020) for such a comparison.

Testing the effects of the following ‘what if’ questions was considered most relevant for the kitchens: what if the kitchens are reused (more); what if the future cycles of the P&P kitchen are not realised; what if the kitchens are used longer or shorter; what if the finishing of the P&P kitchen is exchanged more or less often? Following these questions, we analyzed the sensitivity of varying N_{cycles} and lifespans of (parts of) the kitchen variants. A detailed description of all sensitivity scenarios is included in Appendix B.5.

We analysed the sensitivity of the N_{cycles} by adding one cycle (‘C+1’), two cycles (‘C+2’) and subtracting (up to) three cycles (‘C-1’, ‘C-2’, ‘C-3’) from the baseline scenario. When cycles were added, we assumed local, direct reuse for the entire kitchen cabinet; when cycles were subtracted, we removed the 'outer' cycles (i.e., recycling) first, followed by remanufacturing and reuse, respectively. Only the industry standard incineration for energy recovery and open-loop recycling were retained. For the P&P kitchen, scenario 'C-3' can be considered a linear scenario.

We tested the sensitivity varying $L_{functional}$ and $L_{technical}$ of (parts of) the kitchen variants. In the BAU and Reclaim! kitchen, all parts have the same lifespan and the $L_{functional}$ and $L_{technical}$ are equal. Any changes to either result in the replacement of the entire kitchen. On the other hand, P&P kitchen parts have different lifespans and $L_{technical}$ of finishing parts is longer than $L_{functional}$. So, we varied both $L_{functional}$ of finishing parts and $L_{functional}$ and $L_{technical}$ of all parts in parallel. To make the scenarios comparable, lifespans were varied between ±7 and 80 years. Note that such a long lifespan is unlikely for the BAU and Reclaim! kitchens as their materials have shorter lifespans, and these kitchens are not adaptable.

5.5.5.1 Results of the sensitivity analysis

The results of the sensitivity analysis are included in Appendix B.6. Tables 5.2-5 summarize the percentual savings of each scenario compared to the baseline scenario of the same design variant.

TABLE 5.2 Percentual reduction per scenario compared to the baseline scenario of the BAU kitchen variant

Impact category	BAU					
	Baseline	C+1	C+2	L7	L40	L80
Global warming potential	0%	30%	44%	-200%	50%	75%
Ozone layer depletion potential	0%	32%	47%	-200%	50%	75%
Photochemical oxidation potential	0%	29%	42%	-200%	50%	75%
Acidification potential	0%	30%	45%	-200%	50%	75%
Eutrophication potential	0%	30%	45%	-200%	50%	75%
Abiotic depletion potential for elements	0%	31%	46%	-200%	50%	75%
Abiotic depletion potential for fossil fuels	0%	31%	46%	-200%	50%	75%
Fresh water aquatic ecotoxicity potential	0%	27%	40%	-200%	50%	75%
Human toxicity potential	0%	21%	31%	-200%	50%	75%
Marine aquatic ecotoxicity potential	0%	29%	43%	-200%	50%	75%
Terrestrial ecotoxicity potential	0%	27%	40%	-200%	50%	75%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) for all scenarios per design variant, per impact category.

TABLE 5.3 Percentual reduction per scenario compared to the baseline scenario of the Reclaim! kitchen variant

Impact category	Reclaim!						
	Baseline	C+1	C+2	L7	L20	L40	L80
Global warming potential	0%	7%	19%	-50%	50%	75%	88%
Ozone layer depletion potential	0%	1%	11%	-50%	50%	75%	88%
Photochemical oxidation potential	0%	1%	12%	-50%	50%	75%	88%
Acidification potential	0%	3%	13%	-50%	50%	75%	88%
Eutrophication potential	0%	3%	14%	-50%	50%	75%	88%
Abiotic depletion potential for elements	0%	2%	10%	-50%	50%	75%	88%
Abiotic depletion potential for fossil fuels	0%	3%	13%	-50%	50%	75%	88%
Fresh water aquatic ecotoxicity potential	0%	10%	20%	-50%	50%	75%	88%
Human toxicity potential	0%	6%	14%	-50%	50%	75%	88%
Marine aquatic ecotoxicity potential	0%	7%	18%	-50%	50%	75%	88%
Terrestrial ecotoxicity potential	0%	4%	12%	-50%	50%	75%	88%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) for all scenarios per design variant, per impact category.

TABLE 5.4 Percentual reduction per scenario compared to the baseline scenario of the P&P ktichen variant

Impact category	P&P					
	Baseline	C-3	C-2	C-1	C+1	C+2
Global warming potential	0%	-49%	-12%	3%	18%	30%
Ozone layer depletion potential	0%	-71%	-24%	-4%	18%	31%
Photochemical oxidation potential	0%	-65%	-23%	-3%	17%	28%
Acidification potential	0%	-62%	-19%	-1%	18%	29%
Eutrophication potential	0%	-55%	-16%	2%	17%	29%
Abiotic depletion potential for elements	0%	61%	69%	73%	16%	27%
Abiotic depletion potential for fossil fuels	0%	-61%	-18%	-1%	18%	30%
Fresh water aquatic ecotoxicity potential	0%	-3%	16%	23%	17%	27%
Human toxicity potential	0%	-7%	5%	10%	14%	22%
Marine aquatic ecotoxicity potential	0%	-12%	13%	24%	17%	28%
Terrestrial ecotoxicity potential	0%	-26%	3%	16%	16%	27%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) for all scenarios per design variant, per impact category.

TABLE 5.5 Percentual reduction per scenario compared to the baseline scenario of the P&P ktichen variant

Impact category	P&P					
	Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3,5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Global warming potential	-23%	22%	-527%	-109%	-99%	47%
Ozone layer depletion potential	-25%	25%	-527%	-109%	-99%	46%
Photochemical oxidation potential	-21%	21%	-532%	-111%	-100%	46%
Acidification potential	-23%	22%	-531%	-110%	-100%	46%
Eutrophication potential	-23%	22%	-533%	-111%	-100%	46%
Abiotic depletion potential for elements	-37%	23%	-556%	-119%	-100%	45%
Abiotic depletion potential for fossil fuels	-23%	23%	-528%	-109%	-99%	46%
Fresh water aquatic ecotoxicity potential	-22%	18%	-540%	-113%	-100%	46%
Human toxicity potential	-12%	10%	-545%	-115%	-100%	46%
Marine aquatic ecotoxicity potential	-24%	20%	-538%	-113%	-100%	46%
Terrestrial ecotoxicity potential	-23%	19%	-540%	-113%	-100%	46%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) for all scenarios per design variant, per impact category.

For the BAU, adding two cycles (C+2) reduced impacts between 31% and 47% compared to its baseline scenario; for the Reclaim! kitchen, the reduction is only between 10% and 20%. The deviation is less as the difference between Af is larger when adding a reuse cycle to virgin material then to material in a second use cycle. From the P&P variant we found that additional cycles do not necessarily lead to less allocated impact: removing the outer recycling processes in scenario C-1 resulted in impact savings between -4% and 73% compared to the baseline scenario. So, adding cycles with relatively high impact processes does not reduce impacts. The most beneficial cycles are the direct, local reuse cycles of scenarios C+1 and C+2 which lead to significant savings in all variants on all impact categories.

We found that varying $L_{functional}$ and $L_{technical}$ in parallel results in significant deviations from the baseline scenarios: a proportional relationship is visible. For the P&P, we found that only varying $L_{functional}$ is less impactful: although more finishing parts need to be placed (i.e., R increases), they are also reused more often. Therefore, the Af of finishing parts decreases and less impact is allocated to the kitchen. If all variants are compared on a 20-year $L_{technical}$ (see Appendix B.6, Tables APP. B.22-25), the Reclaim! variant decreases environmental impacts between 35%-60% compared to the BAU. The P&P results in a -38% to 10% reduction compared to the BAU. This has two reasons: finishing parts are still replaced every 10 years; the circular design principle of the P&P design – facilitating partial replacements to keep the whole of the kitchen in use longer – is nullified in this scenario.

5.5.5.2 Conclusions from the CE-LCA

From the CE-LCIA and sensitivity analyses, we conclude the following: First, applying non-virgin material, can reduce the environmental impact. However, if the lifespan of the kitchen is reduced – resulting in a higher replacement rate – reductions in impact can be nullified. Additionally, the impacts of initial production and construction of non-virgin materials remain visible, so using non-virgin is less attractive if these materials had a high(er) initial production and construction impact. Second, facilitating multiple cycles results in a lower (allocated) environmental impact, particularly for direct, local reuse cycles. High-impact recycling cycles are less attractive. Third, we found that the P&P kitchen resulted in the least environmental impacts through longer use of parts, introducing more use-cycles of components, parts and materials and facilitating partial replacement of parts. Yet further environmental impact reduction is possible by combining variants: a P&P kitchen in which non-virgin materials are applied, but only if these materials do not lower the technical lifespan of the kitchen.

TOC

5.6 Evaluation of the CE-LCA model

In 10 semi-structured expert sessions, we evaluated the CE-LCA model with 44 experts and practitioners from academia, industry and government in the field of LCA, circular design, and the circular built environment. The CE-LCA model was presented and the following questions were asked: what are your initial impressions on the CE-LCA model; what are the potential (dis)advantages; how would you improve the model? The answers and discussion following these questions were documented in minutes and analysed using an emergent coding technique (Dahlsrud, 2008; Kirchherr, Reike, & Hekkert, 2017).

Table 5.6 shows the resulting advantages, disadvantages and improvement points of the CE-LCA model.

TABLE 5.6 Evaluation of the CE-LCA model in 10 expert sessions

	Category	Remarks	Implementation of improvements
Advantages	**Applicability**	Suitable for ex-ante assessment (e.g., in policy-making, early-stage design)	
		Suitable to assess multiple cycles	
		Most suitable for (reproducible) building component or product level	
		Supports determining more ideal CE (e.g., ideal vision for back-casting)	
		Also suitable when materials cannot be reused or recycled at same value	
	Incentives CE	Method incentivises not only narrowing, but also slowing and (high-value) closing cycles	
	Levels	CE-LCA introduces 'missing' building component level in LCA	
	Fair accounting impacts	The linear degressive method divides burden fairly between cycles; no double crediting possible	
		All cycles are included; impacts from other cycles (e.g., production, disposal) remain visible in all cycles	
	Ease of use	The allocation formula is understandable and transparent (better than the PEF)	
	Instrument for discussion	Method stimulates (re)discussing problems and incentives in current LCA standards	
		Method shows how we could include CE in LCA	
		Method shows how complex CE in design and the built environment is	
Disadvantages	**Non-applicability**	Less suitable for ex-post assessments and certification	
		Less suitable for building scale (too complex, uncertain, no control by producing supply chain)	
	Uncertainty in assumptions	Difficult to determine and guarantee future cycles; leads to not-accurate results	
		Uncertainty in assumptions far in the future (cycles, processes, energy mix are unknown)	
		Sensitive to assumptions on functional, technical and economic lifespan	
	Greenwashing impacts	Burdens can be shifted towards [non-existent] cycles in the future, diluting impacts	
		Easy to mis-use by industry by adding future cycles	

>>>

TOC

TABLE 5.6 Evaluation of the CE-LCA model in 10 expert sessions

	Category	Remarks	Implementation of improvements
Disadvantages	**Challenging to implement**	Requires transition in building industry to determine all cycles (i.e., from one-off projects to a (closed loop) component-wise industry)	
		Difficult to implement a new LCA methods in practice, it is easier to adapt the current LCA standard	
		All cycles need to be documented and kept tracible over long-term (e.g., government regulation is needed)	
		Current LCA tools in practice cannot do a CE-LCA calculation	
	Difficulties in use	Method is complex	
		Method is time consuming	
	Urgency	Virgin production burdens should be in first cycles to reduce our impacts now	
Improvements	**Improvements ease of use**	Make the method understandable and simple to use, (e.g., include a manual, concrete examples, clarify terms, single indicator system)	Method has been described extensively in paper including description of terms and concrete examples
		Make method affordable and fast to use	Challenges relevant for all LCAs - not addressed in this paper
		Provide (more) background data; make data accessible to industry	Challenges relevant for all LCAs - not addressed in this paper
		Shift burden of proof for CE-LCA from building level to component level (i.e., component-EPD's)	The scope of CE-LCA has been shifted from buildings to building components
		Translate to a design synthesis tool (e.g., guidelines, flowchart) and practice assessment tool	Future research could focus on measuring different building component to develop design guidelines: Direction for future research included in discussion
	Improvement accuracy and certainty in allocation approach	Differentiate between different objects of assessment in CE-LCA	We distinguished 'average' and 'specific' building components in a circular system as objects of assessment
		Differentiate different cycles (i.e., known or unknown, high-value or low-value, open or closed)	Section 5.4.3.1 states different allocation approaches should be used for different types of cycles
		Prefer mLCA approach (i.e., equal distribution) for known cycles, mass production, direct reuse and recycling	Section 5.4.3.1 suggests different allocation approaches have merit in different instances: equal distribution approach should be preferred in instances mentioned on the left
		Include market situation and material quality factors in allocation approach	Direction for future research mentioned in Section 5.6
		Add probability factor for cycles to CE-LCA	Probability factor was included in equation 5.3
		Include (use) time in allocation approach	Use time was included in equation B.1b (equal distribution approach). Use time is not yet included in the CE-LD approach: direction for future research included in Section 5.7

>>>

TABLE 5.6 Evaluation of the CE-LCA model in 10 expert sessions

	Category	Remarks	Implementation of improvements
Improvements	**Improvement ease of implementation in practice**	Differentiate LCA levels (do not interlink them)	One of the requirements for CE-LCA is considering the link between levels of the building. However, the scope of CE-LCA has been limited to building components instead of buildings as a whole
		Develop rules, template or regulation for cycles (i.e., amount, division of impact, types of cycles, system boundary)	Direction for future research mentioned in Section 5.7
		Prefer an LCA 'tax' system: producer takes initial production and EOL impacts; cycles can be added over time	Proposed tax approach was considered unfavourable to incentivise design for multiple future cycles - comment was not further included in the CE-LCA model
		Test the method in a real-life case with stakeholders	Direction for future research mentioned in Section 5.7
	Improvement of certainty and prevention of misuse	Use CE-LCA as an additional informational module "circular potential" next to standard LCA	Suggestion is mentioned in Section 5.7
		Obligatory peer review of CE-LCA	Suggestion is mentioned in Section 5.6
		Include a sensitivity analysis on influence of varying future cycles	Use of and need for sensitivity analysis in CE-LCA is discussed in Sections 5.4.4 and 5.6
	Widen scope CE assessment	Assessment on other criteria should be part of CE assessment (i.e., value, costs, material flow, social factors)	Direction for future research mentioned in Sections 5.6 and 5.7

The experts and practitioners acknowledged the challenges in capturing the environmental burdens and benefits of the CE concept applying EN 15978 (2011) and EN 15804 (2012). They saw the ability to assess multiple cycles as a main advantage of the CE-LCA model. They found that CE-LCA incentivises narrowing, slowing and closing cycles, not only today but also in the future; CE-LCA moves LCA away from a linear "efficiency" focus to a more ideal circular mindset. CE-LCA was considered more suitable in ex-ante assessments in which 'theoretical', multi-cycling scenarios are explored to identify 'ideal' circular building components. For example, in the context of design or policy making.

The experts and practitioners suggested CE-LCA in ex-ante, ex-post and certification assessments in practice poses challenges that will require further development and rigorous testing. Determining all use cycles on all levels of a building component is complex: it extends beyond the control of building component manufacturers and the scope of building projects. Including multiple cycles – some far into the future – increases uncertainty. Burdens could be shifted to cycles which might not come to pass, making CE-LCA sensitive to misuse. Furthermore, including future cycles might undermine efforts to reduce impacts *today*. Therefore, several experts posed

TOC

the EN15804 and EN15978 approach remains preferable. If applied, the experts and practitioners suggested CE-LCA should be combined with extensive sensitivity analysis, include peer reviewing, and/or be done in parallel with a 'standard' LCA.

The majority of the improvement opportunities were concerned with reducing uncertainty, preventing misuse, and improving ease of use and implementation. To refine the accuracy of CE-LCA, the experts posed to differentiate between types of cycles, such as known or unknown cycles, certain or uncertain cycles, short-term or long-term cycles, open or closed cycles, and equal-value or downgrading cycles. Different types of cycles could benefit from different allocation approaches. Additionally, factors for material quality and the market situation could be included in the allocation approach. The experts and practitioners suggested to develop templates and regulations for cycles to reduce the complexity and ensure fair use. Finally, several experts stressed that circular assessment encompasses more than environmental impact assessment, and should include value, costs, material flows, and/or social performance criteria. If and how improvement points were implemented in the CE-LCA model is shown in column 4 of Table 5.6.

5.7 Discussion and conclusion

In this paper, we explored how multiple cycles could be included in the LCA of building components by developing and testing a Circular Economy Life Cycle Assessment (CE-LCA) model for building components. This model builds on existing LCA standards applied in the building sector (EN15804 and EN15978). In CE-LCA, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include Value Retention Processes on all building component system levels, both in- and outside of the assessed building component; the impacts of all cycles can be divided using an 'equal distribution' or CE LD allocation approach. The model has been tested in the case of the Circular Kitchen and evaluated with 44 experts.

Our findings corroborate Allacker et al. (2017): including multiple cycles within the scope of the assessed product results in the best 'physical realism' for multi-cycling products [or building components] within the circular system. Like Malabi Eberhardt et al. (2021), we found the CE-LCA approach suitable in ex-ante assessments in which 'theoretical' scenarios are explored to identify 'ideal' circular building components. However – as concluded by Allacker et al. (2017), De Wolf et al. (2020) and Malabi Eberhardt et al. (2021) – we found that all cycles of the building component system are difficult to determine in a practice setting; this increases uncertainty, makes the approach sensitive to mis-use and could hinder reducing environmental impacts both in the short and long term.

Yet, our recommendation differs from Allacker et al. (2017). They suggested to not include all cycles; we suggest that applying CE-LCA, or equivalent multi-cycling LCA, is necessary to transition to a 'truly' circular built environment. Without including all cycles within the assessment, we cannot get an accurate overview of the burdens and benefits of circularity. Yet, we urge the utmost care with CE-LCA in practice. We propose two pathways to manage the disadvantages of CE-LCA. First, the CE-LCA approach could be developed further to reduce uncertainty, improve accuracy, usability and fair-use: the CE LD allocation approach does not yet incorporate length of use cycles; regulations (or 'templates') on how to approach various types of cycles for different materials could be developed; CE-LCA should be tested with industry. Alternatively, LCA which does not include all cycles could be optimised to incentivise narrowing, slowing and closing (all) cycles now and in the future. Consider, for example, the 'Circular Footprint Formula' as part of the Product Environmental Footprint method (Zampori & Pant, 2019). Yet, blending approaches could also increase complexity and cloud the (dis)advantages of each approach. A second pathway is to exercise awareness of the value and limitations of CE-LCA and use the model appropriately. A CE-LCA should include extensive sensitivity analysis and/or could be done in parallel to standard LCA – functioning as a 'circular potential' informational module. To increase transparency within reporting, the distribution of impacts between cycles could be reported (in line with De Wolf et al., (2020)).

Future research could also focus on CE-LCA for the building level. Although, the testcase in this paper does not support building CE-LCA, theoretically, this model could be applied to buildings. Especially if the building is considered as a composite of building components. Undoubtedly, this increases the complexity of CE-LCA. Additionally, more knowledge is needed on which design variants for circular buildings and components perform best environmentally to support the transition to a 'truly' circular built environment. Finally, this research focused on environmental impact assessment in a CE. Yet, holistic CE assessment should include more criteria. Future research could focus on combining CE-LCA with Material Flow Analysis (MFA), (functional) value and economic performance assessment (e.g., through CE Life Cycle Costing (Wouterszoon Jansen et al., 2020)).

We conclude that the CE-LCA model can successfully support LCAs of circular building components – especially in theoretical setting; the step-by-step description of the model and example case can provide practical guidance for future assessments. However, we see the presented model not as a 'ready for practice' approach to LCA of circular building components, but rather as a tool for further research and discussion. As such it makes an important step to support the assessment of circularity in the built environment and, subsequently, to the transition to a CE in the built environment.

Acknowledgements

This research has been carried out in collaboration with researchers from Aalborg University, Denmark and Delft University of Technology. The research was part of the research projects "REHAB" (carried out by the Delft University of Technology) and "Circular Kitchen (CIK)" (carried out by Delft University of Technology and Chalmers University of Technology). As such, this research has received funding from the Delft University of Technology, Amsterdam Institute for Advanced Metropolitan Solutions, EIT Climate-KIC and the REHAB project partners.

References

Aagaard, N.-J., Brandt, E., Aggerholm, S., & Haugbølle, K. (2013). *Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi*. Copenhagen: Statens Byggeforskningsinstitut (SBi), Aalborg University.

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, *22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Barras, R., & Clark, P. (1996). Obsolescence and performance in the Central London office market. *Journal of Property Valuation and Investment*, *14*(4), 63–78. https://doi.org/10.1108/14635789610153470

Bjørn, A., Owsianiak, M., Laurent, A., Olsen, S. I., Corona, A., & Hauschild, M. Z. (2018). Scope definition. In M. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment - Theory and practice*. Switzerland: Springer International Publishing.

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Brand, S. (1994). *How Buildings Learn*. New York: Viking.

CE Delft, IVAM, & Rebel. (2016). *Hoogwaardige recycling: Gevat in een beleidsformule en een multicyclus-LCA-methodiek*. Delft: CE Delft.

Cooper, T. (1994). Beyond recycling: The longer life option. *The New Economics Foundation*, (November), 1–22. Retrieved from http://irep.ntu.ac.uk/id/eprint/24666/1/201125_7266 Cooper Publisher.pdf

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., & Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, *151*(September 2019), 104498. https://doi.org/10.1016/j.resconrec.2019.104498

Dahlsrud, A. (2008). How corporate social responsibility is defined: an analysis of 37 definitions. *Corporate Social Responsibility and Environmental Management*, *15*, 1–13. https://doi.org/https://doi.org/10.1002/csr.132

de Valk, E., & Quik, J. (2017). *Eenduidig bepalen van circulariteit in de bouwsector: Milieuprestatie als uitgangspunt*. Bilthoven: Rijksinstituut voor Volksgezondheid en Milieu (RIVM).

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Delem, L., & Wastiels, L. (2019). The practical use of module D in a building case study: Assumptions, limitations and methodological issues. *IOP Conference Series: Earth and Environmental Science*, *323*(012048), 1–8. https://doi.org/10.1088/1755-1315/323/1/012048

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

EN 15804. (2012). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019

EN 15978. (2011). *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. Retrieved from European Committee for Standardization (CEN) website: https://infostore.saiglobal.com/preview/is/en/2011/i.s.en15978-2011-lc-2011-11.pdf?sku=1500481

French, M. L., & LaForge, R. L. (2006). Closed-loop supply chains in process industries: An empirical study of producer re-use issues. *Journal of Operations Management*, *24*(3), 271–286. https://doi.org/10.1016/j.jom.2004.07.012

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Genovese, A., Acquaye, A. A., Figueroa, A., & Lenny Koh, S. C. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, 344–357. https://doi.org/10.1016/j.omega.2015.05.015

Geraedts, R. P., Vande Putte, H. J. M., Vercouteren, J., & Binnekamp, R. (2009). Tijd. In J. W. F. Wamelink, R. P. Geraedts, F. A. M. Hobma, L. H. M. J. Lousberg, & P. De Jong (Eds.), *Inleiding Bouwmanagement* (pp. 273–303). VSSD.

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., … Huijbregts, M. A. J. (2001). *Handbook on life cycle assessment: An operational guide to the ISO standards*. Dordrecht: Kluwer Academic Publishers.

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: The case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). Life cycle assessment: Theory and practice. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3

Hossain, M. U., & Ng, S. T. (2018). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production*, *205*, 763–780. https://doi.org/10.1016/j.jclepro.2018.09.120

Huysveld, S., Hubo, S., Ragaert, K., & Dewulf, J. (2019). Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. *Journal of Cleaner Production*, *211*, 1–13. https://doi.org/10.1016/j.jclepro.2018.11.110

ISO 14040. (2006). *Environmental management — Life cycle assessment — Principles and framework*. Retrieved from https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

ISO 14044. (2006). *Environmental management — Life cycle assessment — Requirements and guidelines*. Retrieved from https://www.iso.org/standard/38498.html

ISO 15686. (2011). *Buildings and constructed assets — Service life planning*. Geneve, Switzerland: International Organization for Standardization.

Junnila, S., & Horvath, A. (2003). Environmental sensitivity analysis of the life-cycle of an office building. *Proceeding of Integrated Lifetime Engineering of Buildings and Civil Infrastructures, ILCDES 2003*, 215–220. Kuopio, Finland.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Lützkendorf, T. (2019). Application of "element"-method in sustainability assessment. *IOP Conference Series: Earth and Environmental Science*, *290*, 012052. https://doi.org/doi:10.1088/1755-1315/290/1/012052

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Méquignon, M., & Ait Haddou, H. (2014). The construction industry and lifespan. In *Lifetime Environmental Impact of Buildings. SpringerBriefs in Applied Sciences and Technology* (pp. 3–23). https://doi.org/10.1007/978-3-319-06641-7_1

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, *24*(3), 45–77. https://doi.org/10.2753/MIS0742-1222240302

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075

Seo, S., & Hwang, Y. (2001). Estimation of CO2 emmisions in life cycle of residential buildings. *Journal of Construction Engineering and Management*, *127*(5), 414–418.

Slaughter, E. S. (2001). Design strategies to increase building flexibility. *Building Research and Information*, *29*(3), 208–217. https://doi.org/10.1080/09613210010027693

Stichting Bouwkwaliteit. (2019). *Bepalingsmethode milieuprestatie gebouwen en GWW-werken.* Retrieved from http://www.rijksoverheid.nl/documenten-en-publicaties

Suhariyanto, T. T., Wahab, D. A., & Rahman, M. N. A. (2017). Multi-life cycle assessment for sustainable products: A systematic review. *Journal of Cleaner Production*, *165*, 677–696. https://doi.org/10.1016/j.jclepro.2017.07.123

van der Harst, E., Potting, J., & Kroeze, C. (2016). Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. *Waste Management*, *48*, 565–583. https://doi.org/10.1016/j.wasman.2015.09.027

van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2020). Design guidelines for circular building components based on LCA and MFA: The case of the Circular Kitchen. *IOP Conf. Series: Earth and Environmental Science*, *588*, 1–8. https://doi.org/doi:10.1088/1755-1315/588/4/042045

van Stijn, A., & Gruis, V. (2020). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment*, *9*(4), 635–653. https://doi.org/10.1108/SASBE-05-2019-0063

Wastiels, L., Delem, L., & van Dessel, J. (2013). To module D of not to module D? The relevance and difficulties of considering the recycling potential in building LCA. *LCA Congrès AVNIR*. Retrieved from moz-extension://b989d8ab-889e-1047-958c-a518695fd087/enhanced-reader.html?openApp&pdf=http%3A%2F%2Favnir.org%2Fdocumentation%2Fpowerpoints_congres%2F7b_Wastiels-Delem_Module%2520D.pdf

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, *21*, 1218–1230. https://doi.org/https://doi.org/10.1007/s11367-016-1087-8

Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

Zampori, L., & Pant, R. (2019). Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN. In *Eur 29682 En*. https://doi.org/10.2760/424613

6 Environmental design guidelines for circular building components based on LCA and MFA

Lessons from the circular kitchen and renovation façade

Chapter published in its entirety in 2022 in Journal of Cleaner Production, 357(131375), 1–58. https://doi.org/10.1016/j.jclepro.2022.131375

A van Stijn[1,2], L C M Eberhardt[3], B Wouterszoon Jansen[1,2] and A Meijer[4]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.
[3] Department of The Built Environment (BUILD), Section for Sustainability of Buildings, Aalborg University, Copenhagen, Denmark.
[4] Department of Architectural Engineering and Technology, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.

ABSTRACT The transition towards a Circular Economy (CE) in the built environment is vital to reduce environmental impacts, resource consumption and waste generation. The built environment can be made circular by replacing building components with more circular ones. There are many circular design options for building components and knowledge about which options perform better – from an environmental perspective – is limited. Existing guidelines focussed on single components, single circular design options, applied different assessment methods and provide conflicting guidelines. Therefore, in this article, we develop environmental design guidelines by comparing multiple circular design options for two building components: a kitchen (short service life) and renovation façade (medium service life). First, we synthesize design variants based on distinct circular pathways, such as renewable-, non-virgin material use, and modularity for reuse. Second, we compare their environmental performance to a 'business-as-usual' variant through Material Flow Analysis (MFA) and a multi-cycle Life Cycle Assessment (LCA) including extensive sensitivity analysis on circular parameters. Analysing the 78 LCAs and MFAs, we derive 8 lessons learned on the environmental design of circular building components. We compare our findings to existing guidelines, including those for circular building structures (long service life). Amongst other lessons, we found components with a short service life benefit more from prioritizing circular design options to slow and close future cycles, whilst components with a longer service life benefit more from reducing resources and slowing loops on site. However, applying circular design options does not always result in a better environmental performance. Tipping-points were identified based on the number of use cycles, lifespans and the assessment methods applied.

KEYWORDS Circular Economy (CE), Life Cycle Assessment (LCA), Material Flow Analysis (MFA), design guidelines, building components, multi-cycle

Nomenclature

CE	Circular Economy
VRP	Value Retention Process
MFA	Material Flow Analysis
LCA	Life Cycle Assessment
SL	Service Life
BAU	Business-As-Usual
CE-LCA model	Circular Economy Life Cycle Assessment model
CE LD approach	Circular Economy Linearly Degressive allocation approach
FU	Functional Unit
Rc	(thermal) Resistance construction
RSP	Reference Study Period
ESL	Estimated Service Life
CE-LCI	Circular Economy Life Cycle Inventory
CE-LCIA	Circular Economy Life Cycle Impact Assessment
BIO	Biological design variants applying bio-based and biodegradable materials
Reclaim!	Reclaim! design variants applying non-virgin materials
LIFE+	LIFE+ design variant optimising lifespans and materials
P2P	Product2product design variant facilitating reuse of products
P&P	Plug-and-play design variants: modular design facilitating repair, adjustments, reuse and recycling.
C-n	Sensitivity analysis scenario: n-future cycles removed from baseline scenario
C+n	Sensitivity analysis scenario: n-reuse cycles added to baseline scenario
L n	Sensitivity analysis scenario in which the functional-technical lifespan is n-years
Lf n	Sensitivity analysis scenario in which the functional lifespan is n-years
Lt n	Sensitivity analysis scenario in which the technical lifespan is n-years
GWP	Global Warming Potential
EoL	End of Life
t	time

6.1 Introduction

The building sector is said to consume 40% of resources globally, produces 40% of global waste and 33% of all human-induced emissions (Ness & Xing, 2017). Therefore, the building industry plays a crucial role in society's pursuit to become more sustainable. Transitioning to a Circular Economy (CE) could support minimizing pollution, emissions and waste in the built environment.

The CE model builds on previously developed schools of thought and there is no commonly accepted understanding of the concept (Kirchherr, Reike, & Hekkert, 2017). We understand CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by narrowing, slowing and closing material and energy loops" (adapted from Geissdoerfer, Savaget, Bocken and Hultink (2017 p. 759)). Narrowing loops is to reduce resource use or achieve resource efficiency. Slowing loops is to lengthen the use of a building, component, part or material. Closing loops is to (re)cycle materials from end-of-life back to production (Bocken, de Pauw, Bakker, & van der Grinten, 2016). Value Retention Processes (VRPs) – such as reuse, repair, refurbish, recycle and recover – operationalize narrowing, slowing and closing cycles (Reike, Vermeulen, & Witjes, 2018; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020).

The built environment can gradually be made circular by replacing building components with (more) circular building components during new construction, maintenance and renovation. Integral changes in the design, supply-chain and business model are needed to make building components more circular, involving many design parameters. For each parameter, numerous circular design options can be identified (van Stijn & Gruis, 2020). Consequently, designers can develop different design variants for circular building components, taking different pathways towards a circular built environment. For example, a façade which applies reclaimed materials, a modular façade which will be updated and reused, or a bio-based and biodegradable façade are all more circular in their own respect. This raises the questions: which circular design option(s) will result in the least amount of resource use, environmental impacts and waste generation? And, how can we make such a decision? Designers, policy makers, and other decision-makers could benefit from this knowledge when designing circular building components. In this article, we aim to answer the aforementioned questions and develop environmental design guidelines for circular building components.

6.2 Background on environmental design guidelines for circular building components

Literature already provides numerous circular design aids, such as methods, tools and frameworks. We distinguish between generative and evaluative aids (Bocken, Farracho, Bosworth, & Kemp, 2014; de Koeijer, Wever, & Henseler, 2017). The former includes (e.g.,) rules of thumb, checklists, guidelines and archetypes. They support integration of circular options during design synthesis. The latter help evaluate 'the circularity' of a generated design. Without claiming to be comprehensive, in this section we discuss existing generative and evaluative design aids for circular building components.

Van Stijn and Gruis (2020) reviewed 36 generative design aids and developed a tool to support synthesis of circular building components. They concluded that generative aids provide circular design options, but do not indicate which option(s) lead to the most circular building components. Similarly, Bocken et al. (2016) discussed that merely narrowing loops could result in an environmental performance comparable to applying their circular design strategies to slow and close resource cycles. Cambier, Galle and de Temmerman (2020) found that general circular design guidelines are available but *specific* design guidelines for circular building components are lacking.

Corona, Shen, Reike, Rosales Carreón and Worrell (2019), Elia, Gnoni and Tornese (2017), Pomponi and Moncaster (2017) and Sassanelli, Rosa, Rocca and Terzi (2019) extensively discuss evaluative methods, tools and frameworks for circularity. Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are often identified as suitable methods to evaluate environmental performance of designs in a CE. In MFA, mass balances of a defined system are calculated over time (Corona et al., 2019). MFA can be used to analyse the quality of resource import and export flows (e.g., virgin, renewable, recycled) and resource consumption (Elia et al., 2017; Pomponi & Moncaster, 2017). LCA can be used to analyse environmental impacts over a building components' life cycle in a CE context (Pomponi & Moncaster, 2017; Scheepens, Vogtländer, & Brezet, 2016). Using LCA and MFA when designing could significantly reduce resource use, environmental impacts, and waste generation. However, evaluations with LCA and MFA are often considered time consuming, laborious and expensive by practice (Cambier et al., 2020; De Wolf, Pomponi, & Moncaster, 2017).

Environmental design guidelines based on LCA and MFA results could help bring LCA and MFA knowledge into practice. Table 6.1 summarizes precedent studies that compared the environmental performance of circular design options in building components through LCA and/or MFA. De Wolf (2017) and Malabi Eberhardt, van Stijn, Kristensen Stranddorf, Birkved and Birgisdottir (2021) focus on a building structure, a component with a long Service Life (SL). Buyle, Galle, Debacker and Audenaert (2019), Geldermans, Tenpierik and Luscuere, (2019) and van Stijn, Eberhardt, Wouterszoon Jansen and Meijer (2020) study either partitioning walls or kitchens: components with a short SL. Vandenbroucke, Galle, De Temmerman, Debacker and Paduart (2015) and Cruz Rios, Grau and Chong (2019) studied components with a medium SL such as a roof, floor, exterior wall and façade components. However, Buyle et al. (2019), Cruz Rios et al. (2019) and Vandenbroucke et al. (2015) compared 'only' Business-As-Usual (BAU) variants to one circular design option. So, their results do not compare different circular design options to each other. Furthermore, applied methods and assessment scope differed between studies hindering comparability. Indeed, Table 6.1 shows authors come to different conclusions on which circular design options perform best. Even Malabi Eberhardt et al. (2021) and van Stijn et al. (2020) who compared multiple circular design options and applied the same methods, still come to different conclusions. Malabi Eberhardt et al. (2021) and Buyle et al. (2019) suggested that guidelines could differ between components which might depend on their SL. This raises the question which circular design option(s) result in the best environmental performance for which building component?

TOC

TABLE 6.1 Precedent studies comparing environmental performance of circular design options in building components

Author	Building component	Circular design options compared	Method	Design option(s) with best environmental performance
Buyle et al. (2019)	Interior partitioning wall	4 BAU designs and 3 demountable and reusable designs	Consequential LCA	• Demountable and reusable designs with higher initial impact but low lifecycle impact; • Design with no possibilities for direct reuse but low initial impact.
Cruz Rios et al. (2019)	External framed wall	1 single-use wood-framed wall and 1 reusable steel-framed wall	Hybrid and process-based LCA	•If reused 2 times, a reuse rate of (>70%), and short transport distance then reusable steel-framed wall; •If wood-framed wall is reused, then wood-framed wall has highest environmental benefits.
De Wolf (2017)	Building structure	BAU design and material efficient design with low carbon materials	LCA (embodied carbon only)	• Choosing low carbon materials and optimizing the structural efficiency to reduce the material quantity in the building structure.
Geldermans et al. (2019)	Interior partitioning wall	Adaptable design (modular; demountable); biobased and non-virgin materials.	Circ-flex design guidelines and Activity-based Spatial MFA	• Combining design for adaptation with bio-based and reversible fibre composite materials.
Malabi Eberhardt et al. (2021)	Building structure	1 BAU design, 1 material efficient design; 1 biobased design, 1 demountable and reusable design and 1 on-site adaptable design	CE-LCA (includes all cycles); MFA	• Combining resource efficiency, long use on-site through adaptability, low-impact renewable materials and (only then) facilitating future use cycles (off-site) for parts and materials.
van Stijn et al. (2020)	Kitchen	1 BAU design, 1 biobased design, 1 design with reclaimed materials, 1 optimized design and 1 adaptable design	CE-LCA (includes all cycles); MFA	• Modular design which facilitates partial replacements of parts to prolong use of the entire kitchen and introduces more use-cycles in parts and materials.
Vandenbroucke et al. (2015)	Ground level floor; Flat roof; External wall; Internal Partitioning wall	Per component: 1 BAU design for new built; 1 BAU design for renovation; 1 demountable and adaptable design for renovation	LCA following building standard	• Demountable design for all building components is only useful if the adjustments are done frequently; • Tipping point depends on how much extra material is needed to achieve demountability.

6.3 Goal and method

We developed environmental design guidelines based on MFA and LCA comparing multiple circular design options for two building components: a kitchen and renovation façade. Kitchens are building components with a short SL and high replacement frequency. Hoxha and Jusselme (2017) show domestic furniture and appliances can contribute up to 35% of the building's environmental impacts. We built on the initial circular kitchen study of van Stijn et al. (2020). A renovation façade is a relevant example of a component with a medium SL. It improves the operational energy efficiency and provides an aesthetic upgrade. Such facades can decrease operational carbon emissions but add significantly to embodied impacts (Ibn-Mohammed et al., 2013).

An iterative, stepwise approach was used (Figure 6.1). In step 1, we synthesized circular design variants for the kitchen and renovation façade. In step 2, we compared their environmental performance to a BAU variant through MFA and LCA. In step 3, we analyzed the results to derive environmental design guidelines. In step 4, we evaluated these in expert sessions. The evaluations were used to iteratively improve the design variants, assessments and environmental design guidelines, until the evaluation yielded no new remarks. In Sections 6.3.1-4, we elaborate on the methods applied per step. Sections 6.4-6 present the final iteration of steps 1-3, respectively. In Section 6.7, we compare the guidelines to existing guidelines, including those for circular building structures of Malabi Eberhardt et al. (2021); we discuss our findings and draw conclusions.

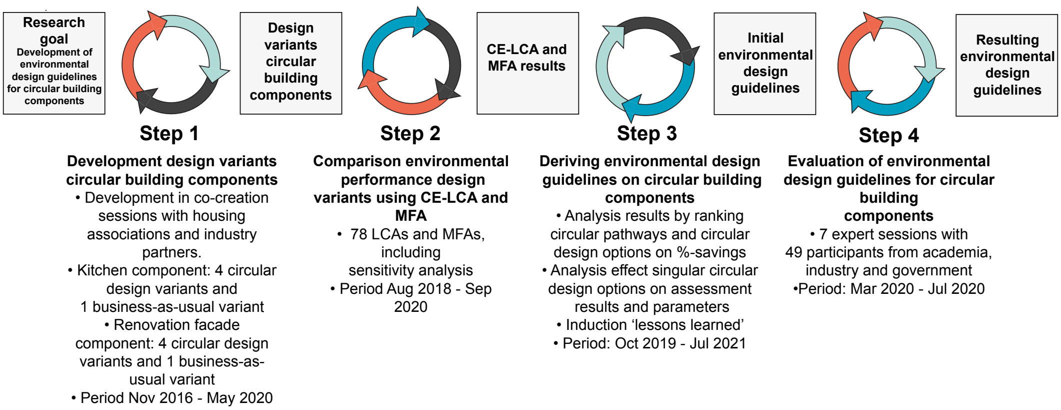


FIG. 6.1 Approach to develop environmental design guidelines

6.3.1 Synthesis circular design variants kitchen and renovation façade

The design variants were developed in co-creation with Delft University of Technology, AMS-institute, Dutch housing associations, and industry partners. The variants were developed by applying the generative tool for circular building components of van Stijn and Gruis (2020): the researchers synthesized design variants through systematically 'mixing and matching' circular design options for each design parameter. Although more variants are imaginable, these variants were considered plausible in the near future, and representative for different CE pathways. The designs were developed to the level of proof-of-concept and consist of a technical, industrial and business model.

6.3.2 Comparison environmental performance through LCA and MFA

The equations and parameters for the LCA and MFA are included in Appendix C.1.

6.3.2.1 Life Cycle Assessment

We employed the 'Circular Economy LCA model for circular building components' (van Stijn, Eberhardt, Wouterszoon Jansen, & Meijer, 2021). This model builds on existing LCA standards applied in the building sector: EN 15804 (2012) and EN 15978 (2011). In the standard LCAs, environmental impacts are assessed over a single use cycle of a building (component), captured in 'life cycle modules A-C'. Module D reports potential burdens and benefits of only one subsequent reuse, recycling or recovery cycle. Such LCAs do not fully capture the burdens and benefits of a CE (see Allacker, Mathieux, Pennington and Pant (2017); De Wolf, Hoxha and Fivet (2020); Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved and Birgisdottir (2020); van Stijn et al. (2021)). In CE-LCA, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include all cycles. For example, if reclaimed material is used in the component, initial production and use of the virgin material is included within the system boundary; if parts will be reused twice, both reuse cycles are included. Impacts were divided between use cycles using the Circular Economy Linearly Degressive (CE LD) allocation approach of Malabi Eberhardt et al. (2020). CE LD is suitable when the use and value of materials is not the same in each cycle (van Stijn et al., 2021) – which was the case in this study. The largest share of impacts from initial production and construction is allocated to the first use cycle and the share of impacts allocated to following cycles decreases linearly. For disposal most impacts are allocated to the last cycle. Impacts of VRPs are distributed equally between all use cycles.

For the kitchen, a lower cabinet was considered representative for the whole kitchen. For the façade, a section of façade for a terraced dwelling was considered representative. The functional unit (FU) for the kitchen was *'the use of a specific configuration of a lower kitchen cabinet in a circular system for the period of 80 years'*. For the façade the FU is *'the use of a specific renovation façade for the reference façade section, with an approximate Rc value 5.0, in a circular system over a period of 90 years'*. Note that the word 'specific' in the FU indicates that we distinguished if the building component, part or material is in its first, second, etc. use cycle rather than assuming an average. Following van Stijn et al. (2021, p. 4), the Reference Study Periods (RSPs) of 80 and 90 years were based on the longest Estimated Service Life (ESL) of parts of the kitchen and façade variants. These RSPs resulted in the fairest comparison between design variants. As we do not directly compare the environmental performance of kitchen to façade variants the RSP could differ for both.

The design variants remain theoretical concepts. When developing the CE-Life Cycle Inventory (CE-LCI), estimations were made on transport distances, production, VRPs and disposal processes, number of use cycles, and ESLs. The ESLs were determined by considering the interplay of functional, economic and technical lifespans on component, part and material level. Assumptions were based on how circular design options might perform compared to the BAU variant and on experience of involved practice partners. The CE-LCIs were modelled in openLCA version 1.9.0 software; the background system was modelled with the Ecoinvent 3.4 APOS database (Wernet et al., 2016), using system processes to get aggregated results. The CE Life Cycle Impact Assessment (CE-LCIA) was calculated using characterization factors from the Centre for Environmental Studies (CML)-IA baseline (Guinée et al., 2001). CML includes 11 environmental, resource-depletion and toxicology midpoint impact categories and is commonly used in the building sector. There are two main approaches for accounting biogenic carbon: the '-1/+1' and '0/0' approach. See also Andersen, Rasmussen, Habert and Birgisdóttir (2021) and Hoxha et al. (2020). In CE-LCA, carbon impacts from production and disposal are divided linearly between all use cycles. The -1/+1 approach would favour the first use cycles unfairly, so we applied the 0/0 approach. We refer to Appendix C.2 for all CE-LCIs and CE-LCIA parameters.

Including multiple cycles into the assessment scope increases uncertainty of the results. Therefore, we conducted a scenario-based sensitively analysis by varying the number of use cycles and lifespans of (parts of) the building components (see Table 6.2). For a detailed description of all sensitivity scenarios, see Appendix C.3.

TABLE 6.2 Scenarios of the sensitivity analysis

Type of sensitivity scenario	Abbreviation	Explanation	Kitchen design variants					Facade design variants				
			BAU*	BIO*	Reclaim! *	LIFE+ *	P&P*	BAU*	BIO*	Reclaim!*	P2P*	P&P*
Number of use cycles	C-n	Removing future cycles					x				x	x
	C+n	Adding future reuse cycles	x	x	x	x	x	x	x	x	x	x
Lifespans of (parts of) the building components	L n	Increasing/decreasing technical and function-al lifespan of all parts in parallel	x	x	x	x	x	x	x	x	x	x
	Lf n	Increasing/decreasing functional lifespan of parts of the building component				x	x					x

** these abbriviations refer to the names of the kitchen and façade design variants and will be further explained in section 6.4.*

6.3.2.2 Material Flow Analysis

In the MFA we calculated the direct material import and export of each design variant over the RSP in kilogram using the inventory developed for the CE-LCA. For the material import, we distinguished virgin or non-virgin flows, and renewable or non-renewable flows. For the export, we distinguished reused, remanufactured, recycled, biodegraded or incinerated for energy recovery, and discarded flows. By subtracting reused, remanufactured and recycled flows from the total import, we calculated the material consumption. As MFA is based on the law of matter conservation, no flows from prior or subsequent use cycles were allocated to the assessed building component.

6.3.3 Environmental design guidelines development

The environmental performance of design variants differed from one environmental impact-, or material flow category to another. Furthermore, between design variants many parameters differed simultaneously, such as lifespan, materialisation, number of use cycles. This inhibited selection of the best performing circular design option(s). Therefore, in step 3, we analysed the results to determine which circular design option(s) resulted in the best environmental performance and induce design guidelines (see Figure 6.2).

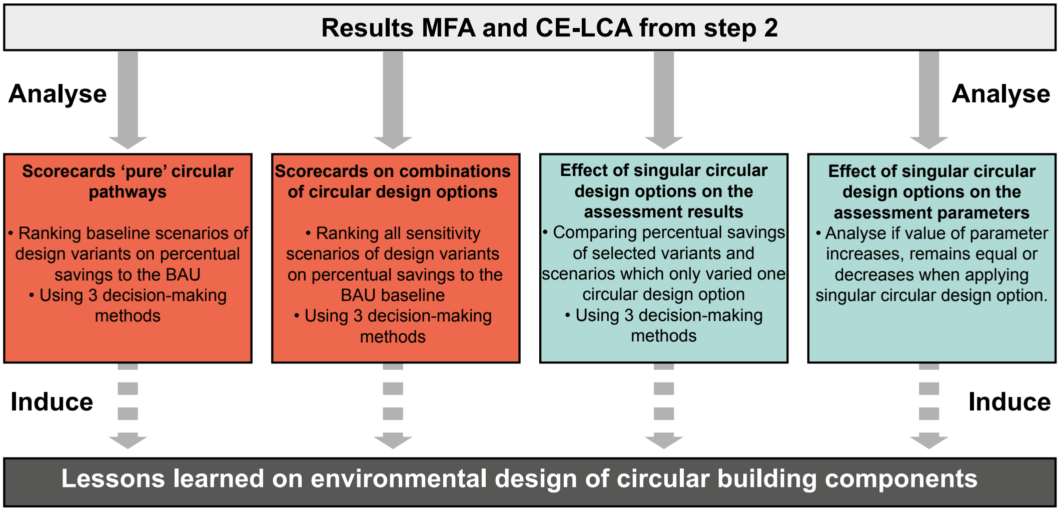


FIG. 6.2 4 Analyses to induce lessons learned

Multiple procedures can be used to support decision-making. These vary in how the CE-LCA and MFA are valued to each other as well as the relative importance of different environmental impact categories. Each procedure has (dis)advantages. We ranked the variants based on percentual savings to the BAU baseline using multiple procedures in parallel. In the CE-LCA, (i) applying no weighting factors, we calculated the average percentual reduction of the 11 midpoints. (ii) We applied the 'single' issue approach. As Global Warming Potential (GWP) is often a focal point in industry and governmental policy, we singled out the percentual savings based on GWP. (iii) We calculated the percentual savings based on the prevention-based, single indicator: 'shadow costs' (Stichting Bouwkwaliteit, 2019). Shadow costs are commonly applied in the Dutch building context. For the MFA, we considered the unweighted average of the percentual reduction on 5 categories: (1) the total material import and (2) material consumption and the percentage of (3) virgin, (4) non-renewable-, and (5) (bio)degraded, recovered, or discarded flows. We counted the CE-LCA and MFA equally. By ranking the savings of circular variants baseline scenarios to the BAU baseline, we developed a scorecard for the 'pure' circular pathways. By ranking the savings of all assessed scenarios to the BAU baseline, we developed a scorecard for combinations of circular design options.

TOC

The effect of ‘singular’ circular design options was investigated in depth. We analysed the effect of (1) applying non-virgin materials, (2) applying renewable materials, (3) increasing the functional- and technical lifespan in parallel, (4) increasing the functional lifespan, (5) adding future use cycles. We analysed their savings by comparing the results of selected variants and scenarios which only varied this one circular design option. Additionally, we analysed how these options affected the parameters in the CE-LCA and MFA equations.

From these 4 analyses, we induced lessons-learned on the environmental design of circular building components.

6.3.4 Evaluation of the environmental design guidelines

The environmental design guidelines were evaluated in 7 semi-structured expert sessions, with 49 experts and practitioners from academia, industry and government in the field of LCA, CE design and circular built environment. The researchers presented the methods, results and conclusions. The participants were asked the following questions: do you think the environmental design guidelines are valid or not; how would you improve them? The answers and discussion were documented in minutes and analysed using an emergent coding technique (Dahlsrud, 2008; Kirchherr et al., 2017). See Appendix C.4 for the results.

6.4 Design variants for the kitchen and renovation façade

Figures 6.3 and 6.4 visualize the technical models for the kitchen and façade design variants.

The kitchens in Dutch social housing are sober and appliances are typically not provided. So, the design focussed on the cabinetry. Similar countertop options were available for each variant. Therefore, they were left outside of the design scope. The BAU kitchen represents the current practice: a melamine-coated chipboard kitchen with a 20-years ESL. In the Biological (BIO) kitchen, bio-based and biodegradable

TOC

materials are applied; after 10 years, the cabinet is industrially composted. The Reclaim! kitchen is similar to the BAU kitchen but applies directly reused materials; it has a reduced ESL of 10 years. The LIFE+ kitchen optimizes the BAU kitchen by changing materials to optimize lifespans of parts. The construction is designed for long life (40 years) by substituting the chipboard with plywood. Fronts are designed for a shorter use (10 years) by applying low-impact, biological materials. The Plug-and-Play (P&P) kitchen applies a combination of circular design options to slow and close future cycles. Through a modular design, kitchen parts can be replaced at different rates so the whole kitchen can be kept for 80 years. The cabinets consist of a construction frame with an 80-year lifespan, drawers, shelves with a 40-year lifespan, and fronts with a use cycle of 20 years. The design facilitates repair and future adjustments. Additionally, parts and materials have reuse, remanufacturing, recycling and/or recovery cycles. The kitchen is constructed with long-life material (plywood), to facilitate longer and multiple use-cycles.

The BAU façade is an integrated and lightweight solution in which EPS and mineral brick strips are glued onto the existing façade. It is typically placed for an exploitation period of 30 years. After use, the materials are incinerated or landfilled. In the Biological (BIO) façade, bio-based and biodegradable materials are applied; after 30 years, the façade is industrially composted. The Reclaim! façade applies non-virgin materials. Demountable connectors are used. After 30 years, the façade can be disassembled and materials reused, recycled and/or recovered. The Product2Product (P2P) façade applies long-life materials in standardized sizes. De-, and remountable connectors facilitate multiple reuse cycles after 30 years. The Plug-and-Play (P&P) façade combines circular design options to slow and close future cycles. The façade is modular. Standard-sized façade panels are attached to insulation modules with click-on connectors. This design allows repair and adjustment of the façade and reuse(s) of parts after 30 years. At End of Life (EoL) of the modules, materials are recycled and/or recovered. An elaborate description of the design variants, flowcharts, and (re)placement charts have been included in Appendix C.5.

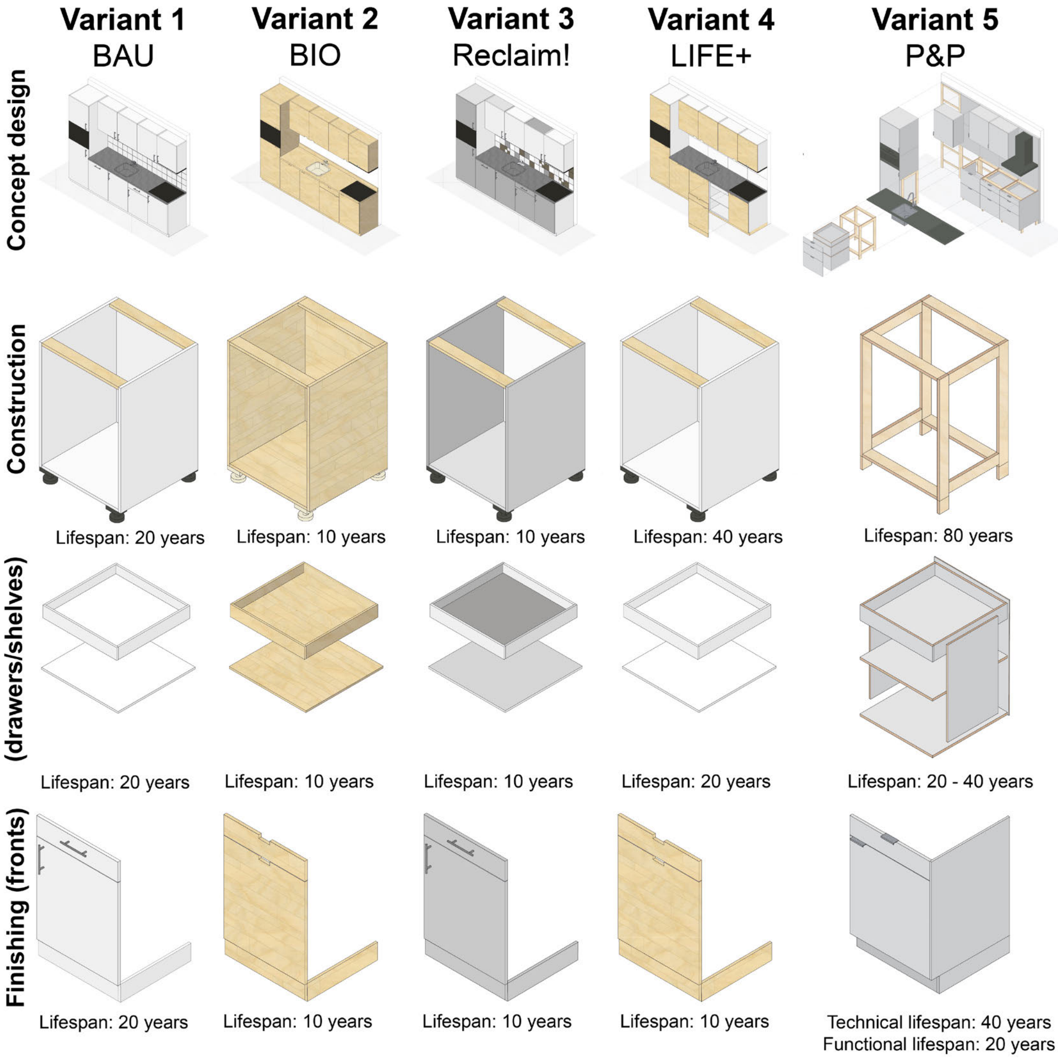


FIG. 6.3 Technical model of the kitchen design variants showing materialisation and lifespans

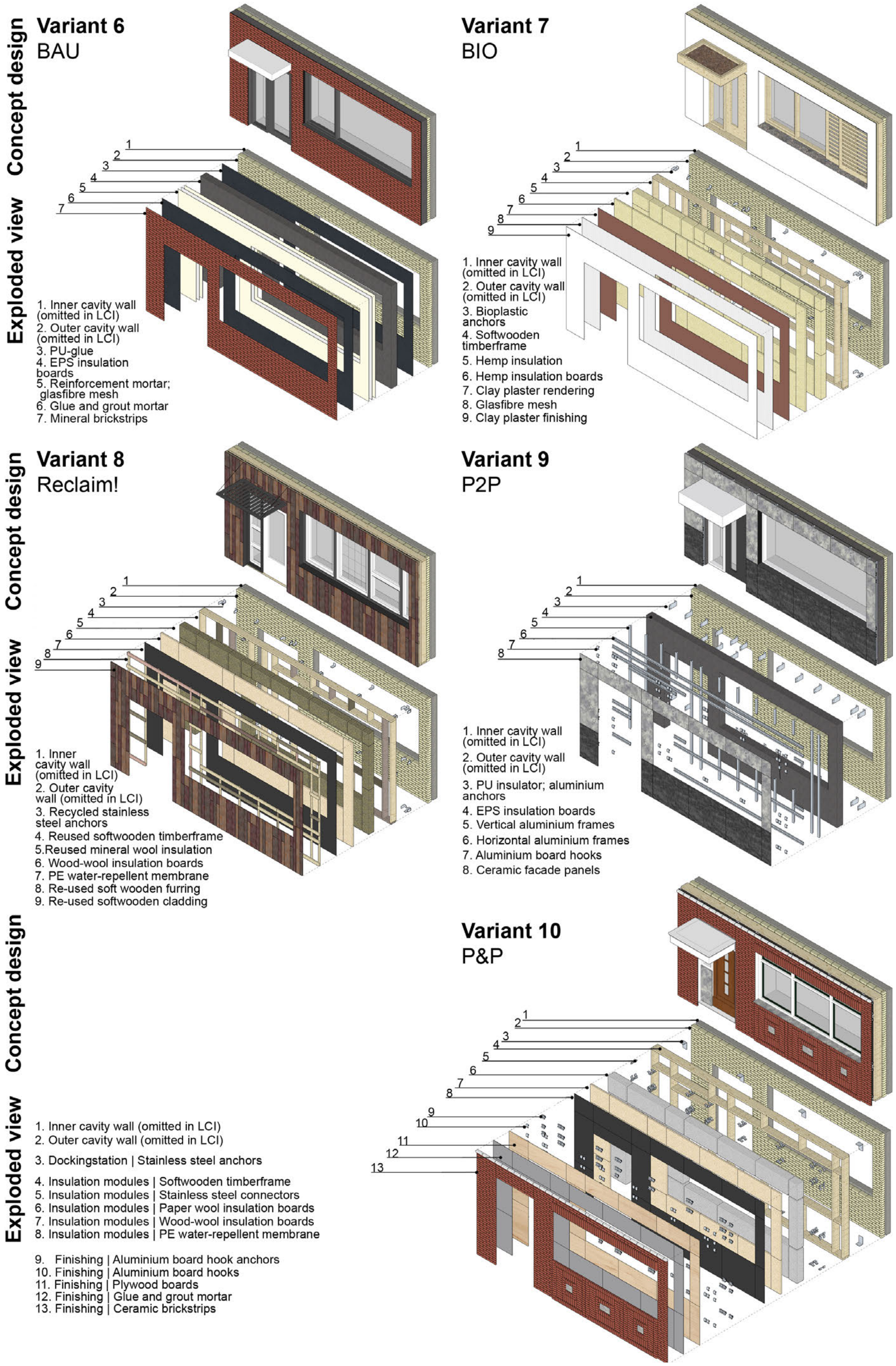


FIG. 6.4 Technical model of the façade design variants showing materialisation

TOC

6.5 MFA and CE-LCA results

The CE-LCIA and MFA results are provided in Table 6.3. Figures 6.5-6 provide a temporal perspective, showing the GWP over the RSP. Note, tipping points might differ for other impact categories.

Both the BIO and Reclaim! kitchens have a higher material import and consumption than the BAU. Although the mass of a single placement is similar to a BAU, the reduced ESL of both variants result in more placements over time. In the Reclaim! variant, virgin material flows are reduced by 100%; In the BIO kitchen, non-renewable flows are reduced 100%. Both variants also have lower environmental impacts for one placement. Yet, they realise a lower impact on only 6 of the 11 impact categories over the RSP due to the higher replacement rate.

The LIFE+ kitchen has a slightly lower material import (13%) and material consumption (13%) than the BAU, due to the longer lifespan of the construction. The P&P reduces material import by 24% due to the longer lifespan of the construction, drawers and shelves. The P&P also reduces material consumption by 93%, as materials still have a cycle(s) after use in the kitchen. Both LIFE+ and P&P kitchens reduce impacts in all categories compared to the BAU: for the LIFE+ between 8%-38%, and for the P&P, between 37%-57%. The reduction stems from partial replacements. When only parts of the kitchen are replaced (e.g., at t=10, t=20), the impact is significantly less than during full replacements (e.g., at t=0). For the LIFE+ kitchen, reductions also stem from using less impactful material for the fronts. For the P&P kitchen, substituting the particle board with plywood does not reduce impacts much. However, the multiple use cycles of parts and materials result in a lower share of impacts allocated to the P&P kitchen.

TABLE 6.3 Environmental impacts and material flows over the RSP per kitchen and façade variant

	Impact category	Unit	Design variants kitchen				
			BAU	BIO	Reclaim!	Life +	P&P
MFA	Import | Total	kg	132	210	264	115	101
	Import | Virgin	kg	92	210	0	103	63
	Import | Non-virgin	kg	40	0	264	11	38
	Import | Renewable	kg	92	210	184	85	76
	Import | Non-renewable	kg	40	0	80	30	25
	Export | Reused	kg	0	0	0	0	28
	Export | Remanufactured	kg	0	0	0	0	34
	Export | Recycled	kg	9	0	18	8	30
	Export | Recovered/ biodegraded	kg	123	210	246	107	8
	Export | Discarded	kg	0	0	0	0	0
	Material consumption	kg	123	210	246	107	8
CE-LCA	Global warming potential	kg CO_2 eq	1,48E+02	1,20E+02	1,50E+02	1,08E+02	6,40E+01
	Ozone layer depletion potential	kg CFC_{-11} eq	1,32E-05	1,83E-05	1,12E-05	1,02E-05	6,92E-06
	Photochemical ozone creation potential	kg C_2H_4 eq	5,10E-02	4,05E-02	4,71E-02	4,06E-02	2,54E-02
	Acidification potential	kg SO2 eq	5,99E-01	7,02E-01	5,34E-01	4,66E-01	2,99E-01
	Eutrophication potential	kg PO_4^{3-} eq	2,22E-01	2,45E-01	1,98E-01	1,77E-01	1,05E-01
	Abiotic depletion potential for elements	kg Sb eq	1,55E-03	1,71E-03	1,24E-03	9,62E-04	9,77E-04
	Abiotic depletion potential for fossil fuels	MJ	1,81E+03	1,73E+03	1,56E+03	1,27E+03	7,88E+02
	Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq.	8,30E+01	3,59E+01	9,37E+01	5,87E+01	3,73E+01
	Human toxicity potential	kg 1,4-DB eq.	1,82E+02	5,41E+01	2,37E+02	1,51E+02	9,11E+01
	Marine aquatic ecotoxicity potential	kg 1,4-DB eq.	1,70E+05	1,05E+05	1,71E+05	1,17E+05	7,62E+04
	Terrestrial ecotoxicity potential	kg 1,4-DB eq.	4,93E-01	6,64E-01	4,94E-01	4,52E-01	2,81E-01

>>>

TOC

TABLE 6.3 Environmental impacts and material flows over the RSP per kitchen and façade variant

	Impact category	Unit	Design variants façade				
			BAU	BIO	Reclaim!	P2P	P&P
MFA	Import | Total	kg	801	1488	1857	987	1731
	Import | Virgin	kg	801	1488	4	329	518
	Import | Non-virgin	kg	0	0	1853	658	1213
	Import | Renewable	kg	0	1483	1752	0	1035
	Import | Non-renewable	kg	801	4	105	987	696
	Export | Reused	kg	0	0	856	899	1416
	Export | Remanufactured	kg	0	0	0	0	0
	Export | Recycled	kg	350	0	610	87	206
	Export | Recovered/ biodegraded	kg	138	1488	391	0	109
	Export | Discarded	kg	313	0	0	0	0
	Material consumption	kg	451	1488	391	0	109
CE-LCA	Global warming potential	kg CO_2 eq	9,78E+02	3,17E+02	3,36E+02	5,33E+02	3,78E+02
	Ozone layer depletion potential	kg CFC_{-11} eq	3,25E-05	2,81E-05	3,60E-05	3,38E-05	4,74E-05
	Photochemical ozone creation potential	kg C_2H_4 eq	1,95E-01	1,65E-01	1,55E-01	1,38E-01	1,39E-01
	Acidification potential	kg SO2 eq	2,81E+00	2,20E+00	2,13E+00	2,31E+00	1,64E+00
	Eutrophication potential	kg PO_4^{3-} eq	5,96E-01	3,23E+00	5,70E-01	7,35E-01	7,43E-01
	Abiotic depletion potential for elements	kg Sb eq	1,15E-03	8,02E-03	9,11E-04	2,86E-02	5,93E-03
	Abiotic depletion potential for fossil fuels	MJ	1,36E+04	2,87E+03	3,83E+03	6,27E+03	4,11E+03
	Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq.	2,95E+02	1,16E+02	1,68E+02	6,49E+03	1,83E+03
	Human toxicity potential	kg 1,4-DB eq.	2,85E+02	1,25E+02	2,25E+02	4,88E+02	5,79E+02
	Marine aquatic ecotoxicity potential	kg 1,4-DB eq.	1,27E+06	3,01E+05	6,45E+05	2,74E+06	1,37E+06
	Terrestrial ecotoxicity potential	kg 1,4-DB eq.	5,87E-01	1,39E+00	9,95E-01	1,35E+00	1,79E+00

Note: The colour shows a gradient between the worst (blue) and best (light blue) value. The best value is the lowest value in all categories, except for the renewable-, and non-virgin import, and the reused-, remanufactured-, and recycled material export.

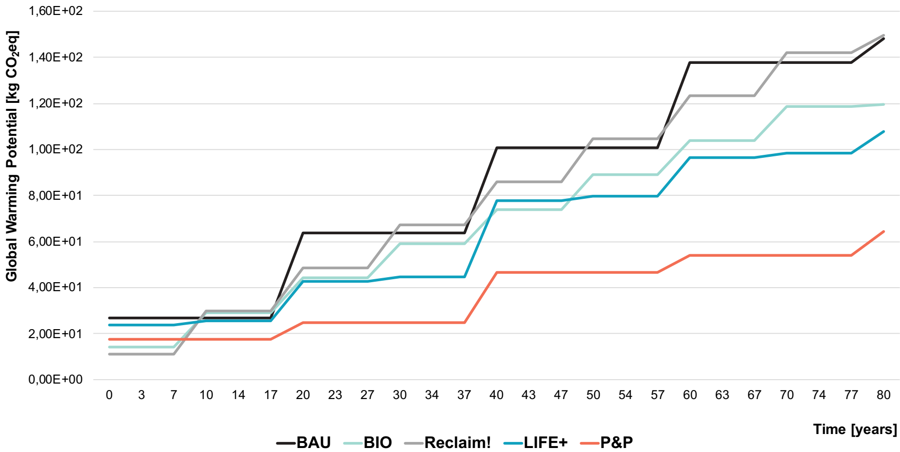


FIG. 6.5 GWP per kitchen variant over the RSP

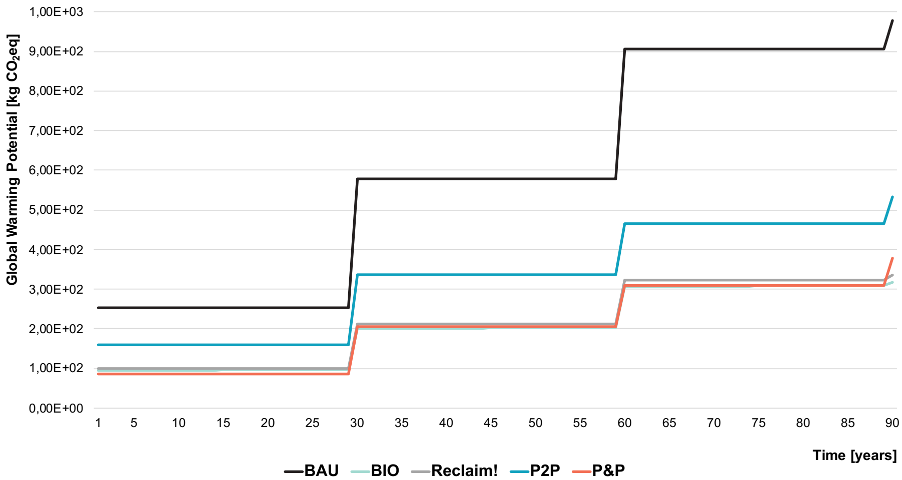


FIG. 6.6 GWP per façade variant over the RSP

The BAU façade contains plastics, cement and brick. In all other façades, metals and renewable materials are applied causing a shift of burdens to other impact categories. All circular façades increase material import compared to the material-efficient BAU. In the BIO façade, more renewable insulation material was needed to reach a comparable insulation value. All circular variants have additional structural materials. In the Reclaim!, P2P and P&P façades, additional metal connectors were needed to allow dis- and reassembly.

In the BIO façade, non-renewable flows were reduced by nearly 100% compared to the BAU. Impacts are lower on 8 out of 11 categories, ranging between -600% and 79%. Notably, burdens were shifted towards eutrophication, abiotic depletion and terrestrial ecotoxicity categories: categories related to growth of renewable materials. The Reclaim! façade reduced virgin material flows 100%. Although material import was more than doubled, a large part is wood. Wood has a relatively low-impact and was modelled with 5 use cycles. So, a low share of impacts is allocated to the façade. As such, the Reclaim! variant reduces impacts on 9 categories.

The P2P and P&P façades reduced 4 and increased 7 impact categories: burdens are shifted to abiotic depletion and toxicity impact categories caused by the metals. The multiple use cycles of parts and materials result in a lower share of impacts allocated to these façades. Figure 6.6 illustrates the benefit of placing second-, and third-hand parts during replacements (t=30 and t=60): lower shares of impact are allocated to the façade than during the placement of virgin parts at t=0. However, these gains only (partially) make up for the high production impacts and higher material mass. Due to the multiple reuse cycles of parts and materials, the P2P and P&P reduce material consumption by 100% and 76%, respectively.

6.5.1 Results of the sensitivity analysis

To support comparison of scenarios, we included charts visualising the MFA and GWP over the RSP in Appendices C.6-9. The results for all impact categories and material flows are provided in Appendix C.10, Appendix C.11 contains additional analysis on the contribution of materials and processes.

When adding 1 or 2 reuse cycles (scenarios C+1 and C+2), impacts decrease for all kitchen and façade variants. Savings are highest for variants which apply virgin materials and do not yet have future cycles (i.e., BAU, BIO and LIFE+). For example, adding one cycle to the BAU, BIO and LIFE+ kitchens, reduces impacts between 18% to 34% compared to their baseline scenarios and between 27% and 50% when adding 2 reuses. Adding a reuse cycle to non-virgin material does not decrease the fraction of impacts allocated to the building component as much as for virgin materials. For the Reclaim! kitchen, impacts are only reduced between 1% and 10% when adding one reuse. For the Reclaim! façade this is between 7% and 16%. In the P2P and P&P variants, the scenarios in which cycles are removed (C-1, C-2, and C-3) show that not all future cycles reduce impacts. In C-1, impactful recycling processes no longer take place. Although a higher share of impacts is allocated to the component, this is offset

TOC

by reducing (heavy) impacts from these cycles. In the P&P C-1 scenarios, impacts are reduced between -4% and 73% for the kitchen and between -1% and -9% for the façade. In scenarios C-2 for the façade and C-3 for the kitchen impacts increase because reuse cycles are no longer realised. In the MFA, when adding cycles, all materials become reused flows. Subsequently, material consumption is lowered to 0. Likewise, subtracting cycles leads to a significant increase in material consumption.

The sensitivity is highest when varying the technical and functional lifespan in parallel: there is a proportional relationship between the environmental impacts, mass of flows and the technical-functional lifespan. In their baseline, the BIO and Reclaim! kitchen have shorter ESLs than the BAU, whereas the LIFE+ and P&P kitchen have longer ESLs. Compared on a ±20-year ESL, BIO and Reclaim! have half the impacts, material import and consumption compared to their baseline. The BIO now reduces impacts between 31% and 85% compared to the BAU and the Reclaim! between 35% and 60%, whilst having a similar material import and consumption. In the LIFE+ and P&P kitchens, a 20-year technical lifespan increases material import, consumption and impacts compared to their baseline. The LIFE+, now only has a -1% and 41% impact reduction compared to the BAU; for the P&P this is between -38% to 10%. Note that a key circular design option of the LIFE+ and P&P – facilitating partial replacements to keep the whole kitchen in use longer – is nullified in this scenario. Furthermore, in the P&P kitchen, finishing parts are still exchanged every 10 years preventing full comparability.

Varying only the functional lifespan of parts of the LIFE+ kitchen and P&P kitchen and façade results in less impact deviation from their baseline. When reducing the functional lifespan, more finishing parts are placed throughout the RSP. However, in the LIFE+ kitchen, these parts are made of low-impact renewable materials, keeping impacts low. In the P&P kitchen and façade, although more finishing parts are placed, they are also reused more often as the technical lifespan remains the same. So, a lower amount of impact is allocated to the components.

6.5.2 Interpretations of the results

From results of the kitchen baseline scenarios, we found that the P&P kitchen has the lowest environmental impacts, material import and consumption over time. However, in the sensitivity analyses we found clear tipping points. Any savings are dependent on realizing the longer technical lifespans of parts and future cycles, in particular the low-impact reuse cycles. Furthermore, were the BIO and Reclaim! kitchen to have a longer lifespan and/or reuse cycle(s), these variants could reduce impacts, material

TOC

import and/or consumption equally or more than the P&P. But these kitchens are currently not designed for long use and multiple cycles. Their designs would need adaptations, effectively merging different circular design options.

The baseline scenario for the façade does not indicate a variant which consistently reduces impacts and material flows on all categories. The Reclaim! façade has the most stable reductions. From the sensitivity analysis we found that if this variant were combined with longer lifespans and/or reuse cycle(s), further savings could be achieved on impact. However, in all these scenarios the material import still increases compared to the BAU. Realizing reuse cycle(s) or longer lifespans in the BAU variant could result in equal or higher impact reductions than the Reclaim! façade. However, the BAU would then likely need redesign. In the other façades, changes in materials cause shifts in burdens which inhibit the evaluation of these variants.

The results of these assessments are interpretable in multiple ways depending on where priorities are placed and what approach is used to make decisions, inhibiting selection of the best performing circular design option(s).

6.6 Resulting environmental design guidelines for circular building components

In this section, we present the analysis of the assessment results and induce lessons-learned.

6.6.1 Scorecards for circular pathways and combinations of circular design options

In Appendix C.12, we show the percentual savings of the design variants for all scenarios compared to the BAU baseline, and their rankings following the ranking methods described in Section 6.3.3. Tables 6.4-5 show the resulting scorecards for pure circular pathways (baseline scenarios); Tables 6.6-7 present the scorecard for combinations of circular design options (all analysed scenarios).

TABLE 6.4 Scorecard circular pathways for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Applied design principles		
				Technical model	Industrial model	Business model
1	1	1	**P&P**	Adjustable modular design, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recovery)	Maintenance, updates and reuse by manufacturer, reman. recycl. and recov. in collaboration with third parties	Lease, or sale with take- or buy-back, maintenance and update services
2	2	2	**LIFE+**	Optimising lifespans (40-20-10-20 years), long-life materials, bio-based, biode-gradable materials	Open-loop recycling, recovery, industrial com-posting by third parties	Sale
4	3	3	**BIO**	Bio-based, biodegradable materials, short lifespan (10 years)	Industrial composting by third parties	Sale
3	4	4	**BAU**	Linear design	Open-loop recycling and recovery by third parties	Sale
5	5	5	**Reclaim!**	Non-virgin materials, short lifespan (10 years)	Open-loop recycling and recovery by third parties	Sale

TABLE 6.5 Scorecard circular pathways for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Applied design principles		
				Technical model	Industrial model	Business model
1	3	1	**Reclaim!**	Non-virgin materials, easy to disassemble	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
3	1	2	**P&P**	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, op-timising lifespans, durable materials, multiple cycles (reuse, recycling, recovery)	Maintenance, updates, reuse by provider. Recycling and recovery in collabora-tion with third parties	Lease, or sale with take- or buy-back, mainten. and update services
2	5	3	**BAU**	Linear design	Open-loop recycling and recovery by third parties	Sale
4	4	4	**BIO**	Bio-based, biodegradable materials	Industrial composting by third parties	Sale
5	2	5	**P2P**	Easy to dis-, and re-as-semble, durable materials, standard sized parts, reuse of parts	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale

For the kitchens, different ranking methods lead to a similar ranking. For the façade, rankings deviate significantly. The ranking from the single-issue method differs most from the other two methods. The P2P and P&P have negative savings based on the shadow-costs and the average of all impact categories. However, they do reduce GWP causing the shift in rankings.

In Tables 6.4-5, the BAU kitchen scores significantly lower than the BAU façade. The BAU façade is more material efficient compared to the circular façades. However, all circular façades reduce the GWP impacts, so the BAU ranks lower using the GWP-based method. For the kitchens, the LIFE+ and P&P variants based on optimising or prolonging the lifespan of parts of the kitchen and adding future cycles rank highest. Similarly, the P&P façade ranks high, whilst the P2P ranks lowest. In the P2P, benefits of multiple reuse cycles do not compensate the high production impacts and mass. The Reclaim! kitchen scores low due to the reduced ESL, whilst for the façade it scores highest. The ESL of the Reclaim! façade is shorter than the technical lifespan of the non-virgin materials. So, initial impact savings accumulate with each new placement. The BIO kitchen suffers from its reduced ESL but still provides some impact savings compared to the BAU, resulting in a third place. Even though the BIO façade reduces the shadow costs most (57%) compared to the BAU, due to the shifts in burdens and its high material import and consumption, the BIO façade is placed below the BAU.

By ranking all sensitivity scenarios, we found that 'pure' circular pathways do not rank highest on environmental performance. Both in the kitchen and façade, the highest-ranking scenarios are combinations of circular pathways. Variants rank high which combine circular materials, longer lifespans, and/or reuse cycles. This combination reduces environmental impacts and virgin and/or non-renewable import during initial placement (narrowing loops); it reduces impacts, material import and consumption over time (slowing and closing loops). However, these higher scoring variants are likely either unfeasible or require some redesign.

TABLE 6.6 Scorecard of circular design options for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
1	1	1	**Reclaim!**	L80	Non-virgin materials, very long lifespan (80 years)	Open-loop recycling and recovery by third parties	Sale
2	2	2	**BIO**	L80	Bio-based, biodegradable materials, very long lifespan (80 years)	Industrial compost-ing by third party	Sale
3	3	3	**P&P**	Lt=80-80-80-80, Lf=80-80-40-80	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, durable materials, multiple cycles (reuse, reman., recycling, recov.), very long lifespan (80 years)	Maintenance, updates, reuse by manufacturer. Remanufactur-ing, recycling and recovery in collab-oration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
6	7	4	**BIO**	L40	Bio-based, biodegradable materials, long lifespan (40 years)	Industrial compost-ing by third party	Sale
5	4	5	**P&P**	C+2	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recov.), 2 additional reuse cycle	Maintenance, updates, reuse by manufacturer. Remanufactur-ing, recycling and recovery in collab-oration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
4	6	6	**Reclaim!**	L40	Non-virgin materials, long lifespan (40 years)	Open-loop recycling and recovery by third parties	Sale
7	5	7	**P&P**	C+1	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recov.), 1 additional reuse cycle	Maintenance, updates, reuse by manufacturer. Remanufactur-ing, recycling and recovery in collab-oration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
14	12	8	**BIO**	C+2	Bio-based, biodegradable materials, short lifespan (10 years), 2 reuse cycles	Local reuse. Indus-trial composting by third party	Sale
8	9	9	**BAU**	L80	Linear design, very long lifespan (80 years)	Open-loop recycling and recovery by third parties	Sale

>>>

TOC

TABLE 6.6 Scorecard of circular design options for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
9	8	10	**P&P**	Lt=80-40-40-40, Lf=80-40-40-40	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recov.), long function. lifespan finishing (40 years)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
10	11	11	**LIFE+**	L=80-80-80-80	Long-life materials, bio-based, biodegradable materials, very long functional-technical lifespan (80 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
18	16	12	**BIO**	C+1	Bio-based, biodegradable materials, short lifespan (10 years), 1 reuse cycle	Local reuse. Industrial composting by third party	Sale
11	10	13	**P&P**	Baseline	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recovery)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
12	14	14	**P&P**	C-1	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, 1 cycle not realised (reuse, reman., open-loop recycling and recovery)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
13	13	15	**LIFE+**	C+2	Optimising lifespans, long-life materials, bio-based, biodegradable materials, 2 reuse cycles	Local reuse, open-loop recycling, recovery, and industrial composting by third parties	Sale
22	20	16	**BIO**	L20	Bio-based, biodegradable materials, medium lifespan (20 years)	Industrial composting by third party	Sale

>>>

TOC

TABLE 6.6 Scorecard of circular design options for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
15	15	17	**LIFE+**	C+1	Optimising lifespans, long-life materials, bio-based, biodegradable materials, 1 reuse cycle	Local reuse, open-loop recycling, recovery, and industrial composting by third parties	Sale
17	19	18	**LIFE+**	L=80-40-20-40	Optimising lifespans, long-life materials, bio-based, biodegradable materials, long functional-technical lifespan (80-40-20-40 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
19	18	19	**P&P**	Lt=80-40-40-40, Lf=80-40-7-40	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recov.), very short function. lifespan finishing (7 years)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
16	17	20	**BAU**	C+2	Linear design, 2 reuse cycles	Local reuse, open-loop recycling and recovery by third parties	Sale
20	21	21	**P&P**	C-2	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, 2 cycles not realised (reuse, open-loop recycling and recovery)	Maintenance, updates, reuse by manufacturer. Open-loop recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
23	23	22	**BAU**	L40	Linear design, long lifespan (40 years)	Open-loop recycling and recovery by third parties	Sale
24	22	23	**BAU**	C+1	Linear design, 1 reuse cycle	Local reuse, open-loop recycling and recovery by third parties	Sale
21	24	24	**Reclaim!**	L20	Non-virgin materials, medium lifespan (20 years)	Open-loop recycling and recovery by third parties	Sale

>>>

TOC

TABLE 6.6 Scorecard of circular design options for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
25	25	25	**Reclaim!**	C+2	Non-virgin materials, short lifespan (10 years), 2 reuse cycles	Local reuse, open-loop recycling and recovery by third parties	Sale
27	30	26	**P&P**	C-3	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, 3 cycles not realised (only open-loop recycling and recovery)	Maintenance, updates, by manufacturer. Open-loop recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
29	27	27	**P&P**	Lt=40-20-20-20, Lf=40-20-10-20	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, reman., recycling, recov.), medium lifespan (40-20-20-20 years)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
26	26	28	**Reclaim!**	C+1	Non-virgin materials, short lifespan (10 years), 1 reuse cycle	Local reuse, open-loop recycling and recovery by third parties	Sale
28	28	29	**LIFE+**	Lf=40-20-20-20	Optimising lifespans, long-life materials, bio-based, biodegradable materials, medium functional lifespan finishing (20 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
31	29	30	**P&P**	Lt=20-20-20-20, Lf=20-20-10-20	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, durable materials, multiple cycles (reuse, reman., recycling, recov.), medium lifespan (20 years)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
30	31	31	**LIFE+**	Baseline	Optimising lifespans (40-20-10-20 years), long-life materials, bio-based, biodegr. materials	Open-loop recycling, recovery, and industrial composting by third parties	Sale
34	33	32	**BIO**	Baseline	Bio-based, biodegradable materials, short lifespan (10 years)	Industrial composting by third party	Sale

>>>

TABLE 6.6 Scorecard of circular design options for the circular kitchen

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
32	32	33	**LIFE+**	Lf=40-20-7-20	Optimising lifespans, long-life materials, bio-based, biodegradable materials, very short functional lifespan finishing (7 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
33	34	34	**BAU**	Baseline	Linear design	Open-loop recycling and recovery by third party	Sale
35	35	35	**Reclaim!**	Baseline	Non-virgin materials, short lifespan (10 years)	Open-loop recycling and recovery by third parties	Sale
37	37	36	**BIO**	L7	Bio-based, biodegradable materials, very short lifespan (7 years)	Industrial composting by third party	Sale
36	36	37	**LIFE+**	L=20-10-7-10	Optimising lifespans, long-life materials, bio-based,biodegradable materials, short lifespan (20-10-7-10 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
38	38	38	**Reclaim!**	L7	Non-virgin materials, very short lifespan (7 years)	Open-loop recycling and recovery by third parties	Sale
40	39	39	**P&P**	Lt=7-7-7-7, Lf=7-7-3,5-7	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, durable materials, multiple cycles (reuse, reman., recycling, recov.), very short lifespan (7 years)	Maintenance, updates, reuse by manufacturer. Remanufacturing, recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
39	40	40	**LIFE+**	L=7-7-7-7	Long-life materials, bio-based, biodegradable materials, very short functional-technical lifespan (7 years)	Open-loop recycling, recovery, and industrial composting by third parties	Sale
41	41	41	**BAU**	L7	Linear design, very short lifespan (7 years)	Open-loop recycling and recovery by third parties	Sale

TABLE 6.7 Scorecard of circular design options for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
1	1	1	**Reclaim**	L90	Non-virgin materials, easy to disassemble, very long lifespan (90 years)	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
10	7	2	**BIO**	C+2	Bio-based, biodegradable materials, 2 reuse cycles	Local reuse, industrial composting by third party	Sale
5	2	3	**P&P**	L90	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), very long lifespan (90 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
3	6	4	**Reclaim**	L45	Non-virgin materials, easy to disassemble, long lifespan (45 years)	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
14	10	5	**BIO**	C+1	Bio-based, biodegradable materials, 1 reuse cycle	Local reuse, industrial composting by third party	Sale
4	4	6	**Reclaim**	C+2	Non-virgin materials, easy to disassemble, 2 reuse cycles	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
7	9	7	**Reclaim**	C+1	Non-virgin materials, easy to disassemble,1 reuse cycle	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
2	15	8	**BAU**	L90	Linear design, lightweight, very long lifespan (90 years)	Open-loop recycling and recovery by third party	Sale
6	24	9	**BAU**	C+2	Linear design, lightweight, 2 reuse cycles	Local reuse, open-loop recycling and recovery by third party	Sale
13	21	10	**BIO**	L90	Bio-based, biodegradable materials, very long lifespan (90 years)	Industrial composting by third party	Sale

>>>

TOC

TABLE 6.7 Scorecard of circular design options for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
12	5	11	**P&P**	Lf90	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), very long functional lifespan insulation modules and finishing panels (90 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
20	3	12	**P2P**	L90	Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts, very long lifespan (90 years)	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale
11	20	13	**Reclaim**	Baseline	Non-virgin materials, easy to disassemble	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
8	25	14	**BAU**	C+1	Linear design, light-weight, 1 reuse cycle	Local reuse, open-loop recycling and recovery by third party	Sale
9	26	15	**BAU**	L45	Linear design, lightweight, long lifespan (45 years)	Open-loop recycling and recovery by third party	Sale
15	8	16	**P&P**	L45	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), long lifespan (45 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
17	12	17	**P&P**	Lf45	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), long functional lifespan insulation modules and finishing panels (45 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services

>>>

TOC

TABLE 6.7 Scorecard of circular design options for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
21	29	18	**BIO**	L45	Bio-based, biodegradable materials, long lifespan (45 years)	Industrial compost-ing by third party	Sale
18	13	19	**P&P**	C+2	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), 2 addition-al reuse cycles	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
19	14	20	**P&P**	C+1	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), 1 addition-al reuse cycle	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
22	18	21	**P&P**	Baseline	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
16	34	22	**BAU**	Baseline	Linear design, lightweight	Open-loop recycling and recovery by third party	Sale
24	23	23	**P&P**	C-1	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), 1 cycle not realised	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
26	33	24	**BIO**	Baseline	Bio-based, biodegradable materials	Industrial compost-ing by third party	Sale
29	11	25	**P2P**	L45	Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts, long lifespan (45 years)	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale

>>>

TABLE 6.7 Scorecard of circular design options for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
25	35	26	**Reclaim**	L15	Non-virgin materials, easy to disassemble, short lifespan (15 years)	Open-loop (local) reuse, recycling and recovery by third parties	Sale and re-sale
27	27	27	**P&P**	C-2	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), 2 cycles not realised	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
30	16	28	**P2P**	C+2	Easy to dis-, and re-as-semble, durable materials, standard sized parts, reuse of parts, 2 additional reuse cycles	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale
23	36	29	**BAU**	L15	Linear design, lightweight, short lifespan (15 years)	Open-loop recycling and recovery by third party	Sale
28	30	30	**P&P**	Lf15	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), short functional lifespan insulation modules and finishing panels (15 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
32	17	31	**P2P**	C+1	Easy to dis-, and re-as-semble, durable materials, standard sized parts, reuse of parts, 1 additional reuse cycle	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale
33	19	32	**P2P**	Baseline	Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale
35	22	33	**P2P**	C-1	Easy to dis-, and re-as-semble, durable materials, standard sized parts, reuse of parts, 1 cycle not realised	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale

>>>

TOC

TABLE 6.7 Scorecard of circular design options for the circular renovation façade

Rank all impact categ.; MFA	Rank GWP; MFA	Rank Shadow costs; MFA	Variant	Scenario	Applied design principles		
					Technical model	Industrial model	Business model
34	37	34	**BIO**	L15	Bio-based, biodegradable materials, short lifespan (15 years)	Industrial composting by third party	Sale
36	28	35	**P2P**	C-2	Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts, 2 cycles not realised	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale
31	32	36	**P&P**	L15	Adjustable, modular design, standard sizes, easy to dis-and re-assemble, optimising lifespans, durable materials, multiple cycles (reuse, recycling, recovery), short lifespan (15 years)	Maintenance, updates, reuse by provider. Recycling and recovery in collaboration with third parties	Lease, or sale with take- or buy-back, mainten. and update services
37	31	37	**P2P**	L15	Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts, short lifespan (15 years)	Reuse by provider or client, recycling and recovery by third parties	Lease, sale-with takeback, or sale and re-sale

6.6.2 Analysis effect of circular design options on assessment results and parameters

The analysis of the effect of singular circular design options on the assessment results is included in Appendix C.13; the analysis of their effect on assessment parameters is provided in Appendix C.14.

Increasing the ESL (technical-functional in parallel) results in consistent savings on all impact categories and mass of flows. It only decreases one parameter: the 'rate' in which materials are replaced and impacts occur. All other circular design options influenced two or more parameters with trade-offs between them. How parameters were affected differed between the kitchen and façade variants, making savings inconsistent. Applying non-virgin material reduces the impacts allocated to the building component. For non-virgin and bio-based, biodegradable materials, the effect on impact/kg, technical lifespans or required mass varied. Adding a direct reuse cycle resulted in consistent impact savings because the added impacts from reuse were outweighed by the lower share of impacts allocated to the component. However, adding higher-impact recycling cycles, could result in less or no savings. It depends if the lower allocation share outweighs the increased impacts of the recycling cycles.

We conclude that most of the circular design options do not lead to a better environmental performance 'by default'. It depends on how they are applied and in which context.

6.6.3 Lessons learned on the environmental design of circular building components

From the analyses above, we induce 8 lessons-learned on the environmental design of circular building components. An overview has been included in Appendix C.15.

(Lesson 1) We found that environmental performance improves most by combining circular design options to narrow, slow and close cycles. **(Lesson 2)** For the kitchen, we found that facilitating partial replacements to increase the overall lifespan of the component, introducing multiple use cycles of parts and materials and applying bio-based or non-virgin materials results in the lowest material use, impacts and waste. For the façade the emphasis seems to slightly shift: the 'best' performing façade combines non-virgin materials with long lifespans and/or multiple reuse cycles on site. Material investments to make the facade modular for facilitating repair, adjustments and reuse of parts were 'larger' than in the kitchen and took longer to pay back. We stress that multiple trade-offs and changes in assumptions can cause tipping points.

First, the environmental performance of components is dependent on the ability to design, determine, guarantee and realise multiple cycles. **(Lesson 3)** When designing circular components all future cycles need to be considered, understanding the building component as a composite of parts and materials **(Lesson 4)**. Additionally, circularity should not only be facilitated in the technical model, but future cycles also need to be organised and incentivised in the supply-chain and business models. **(Lesson 5)** As such, circular building components should be designed 'integrally' and in cocreation with all supply chain partners. **(Lesson 6)** If it seems unlikely that future cycles can be organized or incentivised, it could be more beneficial to develop a circular component which is efficient, lightweight and kept in use as long as possible; low impact, non-virgin, and/or bio-based materials could be applied which are biodegradable or recyclable in an open-loop supply chain.

Circular design options have trade-offs. Their environmental performance depends on how they are applied and in which context. Facilitating repair, adjustments and reuse cycles through modularity, easy de- and remountable joints and applying materials with a longer technical lifespan can both improve environmental performance (the P&P kitchen) or reduce it (P2P façade). A balance should be found between the higher impact of the material/kg for long-life materials, the additional mass needed to make a modular design and the savings due to the longer lifespan and/or increased number of use cycles. Applying renewable or non-virgin material means carefully balancing the environmental impacts per kg, material required initially and replacement rate. **(Lesson 7)** In other words, all design parameters need to be considered in parallel.

Finally, we found that for relatively light-weight components (such as the kitchen and façade) most of the impact is related to the material production and remanufacturing, recycling or waste treatment processes. **(Lesson 8)** Increased transport to realise VRPs has less impact than replacement with a new building component. Although minimizing and optimizing transport remains preferable, all VRPs need not occur locally.

6.7 Discussion and conclusion

The built environment can gradually be made circular by replacing building components with more circular ones. There are many possible design alternatives for circular building components. Industry could benefit from knowledge on what the most circular design options are from an environmental performance perspective. Environmental design guidelines based on LCA and MFA could help bring this knowledge into practice. Existing guidelines are conflicting: some focus on singular circular design options and different assessment methods are applied. Guidelines also differ for different building component which might depend on their Service Life (SL). Therefore, we developed environmental design guidelines by comparing 4 circular design options and a business-as-usual design for two building components: a kitchen (short SL) and renovation façade (medium SL). We compared their environmental performance through Material Flow Analysis (MFA) and Circular Economy Life Cycle Assessment (CE-LCA) including extensive sensitivity analysis. We derived 8 lessons learned from 78 CE-LCAs and MFAs. One of the key lessons found for both components is that the environmental performance improves most by combining circular design options to narrow, slow and close cycles. Cruz Rio et al. (2019), De Wolf (2017), Geldermans et al. (2019) and Malabi Eberhardt et al. (2021) – who also compared multiple circular design options – support our finding: their best performing variants apply combinations of circular design options. Furthermore, we conclude that different building components could benefit from different combinations of circular design options: components with a shorter SL seem to benefit from prioritising circular design options to slow and close future cycles; components with a medium SL benefit more from prioritising reducing resource use now and slowing loops in the future. This guideline is in line with those of Malabi Eberhardt et al. (2021). Their guidelines emphasize – even stronger – reducing production impacts now and prolonging use on site for components with a long lifespan. Likewise, Buyle et al. (2019) and Vandenbroucke et al. (2015) found facilitating future adjustments or reuse was only beneficial for components or parts with a short SL.

We do not claim that our guidelines are entirely novel: the circular design options have been proposed before and parts of our guidelines overlap with existing guidelines. Our contribution lies in having compared the environmental performance of multiple circular design options for different building components. As such we provide a preliminary answer to the knowledge gaps posed in Bocken et al. (2016) and Cambier et al. (2020): what *specific* circular design option(s) would result in the most environmental savings, specifically for *different* circular building components? Applying our guidelines can support designers, policy makers and other decision makers to develop more circular building components in research and practice. Furthermore, our step-by-step approach could support others in comparing environmental performance of different circular design variants and decision-making. However, completing this study revealed additional questions. We stress that our guidelines should be understood as ‘preliminary’ for the following five reasons.

First, even though our guidelines align with existing design guidelines, we still urge utmost care with generalising them. Our guidelines are based on assessments. We identified multiple trade-offs and tipping points depending on how circular design options were applied and what assumptions were made. Circular design options can increase and decrease environmental performance of a building component (see also Buyle et al. (2019) and Vandenbroucke et al. (2015)). Moreover, this study and the precedent studies took place in the context of the Netherlands, Belgium, Denmark and the USA. So, the guidelines might not be valid for all components, for always, everywhere. Experience in circular design could be beneficial to estimate in which design context assumptions align or differ with those underlying our guidelines. Application of our guidelines should be validated case-per-case through additional environmental performance assessments. Also, additional assessments on other circular components, in other contexts and varying individual circular design parameters could further validate and specify our guidelines.

Second, determining what is ‘most’ circular depends on how we define and measure circularity. How the LCA and MFA were executed influenced our findings. Malabi Eberhardt et al. (2020) already showed the effects of using different LCA allocation approaches; the CE-LCA model could benefit from further development (van Stijn et al., 2021). The single-cycle MFA does not match the CE-LCA system boundary. Future research could explore how to embed flows of multiple cycles within the system boundary. Moreover, we focused on the environmental performance based on resource use, impacts and waste. Circular assessment could also include economic, value, and/or social performance assessments. Already, each design variant provides different burdens and benefits on different assessment criteria. Future research on circularity metrics should be equally concerned with prioritization: (e.g.,) environmental performance versus economic, environmental impact reduction versus increasing quality of resource flows, reducing GWP versus ecotoxicity. Priorities might be context specific: circular for whom? Also, they have a temporal perspective. Some circular design options provide more savings over time but what if benefits only arrive in the future? Decisions could be based on average savings or disqualifying criteria could be set. We showed that different decision-making approaches result in different rankings of circular design options. Other assessment methods and decision-making approaches could lead to different guidelines.

Third, our guidelines could be unfeasible in practice. Experts indicated these could increase cost and might not comply with legislation. Testing the presented guidelines in practice cases could validate their feasibility. Also, the construction industry is characterised by its fragmented supply chain where partners temporarily collaborate in a project setting. Our findings suggest that we need to design for and realise multiple future cycles. The experts questioned if such multi-cycle scope is feasible in current practice. This would require developing different ways of collaborating. Alternatively, it implies that in todays practice the transition to the ‘most’ circular built environment is not (yet) feasible.

Fourth, we question whether we can yet speak of a ‘best’ performing variant. Despite significant savings, all variants result in resource use, impacts and waste. Applying circular design options might limit resource use, impacts and waste generation but does not nullify them. Subsequently, we should speak of ‘more’ rather than ‘most’ circular. Additional sufficiency-oriented strategies might be needed to reduce consumption of building components altogether.

Fifth, to support uptake of these guidelines in practice further development can focus on improving their usability by adding more concrete examples and clarification, providing guidelines on individual design parameters and by developing a synthesis tool. The abovementioned opportunities to further develop the environmental design guidelines remain open for further discussion and inquiries. Our study can therefore be seen as an introduction on the environmental design of circular building components rather than a final answer. Nevertheless, the presented guidelines, supported by extensive LCAs and MFAs, make an important contribution to supporting industry in developing more circular building components.

Acknowledgements

This research has been carried out in collaboration with researchers from Aalborg University and Delft University of Technology. The research was part of the research projects "REHAB" (carried out by the Delft University of Technology) and "Circular Kitchen (CIK)" (carried out by Delft University of Technology and Chalmers University of Technology). As such, this research has received funding from the Delft University of Technology, Amsterdam Institute for Advanced Metropolitan Solutions, EIT Climate-KIC and the REHAB project partners.

Addendum: comparing environmental and economic performance

In the research presented in this chapter, we aimed to identify which circular design options result in the most ideal – or desirable – circular building components. In our research, we defined ideal as those components which reduce resource use, environmental impacts and waste generation the most. However, following our definition of circularity, the assessment of desirability should also include the economic performance perspective. Therefore, the results of our environmental performance study were compared to outcomes of an economic performance assessment in research led by Bas Jansen. This research has been published in: 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*(11). https://doi.org/10.1016/j.spc.2022.10.008

To determine which circular design options are the most circular, the environmental and economic performance of multiple circular design variants for a circular kitchen and renovation façade were compared with a 'business-as-usual' (BAU) component. The following variants were compared: the 'bio-kitchen' and 'bio-skin' representing the biological pathway to a CE; the P&P kitchen and P2P façade, representing the technical pathway to a CE; The P&P façade variant as a hybrid between technical and biological cycles. Our results of the environmental performance assessment were compared to an economic performance assessment made using the novel Circular Economy Life Cycle Costing (CE-LCC) model developed in Wouterszoon Jansen, van Stijn, Gruis and van Bortel (2020). The results showed that the biological kitchen and façade consistently performed best in the CE-LCA, but performed second best and worst in the MFA respectively, and consistently performed the worst in the CE-LCC. Technical solutions performed best in the MFA. However, while the technical kitchen performed second best in the CE-LCA and best in the CE-LCC, the technical façade performed worst in the CE-LCA and third best in the CE-LCC. We found that a purposeful, reversible, hybrid application of biological and technical materials yielded the most consistent circular performance overall, and performed 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).

As such, this study showed that use of bio-based, biodegradable materials can reduce the environmental impact, whilst circular design options which slow and close technical loops in the future reduce material consumption. A purposeful combination of both biological and technical materials, which can be separated after use, yielded the best economic and environmental performance. However, we stress that assessment of more building components and other hybrid variants is needed to further validate these findings.

Addendum: development environmental design guidelines circular building structure

The environmental design guidelines presented in this chapter were derived from the assessments of two building components: a kitchen as example of a component with a relatively short lifespan; a renovation façade as example of a component with a medium lifespan. Together with researchers from Aalborg University, we developed additional environmental design guidelines for a building component with a long lifespan: a circular building structure. This research has been published in Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability, 13*(10), 5621. https://doi.org/10.3390/su13105621

In this article, environmental design guidelines for circular building components were developed following the same steps as in our research. First, 4 circular variants for a building structure were synthesized using the circular design tool presented in (van Stijn & Gruis, 2020). The following variants were developed: (1) the eco-efficient variant which reduced material use; (2) the bio-structure which applied bio-based materials; (3) the Design-for-Disassembly structure which consisted of demountable and reusable concrete modules; (4) the open structure which allowed for future adjustments on site. Second, the environmental performance of these variants was compared with a business-as-usual variant through CE-LCA and MFA, including extensive sensitivity analysis. Third, from the analysis of 24 LCAs and MFAs, nine environmental design guidelines were derived. Amongst all, we found that building components with a long lifespan benefit most from combining the following circular design options (in order of preference): resource efficiency, longer use through adaptable design, low-impact biomaterials and – only then – facilitating multiple cycles after end of use. Fourth, the design guidelines were evaluated by 49 experts from academia, industry and government in seven expert sessions. Comparing the findings of this study to the ones presented in this chapter, we found that they align. In this chapter we concluded that components with a medium lifespan benefited more from reducing resource use now and slowing loops on site. The design guidelines for building components with a long lifespan emphasized – even stronger – prioritising reducing resource use now and slowing loops on site.

References

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, *22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Andersen, C. E., Rasmussen, F. N., Habert, G., & Birgisdóttir, H. (2021). Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods. *Frontiers in Built Environment*, *7*, 120. https://doi.org/10.3389/fbuil.2021.729096

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bocken, N. M. P., Farracho, M., Bosworth, R., & Kemp, R. (2014). The front-end of eco-innovation for eco-innovative small and medium sized companies. *Journal of Engineering and Technology Management*, *31*(1), 43–57. https://doi.org/10.1016/j.jengtecman.2013.10.004

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019). Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, *218*, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306

Cambier, C., Galle, W., & De Temmerman, N. (2020). Research and development directions for design support tools for circular building. *Buildings*, *10*(142), 1–20. https://doi.org/10.3390/buildings10080142

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., & Worrell, E. (2019, December 1). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, Vol. 151, p. 104498. https://doi.org/10.1016/j.resconrec.2019.104498

Cruz Rios, F., Grau, D., & Chong, W. K. (2019). Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment. *Waste Management*, *94*, 120–135. https://doi.org/10.1016/j.wasman.2019.05.040

Dahlsrud, A. (2008). How corporate social responsibility is defined: an analysis of 37 definitions. *Corporate Social Responsibility and Environmental Management*, *15*, 1–13. https://doi.org/https://doi.org/10.1002/csr.132

de Koeijer, B., Wever, R. and, & Henseler, J. (2017). Realizing product-packaging combinations in circular systems: shaping the research agenda. *Packaging Technology and Science*, *30*, 443–460.

De Wolf, C. (2017). *Low carbon pathways for structural design: Embodied life cycle impacts of building structures (doctoral dissertation).* Massachusetts Institute of Technology, Cambridge, MA, USA.

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, *140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

De Wolf, Catherine, Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

EN 15804. (2012). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019

EN 15978. (2011). *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method*. Retrieved from European Committee for Standardization (CEN) website: https://infostore.saiglobal.com/preview/is/en/2011/i.s.en15978-2011-lc-2011-11.pdf?sku=1500481

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geldermans, B., Tenpierik, M., & Luscuere, P. (2019). Circular and flexible indoor partitioning-a design conceptualization of innovative materials and value chains. *Buildings*, *9*(9). https://doi.org/10.3390/buildings9090194

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., … Huijbregts, M. A. J. (2001). *Handbook on life cycle assessment: An operational guide to the ISO standards*. Dordrecht: Kluwer Academic Publishers.

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., … Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities*, *1*(1), 504–524. https://doi.org/10.5334/bc.46

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. *Energy and Buildings*, *66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability*, *13*(10), 5621. https://doi.org/10.3390/su13105621

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055
Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027
Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019
Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075
Stichting Bouwkwaliteit. (2019). *Bepalingsmethode milieuprestatie gebouwen en GWW-werken*. Retrieved from http://www.rijksoverheid.nl/documenten-en-publicaties
van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2020). Design guidelines for circular building components based on LCA and MFA: The case of the Circular Kitchen. *IOP Conf. Series: Earth and Environmental Science*, *588*, 1–8. https://doi.org/doi:10.1088/1755-1315/588/4/042045
van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling*, *174*(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105683
van Stijn, A., & Gruis, V. (2020). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment*, *9*(4), 635–653. https://doi.org/10.1108/SASBE-05-2019-0063
Vandenbroucke, M., Galle, W., De Temmerman, N., Debacker, W., & Paduart, A. (2015). Using life cycle assessment to inform decision-making for sustainable buildings. *Buildings*, *5*(2), 536–559. https://doi.org/10.3390/buildings5020536
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, *21*, 1218–1230. https://doi.org/https://doi.org/10.1007/s11367-016-1087-8
Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

7 Towards implementation of circular building components

A longitudinal study on the stakeholder choices in the development of 8 circular building components

This chapter has been submitted in its entirety for publication to Journal of Cleaner Production in 2022.

A van Stijn[1,2], B Wouterszoon Jansen[1,2], V Gruis[1] and G van Bortel[1]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

ABSTRACT The implementation of circular building components can contribute to the transition to a circular economy. There are many possible circular design options for building components. Knowledge on which options are feasible to implement remains limited. Existing feasibility studies do not compare multiple circular design options, building components and/or are based on interviews rather than observation. They list barriers but do not identify their relative importance. In this article we present a longitudinal study on stakeholder choices in 5 development processes of 8 circular building components. The researchers co-created with stakeholders from initiative to market implementation. Through process reflection and analysis, we identified

choices which influenced the perceived feasibility of circular design options within different building components throughout their development. We found that circular design options perceived as feasible vary between different building components. Specific applications and context influence their feasibility. Moreover, perceived feasibility changes throughout the development process.

KEYWORDS Circular Economy (CE), circular design, building components, feasibility, co-creation

7.1 Introduction

The “take-make-use-dispose” economic model contributes to increasing pressure on natural resources, environmental pollution, carbon emissions and waste generation. The building sector is said to consume 40% of resources globally, produces 40% of global waste and 33% of all human-induced emissions (Ness & Xing, 2017). Implementing Circular Economy (CE) principles could support minimizing resource use, environmental impacts and waste in the built environment.

The CE model builds on previously developed schools of thought and there is no commonly-accepted definition (Kirchherr, Reike, & Hekkert, 2017). Geissdoerfer, Savaget, Bocken and Hultink (2017 p. 759) defined 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”. Narrowing loops is to reduce resource use up front. Slowing loops is to lengthen the use of a building, component, part or material. Closing loops is to (re)cycle materials at End of Life (EoL) back to production (Bocken, de Pauw, Bakker, & van der Grinten, 2016). Value Retention Processes (VRPs), such as reduce, reuse, repair, refurbish, and recycle, are used to narrow, slow and close cycles (Reike, Vermeulen, & Witjes, 2018; Bas Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Multiple cycles of the building, component, part and material need to be considered with a systems perspective to keep them cycling at their highest utility and value (Blomsma, Kjaer, Pigosso, McAloone, & Lloyd, 2018; Malabi Eberhardt, van Stijn, Kristensen Stranddorf, Birkved, & Birgisdottir, 2021).

The built environment can gradually be made circular by replacing building components with (more) circular building components during new construction, maintenance and renovation. The design, supply-chain and business model need to be considered integrally to make building components more circular, involving many design parameters. For each parameter, numerous circular design options can be identified (van Stijn & Gruis, 2020). Circular design options such as designing lightweight components or using non-virgin or low-impact materials can support narrowing loops now. Making a modular design, standardizing sizes and applying demountable joints can slow loops through facilitating repair, reuse and adjustments in the future. Applying recyclable or biodegradable materials which can be separated at EoL, can support closing future loops. We distinguish loops which can be realized 'on-site', meaning in the 'same' building where the building component was placed; loops can take place off-site, using the building component, part or material elsewhere. Consequently, different design variants can be developed for circular building components, taking different 'pathways' towards a circular built environment. Previous researchers (e.g., Malabi Eberhardt et al., 2021; van Stijn, Eberhardt, Wouterszoon Jansen, & Meijer, 2022; Wouterszoon Jansen, van Stijn, Eberhardt, Gruis, & van Bortel, 2022) have investigated which circular design options result in a better environmental and economic performance for different building components. They found that combining circular design options purposefully leads to better environmental and economic performances; components with a shorter service life benefit more from design options which slow and close future loops; components with a longer service life benefit more from narrowing loops now and slowing future loops on-site.

However, to actually reduce resource use, environmental impacts and waste, circular building components need to be implemented in practice. Therefore, they ought to be feasible to implement. Designers, policy makers, and other decision-makers in the built environment could benefit from concrete knowledge on which circular design options lead to feasible circular building components.

7.2 Background

Other authors have investigated the feasibility of implementing CE (design) principles in the built environment, including Adams, Osmani, Thorpe and Thornback (2017), Akinade et al. (2020), Azcarate-Aguerre, Klein, Konstantinou and Veerman (2022), Azcarate-Aguerre et al. (2018), Chang and Hsieh (2019), Charef, Ganjian and Emmitt (2021), Condotta and Zatta (2021), Cruz Rios, Grau and Bilec (2021), Galle, Debacker, De Weerdt, Poppe and De Temmerman (2021), Ghisellini, Ripa and Ulgiati (2018), Giorgi et al. (2022), Guerra and Leite (2021), Hjaltadóttir and

Hild (2021), Huang et al. (2018), Kanters (2020), Selman and Gade (2020) and Torgautov et al. (2021). They identified challenges or barriers, and – to a lesser extend – drivers, enablers or opportunities. An overview of these studies is included in Appendix D.1. The majority of studies researched feasibility on construction-industry or building level. Only Azcarate-Aguerre et al. (2022; 2018) focused on façade components. Some studies analyzed the feasibility of a particular circular design option: Azcarate-Aguerre et al. (2022; 2018) looked at façade servitization models; Akinade et al. (2020) focused on Design for Deconstruction. Some authors limited the feasibility scope: Charef et al. (2021) focused on the socio-economic and environmental feasibility whilst Condotta and Zatta (2021) have a policy and regulatory perspective.

Nearly all authors studied completed cases, did a literature review or interviewed stakeholders once. They identified barriers of which an overview is given in Appendix D.2. However, authors did not indicate their relative importance throughout the development process: what specific choices influence how stakeholders perceive the feasibility of circular design options; when are these choices made; who makes them; for what reason are these choices made as such?

Recently, Wouterszoon Jansen, van Stijn, Gruis and van Bortel (2022) compared the perceived feasibility of multiple circular design options for a single building component: a circular kitchen. The researchers were actively involved in the development process. Through a longitudinal study of stakeholder choices during development, they induced five lessons-learned on the development of feasible circular building components. These included lessons on ambition, aesthetics, design scale, participation and focus. However, they noted conclusions could differ for other building components. In this article we built upon their research and present a longitudinal study on the stakeholder choices made in 5 development processes, including 8 circular building components: 1 kitchen, 2 renovation façades, 2 renovation roofs, 1 dwelling extension and 2 climate installation components. Our goal is to identify which specific stakeholder choices throughout the development process led to circular building components that are considered feasible to implement in projects and practice, comparing multiple circular design options and different building components.

7.3 Method

The research was conducted in several steps. In step 1, we developed the circular building components in co-creation with stakeholders. In step 2, we inventoried the choices made by stakeholders in the development process. We systematically and iteratively analyzed these choices and reflected upon the development process to identify which choices influenced the perceived feasibility of circular design options in building components. In step 3, we validated our findings with the core stakeholders involved in the development process.

In Sections 7.3.1-3 of this article, we elaborate on the methods applied per step. In Section 7.4, we describe the developed circular building components. In Section 7.5, we present our findings. We use a selection of the process reflection and analysis of choices to underpin and illustrate our findings. In Section 7.6, we discuss our findings. In Section 7.7, we conclude this article.

7.3.1 Methods in the development of circular building components

The circular building components were developed between 2017 and 2022 (see Table 7.1). They were developed for use by Dutch social housing associations, which are seen as logical initial clients. The Netherlands has high ambitions on achieving circularity and housing associations own one-third of the Dutch housing stock. Housing associations have professional knowledge and a long-term investment perspective, making it a favourable context for implementing circular design options.

TABLE 7.1 Developed components per case and stakeholders involved

Case name	Developed components	Stakeholders	When
1 Circular kitchen Wouterszoon Jansen et al. (2022)	Circular kitchen component including cabinetry and appliances	Researchers: TU Delft[1] Knowledge institute: AMS-institute[1] Kitchen manufacturer 1: Bribus Keukens[1] Appliance manufacturer 1: ATAG[1] Worktop manufacturer 1: Topline Maatwerkbladen BV Contractor 1: Dirkzwager Groep[1] Housing association 1.1: Waterweg Wonen[1] Housing association 1.2: Eigen Haard[1] Housing association 1.3: Ymere[1] Housing association 1.4: Stichting Woonbedrijf SWS[1] Housing association 1.5: Woonstad Rotterdam Housing association 1.6: Portaal[1]	Jan 2017-Dec 2021 108 Co-creation sessions and contact moments
2 Circular skin	Circular renovation concept to improve energy-efficiency of dwellings, including circular renovation façade and -roof components	Researchers: TU Delft[1] Knowledge institute: AMS-institute[1] Contractor 2: Dura Vermeer[1] Housing association 2: Ymere[1] Façade manufacturer 2: Barli Architect 2: Villanova architecten Reclaimed material broker 2: Repurpose Building physics consultant 2: Climatic Design Consult (CDC) Roof manufacturer 2: Linex	Jul 2017-Dec 2021 109 Co-creation sessions and contact moments
3 Circular dwelling extension	Circular dwelling extension component used to enlarge an existing dwelling	Researchers: TU Delft[1] Knowledge institute: AMS-institute[1] Housing association 3: Eigen Haard[1] Contractor 3: ERA Contour[1] Architect 3: DOOR architecten Carpenter 3: Van den Oudenrijn	Mar 2018-Aug 2021 87 co-creation sessions and contact moments
4 Circular NZEB-light[2]	Net-Zero-Energy-Building (NZEB)[2] renovation concept including climate installation, renovation roof and -façade components, optimized on circularity	Researchers: TU Delft[1] Knowledge institute: AMS-institute[1] Housing association 4: Wonion[1] Contractor 4.1: De Variabele Contractor 4.2: Te Mebel Vastgoedonderhoud BV Contractor 4.3: Rudie Jansen Schilders & Totaalonderhoud Contractor 4.4: Lenferink Vastgoedonderhoud Climate-inst. service provider 4.1: Wassink Installatie Climate-inst. service provider 4.2: Klein Poelhuis installatietechniek Climate-inst. service provider 4.3: WSI techniek	Oct 2017-Dec 2021 73 Co-creation sessions and contact moments
5 Circular central heating boiler	Circular central heating system focusing on a circular central heating boiler	Researchers: TU Delft[1] Knowledge institute: AMS-institute[1] Climate systems manufacturer 5: Remeha[1] Climate systems installer 5: Feenstra[1] Housing association 5: Waterweg Wonen[1]	Jan 2017-Sep 2017 9 sessions and contact moments

1 Stakeholders who were committed partners in the research projects Circular Components, CIK and/or REHAB.
2 NZEB renovation stands for the renovation ambition Net Zero Energy Building (in Dutch 'Nul Op de Meter'). In NZEB renovations, a combination of renovation measures is applied to make the dwelling net zero energy, such as an exterior insulation skin, insulating glazing, heat pump and PV panels. These renovations generally require a high upfront investment. 'NZEB-light' refers to making a more cost-efficient NZEB renovation concept.

The components were developed in co-creation sessions organized per case and incidentally cross-case. The researchers played an active role: they initiated collaborations, actively proposed design variants and managed the process. In the later stages, the stakeholders took the lead and the researcher(s) would join to reflect and provide additional knowledge. The researchers documented the choices made during co-creation sessions and other contact moments in summaries. Additionally, presentations, drawings and photos were documented. This documentation formed our dataset.

7.3.2 Methods for the selection, analysis and reflection on stakeholder choices

In our dataset we inventoried the choices made by stakeholders. We understood ‘choice’ as a *consideration of* or *decision between* one or multiple possibilities. We included only choices about the design of the circular building component itself and excluded choices on how to arrange the circular development process. Our dataset contained thousands of choices. To identify which stakeholder choices influenced the feasibility of circular design options, we applied two parallel processes: ‘zooming out’ and ‘zooming in’ (see Figure 7.1).

When zooming out, we took a figurative step back and reflected upon the development process of each case. ‘Zooming out’ is based on the theories of ‘reflection on action’ by Schon (1983) and the Action Research Cycle by Carr and Kemmis (1986). We made a chronological description of the development process in text and images, summarizing the design proposals, stakeholder choices and their effects in different developmental phases. Summarizing allowed us to reflect upon the whole process; it helped us to identify choices which were ‘key’ in developing feasible circular building components. When zooming in, we analyzed singular stakeholder choices in depth. For each of the cases we analyzed the key choices. For case 1 and 2, 600 and 1282 additional choices were analyzed in detail, respectively.

TOC

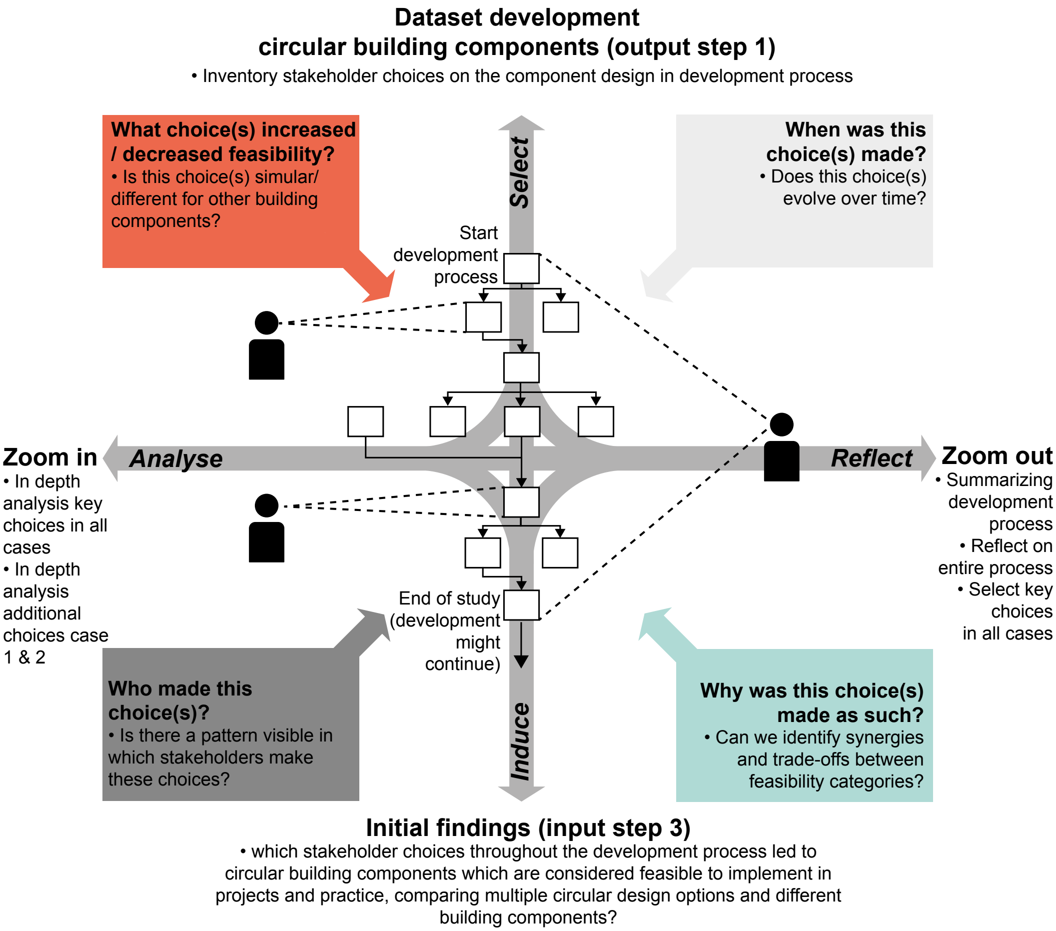


FIG. 7.1 Approach for reflection and analysis of stakeholder choices to induce findings

Our analysis and reflection focused on four questions: (1) *What* choice increased or decreased the perceived feasibility of circular design options in building components; (2) *when* was this choice made? We distinguished the following (iterative) phases of product innovation and building project stages: (2a) 'initiative', (2b) 'proof of principle' including sketch designs and variant studies, (2c) 'proof-of-concept' including preliminary or definitive designs, (2d) 'prototype' including mock-ups, (2e) 'demonstrator' including a test-home, pilots or first project and (2f) market implementation, meaning upscaling and application in multiple projects. (3) *Who* made this choice? Most choices were made by the entire co-creation team. But, sometimes a particular stakeholder had a more dominant role. (4) *Why* was this choice made as such? From the stakeholder's reasoning we can identify why they

TOC

perceive a choice is or is not feasible to implement in projects and practice. We categorized their reasoning by using the categories of feasibility found during our literature study (see Table 7.2). Focusing on these 4 questions, we looked for patterns: we investigated if choices influencing feasibility are similar between components; if choices evolve over time; if it is always the same stakeholder(s) which makes choices; if we can find reoccurring synergies and trade-offs between feasibility categories.

From the analysis and reflection, we induced initial findings. We emphasize that we went 'back and forth' between selecting choices, analyzing them, process reflection and inducing findings.

TABLE 7.2 Analytic frame to categorize stakeholder reasoning on the feasibility of circular building components

Perceived feasibility category	Subcategories *(if applicable)*	Applied definition
Environmental	**Material**	Stakeholders perceive a choice leads to more or less material flows.
	Impact	Stakeholders perceive a choice leads to more or less environmental impact.
Financial & economic	**Initial costs & profit**	Stakeholders perceive a choice leads to more or less initial costs or profits.
	Life cycle costs	Stakeholders perceive a choice leads to more or less costs over the component's lifecycle due to (e.g.,) maintenance, longer lifespan, 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 the clients' needs and the perceived fit of the component in the product portfolio and activities of other stakeholders.
Societal & cultural		Stakeholders perceive a choice leads to a more or less fit with current (building) culture or societal norms.
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 stakeholders including what they believe and trust.
Governmental & regulatory		Stakeholders perceive a choice leads to more or less compliance to governmental policy or regulations.
Technical		Stakeholders perceive a choice for a component can or cannot be technically realized.
Functional & aesthetic		Stakeholders perceive a choice increases or decreases the aesthetic or functional properties of the component.
Supply chain		Stakeholders perceive a choice can or cannot be realized within the supply chain.
Information, skills & educational		Stakeholders perceive a choice increases or decreases the need for additional information, skills or education.

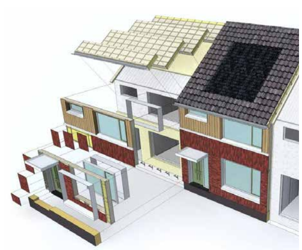
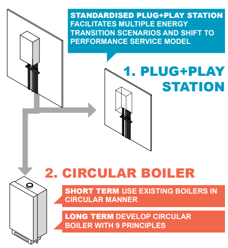
7.3.3 Methods validation

We validated the key choices and initial findings of cases 2, 3 and 4 in two workshops with the stakeholders committed to the research project. In the first workshop, stakeholders identified key choices in the design of the building components. Prior to the second workshop, the stakeholders were asked individually to list key choices influencing the building component's feasibility. The researchers used both inputs to refine their list of key choices and initial findings. These were presented during the second workshop and refined until consensus was achieved between the stakeholders. Case 1 was validated in one stakeholder workshop by Wouterszoon Jansen et al. (2022). As case 5 was finalized in 2017, no validation with stakeholders occurred.

7.4 Description of the developed circular building components

Table 7.3 provides an overview of the developed circular building components. It summarizes the main circular design options applied during their development, indicates which development stages were completed and shows one representative image. A summary of the development process per case and resulting designs has been included in Appendices D.3-7.

TABLE 7.3 Overview of developed circular building components

Case name	Circular design options applied during development process	Stages of development	Representative image developed component
1 Circular kitchen	Modular kitchen - Modular design separating parts based on lifespan, de- and remountable connections - Facilitating future repair, adjustments and reuse on- and off-site - Applying long-life materials	Initiative Proof of principle Proof of concept Prototype 1 Demonstrators 8 (Ongoing) market implementation	
2 Circular skin	Modular energy renovation concept including circular façade and roof components - Modular design and de- and remountable connections - Facilitating future repair and adjustments on site - Applying reclaimed materials	Initiative Proof of principle Prototypes façade 11 Proof of concept Prototype façade 1 (Ongoing) demonstrator	
3 Circular dwelling extension	Standardized circular modules to extend dwellings - Modular design and de- and remountable connections - Facilitating future repair, adjustments and reuse on- and off-site - Applying reclaimed materials	Initiative Proof of principle Proof of concept Demonstrators 2 Demonstrators 42 (Ongoing) market implementation	
4 Circular NZEB-light	Resource and cost-efficient NZEB renovation concept including roof, façade and climate installation components - Using less materials - Using lower-impact, non-virgin and bio-based materials	Initiative Proof of principle (Re)initiative Proof of concept Demonstrators 22 (Re)initiative Proof of concept Demonstrators 2 (Ongoing) market implementation	
5 Circular central heating boiler	Circular climate system focusing on a circular boiler - Modular climate system adjustable to future heating scenarios - Modular boiler facilitating future repair, adjustments and reuse of the boiler and parts	Initiative Proof of principle	

TOC

7.5 Findings on the development of feasible circular building components

In this section, our findings are presented, supported by a selection of the process reflection and analysis of choices. The analysis of all key choices per case has been included in Appendices D.8-12.

7.5.1 Feasibility during comparison of sketch design variants: stacking circular ambitions high

During the initiative phase, 5 collaborations were set-up around the development of one or more building components. The proof of principle stage followed: the researcher developed several sketch designs for each circular building component, including a technical design, supply-chain and business model. Their feasibility was evaluated by the stakeholders. They selected one or a combination of design variants to develop into a concept design. In Table 7.4 we summarized the main circular design options applied per design variant and the main reasoning of stakeholders on their feasibility (see Appendices D.3-7 for the full comparison). We highlighted the selected variant(s) in green.

The stakeholders did not choose for variants which they considered unfeasible within the current technical state of the art and would require decades of technical innovation. The variants '3D kitchen' and '3D boiler', were considered too futuristic. The required 3D-printing technology is not yet feasible on this scale and at competitive costs. Additionally, plastics are not yet infinitely recyclable. Similarly, the 'Green boiler' was considered unfeasible as the manufacturer stated that current bio-based materials would not deliver the required performance in terms of gas safety, water safety and energy performance. Developing such materials would take decades. The stakeholders also discarded variants they thought were not innovative and circular enough. The variant based on recycling and making optimizations of current designs were found too close to the business-as-usual (BAU).

In most cases, combinations of variants were selected for further development. Combining circular design options was found most circular and offered opportunities for merging value propositions associated with individual options. As a basis, a modular variant was chosen to keep building components, parts and materials

TOC

cycling at their highest utility in the future. A modular variant also had scaling potential and facilitates mass-production; it offered customization options to fit different clients' demands and projects-specific requirements. In cases 1-4, modularity was combined with using reclaimed or bio-based materials to reduce environmental impacts now. It also made the component look and feel circular to stakeholders. This was considered conditional to ensure the acceptance of the design's circularity with clients and the market. Notably, the exception lies in the NZEB-light case in which the contractors decided that a combination of variants was most circular. However, the contractors also decided that it was the role of the product manufacturers to design a new circular building component – not theirs. Instead, they chose to make a more circular NZEB renovation solution combining existing products and materials. They focused on finding the most circular products and materials: can reused materials be used; is there a bio-based or low-impact alternative?

In hindsight, it is remarkable that most stakeholders chose these combinations of variants. Although combinations stack circular benefits, they also stacked the stakeholders' concerns on feasibility. At this stage, the high circular ambition might have several reasons. The researchers proposed ambitious circular designs and might have nudged the discussion towards this direction. Selecting the most circular variant may have been appealing as most stakeholders wanted to be (seen as) innovative. Stakeholders might have trusted that feasibility concerns could be solved or knew that concessions would need to be made later on. Finally, the stakeholders might have considered the research and development project as a safe learning environment and emphasized ambition above feasibility in this stage of the development process.

TABLE 7.4 Main reasoning of stakeholders on the feasibility of design variants

Loops & circular design options applied per design variant	Design variants circular kitchen	Design variants circular skin	Design variants circular dwelling extension	Design variants NZEB-light	Design variants circular central heating boiler
Narrowing loops now through using reclaimed materials -Applying non-virgin materials -Sale to client -Waste is separated and discarded at EoL	**Reclaim! kitchen** *-During initiative a choice was made to develop new kitchens rather than reuse existing kitchens. So, this variant was initially not explored*	**Reclaim! skin** +Reduction of resource use and impacts now +Feasible in short term (close to BAU) +Lower initial costs -Unknown quality materials (no guarantees) -Limited availability -Increased maintenance costs	**Reclaim extension** +Reduction of resource use and impacts now +Little transport for reuse on site +Feel-good factor +Technically not far from BAU -Not innovative, can be more circular -Unknown quality materials (no guarantees) -Limited availability -Does not slow and close loops	**Reclaim! skin** +Reduction of resource use and impacts now +Little transport for reuse on site +Fits project scope +Start mater. bank -Reclaimed mater. can have high production impacts -Current buildings not designed for disassembly -Harvesting during multiple moments -Low costs virgin materials -Limited availability at regular retailer -Materials are at end of lifespan	N/A
Narrowing loops now and closing future loops through biological materials -Applying bio-based, biodegradable materials -Sale to client -Industrial composting at EoL	**Green kitchen** +Promising as it is close to BAU +Clear circular design -Composing is not right EoL for long-lasting bio-based materials: we should keep bio-based materials at highest utility and value	**BIO skin** +Reduction of resource use and impacts now +Feel-good factor +Fits with current supply chain -Limited bio-based alternatives and availability -Higher initial costs; no savings in life cycle costs -Certification lacking (non-proven materials) -High land-use for growing materials	**BIO extension** +Reduction of resource use and impacts now +Limited energy needed for VRP +Feel-good factor +Fits market trend -Limited durability: leads to poor image neighbourhood -Higher initial costs; no end value -Difficult to ensure bio-based use and maintenance over time -High land-use for growing materials	**BIO skin** +Reduction of resource use and impacts now +Renewable +Living comfort (breathing buildings) ±Some bio-material is certified -Limited bio-based alternatives -Limited availability at regular retailer -No reuse potential -High land-use for growing materials -Origin materials unknown and far -Higher maintenance costs -Doubt if user accepts bio-based	**Green boiler** +Partially possible technically -Not technically possible now; requires years of innovation -Bio-based materials cannot comply to energy efficiency, gas and drinking-water safety regulations -No added value in business model -Greenwashing if bio-based materials are used as disposable resources.

>>>

TOC

TABLE 7.4 Main reasoning of stakeholders on the feasibility of design variants

Loops & circular design options applied per design variant	Design variants circular kitchen	Design variants circular skin	Design variants circular dwelling extension	Design variants NZEB-light	Design variants circular central heating boiler
Closing future loops through recycling -Applying highly recyclable mono-materials -Demountable connection between different materials	N/A	**Recycle me! skin** +Closes loops in future +Close to BAU -Does not reduce impacts now -Large scale needed for recycling loop	**Recycle me! extension** +Familiar aesthetic +Close to BAU -Shorter loops are better -Uncertainty benefit: benefit lies in distant future -No feel-good factor	**Recycle me! skin** +For regions with reducing number of inhabitants -Transport, storage and degradation of recycling materials	N/A
Narrowing loops and slowing loops through optimization of BAU -Optimizing lifespans of parts to increase overall lifespan of the component -Optimize materials to varying lifespans	**Basic +** + Simple design + Customization options + User awareness of cost = take better care of their kitchen + Close to BAU - Is based on 'old' and 'linear' values - Difficult to find a standard-size that fits all dwellings	N/A	N/A	N/A	N/A
Slowing future loops through reusing building products in the future -Modularity on product level -Standard sizes -Long-life materials -De- and remountable joints between products	N/A	**Product-2-product skin** + Slows future cycles (reuse) + Certainty of market for reuse - Does not reduce impacts now - Hard to apply standard-sizes in renovation - Disassembly not a current supply chain activity -Database needed	**Product-2-product extension** + Slows future cycles (reuse) + Stimulates selling less virgin materials + Familiar aesthetic + Vandal proof - No adjustments - Uncertainty benefit: benefit lies in distant future (no guarantee) - No feel-good factor	**Product-2-product skin** + Slows future cycles (reuse) + Easy to realize and implement when reuse occurs on large scale - Limited aesthetic choices - Not all parts cannot be reused (some degrade too much)	N/A

>>>

TOC

TABLE 7.4 Main reasoning of stakeholders on the feasibility of design variants

Loops & circular design options applied per design variant	Design variants circular kitchen	Design variants circular skin	Design variants circular dwelling extension	Design variants NZEB-light	Design variants circular central heating boiler
Slowing and closing future loops through repair, reuse, refurbishing and recycling of component, parts and materials -Modularity on component and part levels -Standard sizes -Long-life materials -De- and remount-able joints between components and parts	**Plug-and-play kitchen** + Most of the kitchen has a long life due to partial replacements + Flexibility and customiz. options of style and layout + Lower life cycle costs + Versatile and ideal design + Fast adjustments possible	**Plug-and-play skin** + Slows and closes future cycles + Flexibility and customiz. options + Industrialization opportunities - Does not reduce impacts now - Uncertain reuse potential large modules - Benefit lies in distant future (no guarantee) - Very hard to apply large standard-sizes in renovation - Too innovative, big change to BAU - Technical chal-lenges (air-tight-ness, rigidity)	**Plug-and-play extension** + Slows and closes future cycles + Flexibility and customiz. options + Scaling potential - Making standard modules requires support full sector - Large standard modules might become outdated: uncertain reuse potential - Requires closed-loop supply chain - Benefit lies in distant future: guarantees needed -Clash different measurement systems can lead to material loss	**Plug-and-play skin** + Slows and closes future cycles + Partial replacem. + There are existing examples + Potential for mass production = lower costs, more speed, less errors - Limits design freedom - Does not slow loops on part level - Very hard to apply large standard-sizes in renovation - Joints cause thermal perform. challenges - Making standard modules requires support full sector - Misalignment incentives supply chain - Likeliness that modules are exchanged is low	**Plug-and-play climate system** + Slows and closes future cycles +Close to BAU + Flexibility to adjust system per home + Future proof + Unburdens client + Long-term relationship client, manuf. and provider ± Fast mainte-nance - Developments too fast for stan-dardiz. - Uncertainty use gas boiler in future **CE-boiler** + Future-proof + Close to BAU + Long-term relationship client, manuf. and provider ± More mainten. - Bigger boilers - Demount. joints may malfunction - Uncertainty use gas boiler in future
Narrowing loops during use phase -Reduce use-relat-ed material flows through smart design of building component and including addition-al appliances	**All CE kitchen** + Takes all flows of kitchen into account - Too many parts - Complex - Appliances are not included in social housing kitchen	N/A	N/A	N/A	N/A

>>>

TOC

TABLE 7.4 Main reasoning of stakeholders on the feasibility of design variants

Loops & circular design options applied per design variant	Design variants circular kitchen	Design variants circular skin	Design variants circular dwelling extension	Design variants NZEB-light	Design variants circular central heating boiler
Slowing and closing future loops through facilitating repair, and adjustments by recycling materials -Locally 3D printing entire components or parts -(Infinitely) recyclable materials	**3D Kitchen** + Dream scenario - Not yet technically possible	N/A	N/A	N/A	**3D boiler** + Flexibility to adjust to future requirem. + Easy to print less common parts - Too futuristic - Diversification of models - Cannot comply to energy-efficiency, gas and drinking-water safety regulations

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'; stakeholder reasoning which decreased the perceived feasibility is indicated with a '-'.

7.5.2 From principle to realizable design: purposeful application of circular design options

As the selected variants were iteratively developed to proof of concepts, prototypes, and demonstrators, more and more detailed choices on circular design options were made.

7.5.2.1 Feasibility synergies and trade-offs of circular design options

Analyzing detailed choices, we found that all circular design options have trade-offs on at least one feasibility category (see Tables 7.5). Often, the initial trade-off initiates a cascade of trade-offs on the feasibility categories: *value proposition*, *initial costs*, *life-cycle cost*, *risk* and/or *governmental and regulatory*. For example, in the circular skin case, the joints between modular brick-strip façade panels proved difficult to make neatly. This reduced the *aesthetic feasibility* which – in turn – is an important *value proposition* for the client and user. Furthermore, the design required approval from the municipal 'aesthetics committee' (i.e., *governmental and regulatory feasibility*). To make the joints look good cost more time from the manufacturer, which in turn increased the *initial costs*.

TABLE 7.5 Feasibility trade-offs per circular design option

Trade-offs			Case	Examples from cases
Reducing material use	Value proposition	Initial costs	Case 2	Factory prefabrication of components can bring additional value to the client: it can increase the component quality, reduce duration of on-site work and increase the reuse value. To prevent damage and make the component stable for transport and installation, much more material is required. For example, in a prefabricated façade, a timber-frame construction is needed instead of just mounting insulation boards on the façade; a high percentage of timber in the façade increases the thickness of insulation needed to reach the desired insulation value; boards on the inside of the façade panel are needed to protect the vapor-barrier foil.
	Technical	Initial costs	Case 2	Aluminium anchors can be used to install façade panels instead of façade-wide aluminium frames, reducing impactful resource use. However, the process to align panels during installation would take much longer, increasing costs.
	Functional & aesthetic	Value proposition; risk; govern. & regulatory	Case 3	The choice to replace the existing dwelling extension with a higher quality extension resulted in more material use. A sober shed-like extension would have minimized the materials required. However, this would have been harder to get approved by the tenants during their (legal) vote on the renovation plans.
Applying non-virgin materials	Technical	Initial costs; risk	Case 2-3	Applying non-virgin materials posed problems for the machinery used during manufacturing, due to larger size tolerances. This increased stops in production and brought on the risk of breaking machines. Both can be costly.
		Risk; psychological	Case 1	Materials with recycled content might have less durability and might not be moisture proof.
	Risk	Value proposition; life cycle costs	Case 2	There are no technical information sheets informing us about the performance of a non-virgin material; there is no guarantee how long it will last. Clients want the contractor and manufacturers to provide this guarantee; what if it might need replacement sooner than expected; this could incur costs.
		N/A	Case 2	Using reclaimed floor beams in the roof brings a larger risk [than in façade panels]: if one of the beams is not strong enough to support the load, the roof might collapse.
		N/A	Case 3	The recycled cotton insulation took the manufacturer longer to purchase.
	Initial costs	Risk	Case 3	Using non-virgin materials from the project required a lot more communication and planning from the contractor. It is a project in itself to harvest them beforehand. The manufacturer had to put in more time to clean and treat the materials. This increased the costs; it also required more and a different type of laborers. Getting enough labour capacity is currently challenging.
	Functional & aesthetic	Value proposition	Case 3	Not all the reclaimed wood used in the façade of the extension was the same. Some batches had more wear; some batches had grooves whilst others had a smooth surface. So, visually, the façade finishing varied. In was a concern if this would be acceptable to the client and users.

>>>

TOC

TABLE 7.5 Feasibility trade-offs per circular design option

Trade-offs			Case	Examples from cases
Applying bio-based materials	Initial costs	N/A	Case 1-4	Bio-based materials often cost more up-front.
	Psychological	Life cycle costs;	Case 1-5	Stakeholders doubt the performance of bio-based materials over time. Bio-based materials might require more maintenance over time, which is costly.
	Technical	Risk (availability)	Case 1, 3, 4	Not all materials can be successfully replaced with low-impact bio-based materials. Like glass, there is no bio-based alternative.
		Governmental & regulatory; initial costs	Case 1, 5	The boiler has gas-safety, water-safety and energy-efficiency requirements. The kitchen has hygienic requirements and needs to be vapor-proof. Applying bio-based materials will not fulfil these specifications. It could cost years to develop and apply these materials.
		Life cycle costs	Case 2	Brick façade finishing ages well in the Dutch climate and requires less maintenance compared to bio-based materials.
	Risk (availability)	N/A	Case 4	Bio-based materials are not commonly available at the regular building-material wholesaler.
	User behavior; risk	N/A	Case 3	If we apply bio-based materials, there is a chance that tenants and maintenance partners of the housing association might paint over them using non bio-based paint.
	Cultural	Aesth. & funct.; value prop.; govern. & regulatory	Case 2	Brick façade finishing is part of the Dutch architectural culture. Residents often consider this pretty; brick-finishing is often required by housing associations and conditional to get a permit. Even though bio-based materials could offer a low-impact alternative, it is not always accepted.
Design for easy maintenance	Life-cycle costs	N/A	Case 2	If we use a wooden window frame, it will always be repairable and adjustable in the future. We can repair rot and place triple glazing later on. This is different for a plastic or aluminium window frame. If it is scratched or discoloured, we have to replace everything. Comparing total cost of ownership over 20 years, plastic wins. But 40 years might be a different story.
Standardization & modular design	Technical	Initial cost	Case 2, 4	Standard-sized modules or panels do not fit to varying measurements in existing dwellings; smaller modules are difficult and costly to produce and install.
		Material; impact	Case 3	Using standard-sized modules of 60 cm resulted in a slightly larger extension than the existing one. Ultimately, a new foundation was needed which resulted in additional costs and environmental impact from more material use.
	Governmental & regulatory	N/A	Case 2	Standard-sized façade modules fitted best onto the existing façade if they crossed over the boundary line of the dwelling by a bit. The stakeholders considered that this might cause issues in ownership, maintenance and fire regulations.
	Value proposition	Initial costs; risk; psychological	Case 2; Case 3; Case 4	The stakeholders doubted the value of making standard-sized modules to facilitate future adjustments and reuse of modules in other dwellings: how likely is this happening? Doubtful the client will want to invest more for this now. The standard-sized modular system we develop will probably not become the sector standard.

>>>

TOC

TABLE 7.5 Feasibility trade-offs per circular design option

Trade-offs			Case	Examples from cases
Modular design	Technical	Initial cost; risk	Case 1	Manufacturer cannot produce the modular design on existing production line. A new production line is costly and investment is a large risk.
	Functional & aesthetic	Value proposition	Case 1	In modular countertops dirt will get stuck between the joints. This is unhygienic. Small modules with rubbers in between might not be visually attractive to users.
		Init. costs; value prop.; govern. & regulatory	Case 2	The joints between the brick-strip façade panels were hard to get right aesthetically. It also took more time to make. The façade has to look good to satisfy the client and user and to get approval from the municipal 'aesthetics committee'.
	Initial costs	N/A	Case 2	Brick strip panels are more expensive than gluing the brick strips directly onto the façade.
Demountable joints	Initial costs	N/A	Case 2 Case 4	Demountable connections (e.g., aluminium-frame system or click-bricks) are more expensive than non-demountable connections.
Long life materials	Initial costs	N/A	Case 1 Case 3	Long-life materials (e.g., aluminium frames, ceramic tiles, plywood) are more expensive than materials with shorter lifespans.

Circular design options also have synergies on feasibility categories (see Table 7.6). First, reducing (virgin-)material use can decrease *initial costs* and supply-related *risks*. Second, a modular design can initially cost more. However, by facilitating partial replacements the whole building component can last longer, decreasing *life cycle costs*. Modularity can make the building component customizable to different user needs and specific projects, and make the component flexible over time. So, a modular building component can increase the *value proposition* and reduce *risks* to users and clients. When a modular solution can be applied in multiple projects it also increases the perceived feasibility as it increases the potential *profits*. In some applications, circular design options became feasible by smartly combining them (see the last example in Table 7.6).

Comparing trade-offs and synergies, we find that a circular design option can be feasible in one application and context and not in another. A façade component consisting of standard-sized modules was found feasible for new buildings but not for renovation. In the NZEB-light case, the stakeholders investigated using different reclaimed materials. They found reclaimed rooftiles are currently marketed to period-property renovations and have a high *initial cost.* Whereas *initials costs* decreased when contractors reused the existing façade panels. They flipped the used side to the inside of the façade, saving both labor and materials costs. In the circular extension case, the stakeholders concluded that using reclaimed materials decreased the *initial costs* for purchasing materials. However, reclaiming wood required a lot of labor. This can nullify savings on new materials or even increase total *initial costs.*

TABLE 7.6 Feasibility synergies per circular design option

Synergies			Case	Examples from cases
Reducing material use	Initial costs	N/A	Case 4	The stakeholders considered if each intervention was really needed. As such they saved on materials and initial costs in the façade, roof and climate installation.
Applying non-virgin materials	Initial costs	N/A	Case 3-4	Reusing façade panels or windows directly from the renovation project saved material costs.
	Functional & aesthetic	Value prop-osition;	Case 3	After cleaning the reclaimed wood used for the façade finishing, it had the visual quality desired by the client.
	Risk (avail-ability)	Initial costs	Case 3	The price of virgin wood increased during the project. By using reclaimed wood we were more secure of getting materials and getting them for a reasonable price.
			Case 2	Using reclaimed materials now increases demand for reclaimed materials. This likely also creates a larger market for reclaimed materials in the future increasing their availability and reducing costs by making it more mainstream.
Modular design	Functional & aesthetic	Value prop-osition; govern-mental & regulatory	Case 1-3	Making the kitchen, façade, roof and dwelling extension modular facilitates functional and aesthetic customization to tenant wishes; it increases flexibility to adjust (part of) building components in the future. This can also increase the tenant satisfaction and increase the percentage of tenants who vote for the renovation plans.
	Life cycle costs	N/A	Case 1-3, 5	By making the building component modular, we can change part of the component to repair or adjust the component without having to change the whole. This saves costs in the future.
		Value prop-osition	Case 1-3	Making a modular design which facilitates repair allows only changing that part which needs repair, instead of replacing the whole component; this saves costs in the future. The housing associations considered repairability a desirable value proposition.
	Value prop-osition	Initial costs	Case 2-4	A modular design is considered scalable as it can be adjusted to different projects. A scalable design is attractive for the stakehold-ers to develop as the cost of innovation can be spread over multiple projects; there is potential that the design gets cheaper once it is upscaled.
	Technical	Initial costs; risk	Case 3	The modular design of the dwelling extension was feasible to produce in the current production process as it already allowed production in limited numbers.
		Risk; value proposition	Case 2	The renovation façade was separated into an insulation layer and façade finishing layer. The ventilated cavity in between layers reduces the risk of deterioration of the façade finishing. It also brings value to clients allowing easy repair and customization.
	Initial costs; risk	Value prop-osition	Case 2	By making a modular NZEB-renovation concept, the intial costs of renovation can be spread over different investment cycli. It helps the housing association to reach their energy ambitions over time; it increases the flexibility in their management of the housing stock.
			Case 5	A modular climate installation helps the housing association to prepare for the energy transition and increases their flexibility to adjust to multiple scenarios.

>>>

TOC

TABLE 7.6 Feasibility synergies per circular design option

Synergies			Case	Examples from cases
Standardization & modular design	Value proposition	Initial costs	Case 2-3	Standardized, modular components have potential to be mass-produced off-site. This can increase the quality of the component, reduce the duration of on-site work, nuisance for residents and lower initial costs.
	Life-cycle costs	N/A	Case 1, 3	Making a modular, standard-sized, building component facilitates future reuse of the component or its parts, increasing their end-value.
	Technical	N/A	Case 3	Standard-sizes for the dwelling extension will always fit as the new extension does not have to comply to the existing measurements of the dwelling.
Reducing material use; modular design; applying non-virgin and bio-based materials	Technical	Functional & aesthetic; value proposition; governmental & regulatory	Case 2	For the façade, a modular timber-frame design was made in which bio-based and non-virgin materials were used. The resulting design was thick and heavy. This reduced the amount of light incidence (which is important to the residents) and made an additional foundation likely required (increasing costs). The team then designed an alternative variant in which the timber-frame panel was made thinner and the new cavity between the new and existing façade would be filled with reclaimed insulation flakes. Because the cavity insulation was uninterrupted, it insulated better, reducing the total mass of material required. Additionally, making the panel thinner allowed the use of reused wooden floor beams (which are only available up to a certain size).

However, due to the COVID pandemic, virgin-wood prices steeply rose between budget approval and realization. So, in this context, using reclaimed wood decreased the *risk* of price fluctuation and guaranteed timely supply.

The perceived feasibility of circular design options also evolved over time. A circular design option may be considered unfeasible early in the development. During the design of the circular dwelling extension, most stakeholders were concerned that using reclaimed wood as façade finishing would not look good (i.e., *aesthetic* feasibility). During harvesting, the manufacturer found some batches of wood had more wear; some batches had grooves whilst others had a smooth surface. The project team was concerned that the patina and variation would not be acceptable to the client and users. The manufacturer tried different cleaning procedures and together a satisfactory treatment was selected and tested in the prototype. The client was happy with the final result: the cleaned wood 'looked pretty' and variations were not considered a problem. Vice, versa, circular design options which were initially considered feasible can cause more problems than anticipated. In the circular skin case, the team had decided that reclaimed, wooden floor-beams could be used in the timber-frame panel of the façade. During production of a mock-up, the manufacturer found that it was not *technically* feasible to process reused wood on their machines due to the (possible) presence of metals and the larger size tolerances. It could increase stops in production which would increase *initial costs.* Moreover, there was the *risk* of breaking costly machinery. Ultimately, the choice was made to use virgin wood in both the roof and façade components.

In some cases, the application of circular design options required several iterations before a feasible design variant was found. In the circular skin case, the concept design suggested standard-sized façade modules to facilitate future adjustments and reuse. A 30-cm grid was proposed. During further development, standard-sizes were found not *technically* feasible – specifically in the context of renovation. The stakeholders could not find any standard size which would fit over the varying measurements present in existing façades. Furthermore, the manufacturer and contractor concluded that such small modules are difficult to produce and install (i.e., *technical* feasibility*),* making them costly *(*i.e., high *initial costs*). Floor-to-floor and wall-to-wall modules – which could be adjusted by moving the timber frames – were considered feasible. We also found feasibility trade-offs and synergies when combining circular design options. These are elaborated on in Appendix D.13.

7.5.3 From dream to reality: collision between circular ideals and business as usual

In nearly all cases a shift occurred in the development process. Initially, ambitious combinations of design variants were selected, stacking circular design options to optimally narrow, slow and close loops (see Section 7.5.1). In nearly all cases, towards realization the number of circular design options decreased or their application changed. The change was made to increase the feasibility of the building component. Table 7.7 shows the shift per case and lists the main reasoning of stakeholders.

When this shift occurred – and why – varies. In the circular kitchen and circular skin cases, the shift came later in the innovation process. The first kitchen prototypes and demonstrator were made custom built. A new machine park was needed to mass-produce the circular kitchen's frame and mill the slots for the demountable joints: a *risky* investment with *high initial costs*. Stakeholders had initially chosen for the frame construction as it – efficiently – accommodated customization and future adjustments of the kitchen. After realizing the demonstrators, the value proposition was tested again with the housing associations. Repairability was found more important than customization and future adjustments. A demountable panel construction is sufficient to facilitate repair. So, the kitchen manufacturer returned

TABLE 7.7 Reasoning for shift in circular component designs

	Case 1 Circular kitchen	Case 2 Circular skin	Case 3 Circular dwelling extension	Case 4 Circular NZEB	Case 5 Circular boiler
Circular design options applied in 'ambitious' circular design	Modular design: long-life frames to which infill and finishing parts could be attached facilitating repair and adjustments; kitchen as a service model	NZEB renovation concept with modular façade and roof facilitating likely adjustments and reuse; reclaimed and biobased materials are applied	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	NZEB with exterior façade and roof insulation applying more circular materials and demountable con-nections	Modular boiler facilitating repair and updates
Circular design options towards realisation	Kitchen construct-ed with demount-able panels facilitating repair	Modular renovation focusing initially on a modular roof facilitating likely adjustments; applying reclaimed materials where possible	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	(Re)placing less components to achieve NZEB- per-formance; applying more circular materials	Development of circular boiler was halted after proof-of-principle phase
Most important reason for change	1. Frame of the kitchen not man-ufacturable on current machine park 2. Repairability is more important to the client than (future) adjust-ability	1. Reclaimed materials difficult to process on machines & no technical performance guarantee 2. High initial costs façade 3. More demand for roof renovations 4. Step-by-step renovation supports client to realise energy transition	N/A	1. Component development not role of con-tractors leading to focus on narrowing and closing loops now 2. Initial costs too high for NZEB with exterior skin renovation 3. Less building components are (re)placed saving costs and new material use	1. Miss-alignment incentives: costs for applying circular design options lie with manufacturer and benefits with service provider 2. Uncertainty of future use natural gas for heating

to a paneled construction which was easier to produce on their production line. In the circular skin, the shift occurred after developing a detailed technical design. The design was tested in a focus group with housing associations. The clients indicated that placing an exterior renovation façade is not common due to high *initial costs*. And, the circular façade was estimated to be even more expensive. However, exterior roof renovations were needed and more affordable. The housing associations also wanted the contractors to support them in determining the right steps to realize the energy transition in their dwellings. As such the contractor refocused on developing a modular renovation solution consisting of circular building components that can support the energy transition step-by-step, spreading *initial costs*. Their focus shifted to developing building components which could be applied in a first step (i.e., the roof).

On the other hand, in the circular boiler and NZEB-light case, the shift came earlier in the process. In the NZEB-light case, the shift occurred when the design for the first project – which proposed an exterior skin renovation – was found to have too high *initial costs*. In the second project, the stakeholders aimed for a more affordable NZEB-renovation by reducing the interventions as much as possible, simultaneously reducing material use. The roof was insulated internally using flax and low-impact rooftiles were placed; no exterior renovation façade was applied; existing radiators and plumbing were kept. These roof, façade and climate installation designs saved significantly on material use and environmental impacts. In the boiler case, a decision by the government on the continuation of gas use for domestic heating was expected. This created a *risky* innovation climate for a gas boiler. The climate-installation service provider and manufacturer were hesitant to commit to further development. Furthermore, the *value proposition* of the design created a split incentive between stakeholders. Making the boiler and parts easy to repair, refurbish and adjust would ask investments by the manufacturer and would likely reduce their future sales of boilers. Whereas, increased service revenue would benefit the service provider.

In the abovementioned cases, the environmental performance of the design was considered conditional in the (very) beginning. However, the following feasibility categories took priority over the course of the development process: alignment to current production techniques and processes in the *supply-chain*, alignment to the *value proposition* desired by the client and added value to the other stakeholders, reducing or spreading out *initial costs* and reducing *risks*. The abovementioned shifts were needed to fit the circular technical design into the BAU supply-chain and business models. The design of more circular supply-chain and business models was subject in several workshops. However, without a completed circular technical design the discussions on new supply-chain and business models remained hypothetical and abstract. So, the main focus remained on the technical design. Generally, these shifts reduced the number of circular design options or changed how they were applied. However, changing how circular design options are applied did not necessarily result in a design which is perceived as less circular by stakeholders. For example, in the circular skin case, reusing façade modules in other dwellings was not seen as a likely future scenario. Consequently, the removal of circular design options which facilitated universal reuse of the façades modules was not perceived as less circular.

Notably, there is one case in which no shift occurred. In the circular dwelling extension case, the initially selected circular design options were found feasible to realize for multiple reasons. The circular extension was only a small part of the entire renovation project. So even if circular design options increased the *initial costs*, it was relatively small in the scope of the larger budget, limiting the *risk*. Furthermore, the housing association treated circular design options as conditional throughout the development. Likely, because to them learning about circularity was always the underlying *value proposition*. Moreover, the design of the extension could be realized following the existing *supply-chain* processes and was prefabricated within the existing production line of the carpenter's factory. Factory-prefabrication of façades, roofs and extensions already focusses on the production of limited numbers of building components uniquely tailored to a specific project. This made it easier to scale up the circular design.

Finally, we note that the observed shift was also influenced by choices and circumstances not related to circular design options. Both in the case of the circular skin and NZEB-light, too high *initial costs* caused the shifts in the building components' development. However, these were primarily costs for reaching NZEB ambitions, not to apply circular design options. For the boiler, the policy climate on stopping the use of gas inhibited partner commitment to further develop the building component.

7.5.4 Feasibility of circular design options varies per component

We found similarities and differences between the circular design options which are perceived as feasible from one building component to the next. These can be attributed to the varying characteristics of different building component and their development context.

We found that characteristics of some building components are more akin to products whilst others are more akin to buildings. Figure 7.2 shows the characteristics we associate with both types of components.

For product-like components, more circular design options were perceived as feasible. These included design options to narrow loops now, slow future cycles both on- and off-site and (to some extent) close future cycles. Product-like components often had a shorter service-life and lower complexity (e.g., less technical specifications, number of parts and stakeholders involved). They also could be applied in multiple contexts and mass-produced. This allowed the supply chain to think and work in continuous processes, creating a favorable context to optimize all loops. However, as seen in the circular kitchen case, the feasibility of circular design options decreased if costly and risky changes were needed to existing production lines.

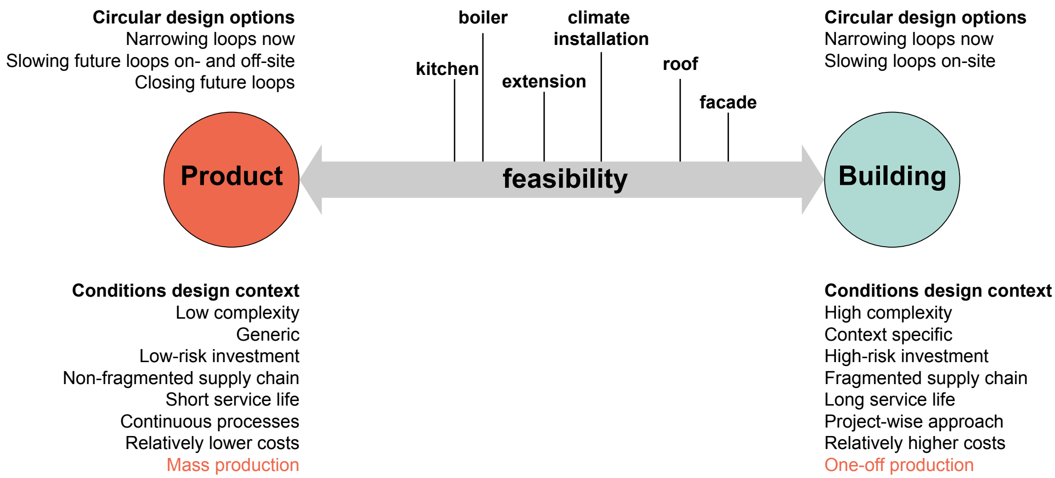


FIG. 7.2 Feasible circular design options per building-component type

In building components with more building-like characteristics, less circular design options were perceived as feasible. Options remained limited to narrowing loops now and facilitating likely repairs and adjustments on-site. Building-like components often required a larger investment making them riskier to innovate. They were designed for a specific context; they were prefabricated or handmade as one-offs or in limited numbers. The supply chain (usually) gathered temporarily, operating in a project setting and dissolved after realization. Loops had to be optimized on a case-per-case basis which required time and made it difficult to optimize all loops. Furthermore, there was less incentive to optimize future loops, especially uncertain loops and those occurring in the long-term. However, as we saw in the circular extension case, a circular building-like component was easier to realize using existing manufacturing facilities and building processes.

We note that building components can also share characteristics with both types (e.g., climate installations are highly complex products). In Figure 7.2 we categorize the developed building components on a gradient between these types. For example, in the circular skin case, standard-sized façade modules which can be reused elsewhere in the future were not considered of added value. Whereas, for the roof,

TOC

standard-sized modules allowing adjustments and reuse off-site were considered feasible. The only difference between these components lies in the context-specificity of the façade. Standard-sized modules did not fit over the varying sizes in existing façades. A roof has less unique features making standardization and modularization easier.

The circular design options considered as feasible varied – even in the development of the same components. In the case of the circular skin and NZEB-light, the goal was initially the same: to develop a circular NZEB renovation including façade and roof components. Yet, the final solution varied. How the innovation process was organized plays a role. Each case had a different model of collaboration in which different supply chain partners were involved to a different extent. Furthermore, one case innovated within the scope of a renovation project and one developed the building component for a (single) pilot. The individuals involved in the innovation also made a difference. What they perceived as feasible depended on their interests, perspective and past-experience. For example, individuals without circular knowledge and experience joining the team required to be updated on the basics of circular design and reasoning behind previous design choices.

7.6 Discussion

We do not claim that all our findings are novel. Many of the barriers we found in our literature review (Appendix D.2) can be recognized throughout our study (e.g., see Table 7.8). The novelty of our findings lay in the following points: first, we showed what specific choices, by which stakeholder, at what moment in the development and for what reason, influenced the perceived feasibility of different circular design options in different building components. Second, we showed that many circular design options are already feasible to implement. So, barriers perceived by stakeholders can already be overcome. Third, we showed that not all circular design options are yet feasible to implement.

TABLE 7.8 Key reasons influencing the perceived feasibility of circular design options, related barriers and suggestions on how to overcome them

Circular design options and building components most affected	Key reasons influencing feasibility circular building components	Most related barriers from the literature review (see Appendix D.2)	Possible directions to help overcome barriers
Circular design options to slow and close future loops; all building components, but building-like components in particular	Fit needed between the circular technical model and the supply-chain and business models	– Circular design options and materials require higher initial investment – Unclear or unviable financial and/or business case – Additional time, labour and cost to design and construct circular design options – Fragmented supply chain leads to misalignment incentives – Lack of financial incentive to design for slowing and closing loops – New equipment or factories are needed to manufacture circular design – Temporary, project-wise building processes hinder finding synergies between supply-chain partners – More collaboration needed between supply chain partners [to optimize loops]	– Application of Life Cycle Costing techniques to develop a circular business case – Develop replicable circular solutions rather than making unique circular projects – Implement feasible circular design options ('low-hanging fruit') now, and optimize step by step. – Develop long-term collaborations which foster continuous processes to optimize all loops – Involve stakeholders needed to realize all cycles and collaborate in value network
All circular design options; all building components	Stakeholders needed to consider circularity as a priority throughout the development process	– Lack of awareness, consideration or concern of CE amongst stakeholders	– Increase feeling of urgency – Develop common goals
All circular design options; all building components	High complexity makes it difficult to optimize all loops	– Complexity of buildings	– Simplify the circular technical, supply-chain and business model
All circular design options; all building components	(Previous) experience of stakeholders influences what is perceived as feasible	– Lack of CE knowledge – Lack of CE experience and skills by stakeholders	– Increase circular (design) knowledge, skills and experience in stakeholders

In Table 7.8, we present 4 'key' reasons which influenced the perceived feasibility of circular design options in our study. We identified the related barriers found in our literature study and we proposed suggestions on how these barriers might be overcome. These barriers and possible solutions require further research and innovation to make more circular building components feasible to implement in the future and, as such, speed up the transition to a circular built environment.

Even though our findings are based on multiple cases, we are careful to claim their generalizability. Our findings remain based on situational knowledge and might not be true for all, for always, everywhere. The building components were all developed in the Dutch social housing context. What is perceived as feasible might differ for other countries or sectors. The building components were developed with particular stakeholders and individuals. Some stakeholders had no or limited involvement, such as tenants, material suppliers, part manufacturers, maintenance companies and recyclers. If other stakeholders and individuals would have been involved, they might have considered different choices feasible. Furthermore, what was considered feasible 5 years ago already differs from what is perceived as feasible today, and likely differs from what will be feasible tomorrow. For example, if the abovementioned barriers can be overcome, more circular design options might become feasible.

We also do not claim that our findings are exhaustive. Other viewpoints might reveal more findings in our dataset. Furthermore, our findings are based on analyzing the choices made. If different possibilities would have been considered, it might have changed our findings. Furthermore, our study investigated what choices in the *design* of the circular building component influenced its feasibility. We already explained that choices on how to arrange the *development process* can also influence what is perceived as feasible. Future research is needed on what makes an effective innovation process for feasible circular building components.

7.7 Conclusion

The built environment can gradually be made circular by replacing building components with (more) circular ones during new construction, maintenance and renovation. There are many circular design options for building components. Designers, policymakers, and other decision-makers in the built environment could benefit from concrete knowledge on which circular design options lead to circular building components that are feasible to implement in projects and practice. Existing studies on the feasibility of CE (design) options focused on building or construction-industry level and did not compare multiple components and/or included multiple circular design options. Furthermore, they were based on interviews, studies of completed cases or literature review. They provided lists of barriers, yet, they did not identify their relative importance throughout the development process. Therefore, in this article, we presented a longitudinal study on the stakeholder choices in 5 development processes of 8 circular building components. The researchers actively co-created with stakeholders in the development process from initiative to market implementation and documented the choices made by stakeholders. Through iterative process reflection and analysis, we identified the choices which influenced the perceived feasibility of different circular design options within different building components throughout their development. We validated our findings with the stakeholders involved in the development process.

We found that different combinations of circular design options were perceived as more feasible for different circular building components. For components with product-like characteristics, circular design options which narrow loops now can be combined with options which slow and close likely future cycles. Circular design options which narrow loops now and slow likely future loops on-site were found more feasible in building-like components. However, the particular application and context influenced the perceived feasibility of circular design options. We identified numerous trade-offs and synergies between circular design options and their perceived feasibility depending on the application(context). Furthermore, what is perceived as feasible changes throughout the development process: more ambitious combinations of circular design options were perceived feasible initially. Throughout the process, compromises on circular design options were made to achieve a fit with the current business and supply-chain model. The circular design options need to pose an acceptable *risk*, fit the *value proposition* desired by the client and other stakeholders, lead to acceptable *initial costs*, and align to current production techniques and processes in the *supply-chain*. Finally, the perceived feasibility of circular design options was also dependent on the development process, the stakeholders and individuals involved and by choices not related to circular design options.

Through our study we identified what specific choices, by which stakeholder, at what moment in the development and for what reason, influenced the perceived feasibility of different circular design options in different building components. We showed that many circular design options are already feasible to implement, but not all. We discussed that four 'key' reasons significantly influenced the feasibility of circular design options in our study: (1) fit of the technical model to the supply-chain and business model, (2) priority given to circularity, (3) high-complexity and (4) previous experience of stakeholders. Future research and innovation can help overcome the related barriers and might make the implementation of more circular building components feasible.

To conclude, we cannot provide any final answer on which circular design options are most feasible for building components. However, the concrete knowledge presented in this article can already support industry stakeholders in developing more feasible circular building components, and through their implementation, speed up the transition towards a circular built environment.

Acknowledgements

We want to thank all the stakeholders who collaborated with us in this research for their expertise and dedication. Without all your hard work and enthusiasm, this research would never have been possible. The research was part of the research projects "Circular Components" and "REHAB" (carried out by the Delft University of Technology) and "Circular Kitchen (CIK)" (carried out by Delft University of Technology and Chalmers University of Technology). As such, this research has received funding from the Delft University of Technology, Amsterdam Institute for Advanced Metropolitan Solutions, EIT Climate-KIC and the REHAB project partners.

Addendum: In depth on the development of the circular kitchen

In this chapter we researched the perceived feasibility of circular design options in multiple building components. In a research led by Bas Jansen, we reflected on the case of the circular kitchen in depth. This research has been described in: Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. A. (2022). Cooking up a circular kitchen: a longitudinal study of stakeholder choices in the development of a circular building component. *Sustainability*, 14, 15761. https://doi.org/10.3390/su142315761.

This research applied the same method as used in this chapter. Through iterative analysis and reflection of the stakeholder choices throughout the development process of the circular kitchen, we identified five lessons-learned for developing feasible, circular building components. These have been summarised in Table 7.9. The findings were validated in a workshop with the involved stakeholders.

TABLE 7.9 Lessons learned for developing feasible, circular building components

Topic	Lesson learned
Ambition	Prioritize implementing feasible circular options now, and improve to the most circular options over time.
Aesthetics	Adjust the aesthetics to satisfy as many clients/users as possible.
Design scale	Design at a large and smaller scale simultaneously, or even to design the details first.
Participation	Involve people with the optimal amount of influence, technical knowledge, and focus on the project, and make sure all the relevant stakeholders are represented.
Focus	To completely redevelop the physical design, supply chain model, and business model integrally takes up valuable time and resources.

Although these lessons-learned should neither be considered exhaustive nor applicable in all contexts, they give an insight into the decisions that could help the development of future components. These lesson-learned align with the findings presented in this chapter. In this chapter, we also recommended to apply low-hanging fruit first. We also found that aesthetics of circular building components needed to comply to the desired value proposition to ensure their feasibility. The last 3 lessons-learned provide recommendations on how to arrange the *innovation process* in order to develop feasible circular building components. Reflection upon the innovation process was explicitly not the scope in this chapter. However, we still recognize these findings in our study. For example, in this chapter, we also concluded that the stakeholders and individuals participating in the development process influenced the perceived feasibility of circular design options. We also saw that the stakeholders focused their time on developing a circular technical design, taking considerable expertise and time. This left little capacity available to innovate the supply-chain and business model simultaneously. We recommend – again – that future research is needed on what makes an effective innovation process for feasible circular building components.

References

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Akinade, O., Oyedele, L., Oyedele, A., Davila Delgado, J. M., Bilal, M., Akanbi, L., … Owolabi, H. (2020). Design for deconstruction using a circular economy approach: barriers and strategies for improvement. *Production Planning and Control*, *31*(10), 829–840. https://doi.org/10.1080/09537287.2019.1695006

Azcarate-Aguerre, Juan F., Klein, T., Konstantinou, T., & Veerman, M. (2022). Façades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope. *Applied Sciences (Switzerland)*, *12*(3). https://doi.org/10.3390/app12031267

Azcarate-Aguerre, Juan Francisco, Klein, T., den Heijer, A., Vrijhoef, R., Ploeger, H., & Prins, M. (2018). Façade Leasing: Drivers and barriers to the delivery of integrated Façades-as-a-Service. *Real Estate Research Quarterly*, *17*(3), 11–22.

Blomsma, F., Kjaer, L., Pigosso, D., McAloone, T., & Lloyd, S. (2018). Exploring circular strategy combinations - Towards understanding the role of PSS. *Procedia CIRP*, *69*(May), 752–757. https://doi.org/10.1016/j.procir.2017.11.129

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Carr, W., & Kemmis, S. (1986). *Becoming critical*. Lewes: Falmer Press.

Chang, Y. T., & Hsieh, S. H. (2019). A Preliminary Case Study on Circular Economy in Taiwan’s Construction. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 12069. https://doi.org/10.1088/1755-1315/225/1/012069

Charef, R., Ganjian, E., & Emmitt, S. (2021). Socio-economic and environmental barriers for a holistic asset lifecycle approach to achieve circular economy: A pattern-matching method. *Technological Forecasting and Social Change*, *170*(April), 120798. https://doi.org/10.1016/j.techfore.2021.120798

Condotta, M., & Zatta, E. (2021). Reuse of building elements in the architectural practice and the European regulatory context: Inconsistencies and possible improvements. *Journal of Cleaner Production*, *318*(January 2020), 128413. https://doi.org/10.1016/j.jclepro.2021.128413

Cruz Rios, F., Grau, D., & Bilec, M. (2021). Barriers and Enablers to Circular Building Design in the US: An Empirical Study. *Journal of Construction Engineering and Management*, *147*(10), 04021117. https://doi.org/10.1061/(asce)co.1943-7862.0002109

Galle, W., Debacker, W., De Weerdt, Y., Poppe, J., & De Temmerman, N. (2021). Can Circularity Make Housing Affordable Again? Preliminary Lessons About a Construction Experiment in Flanders Taking a Systems Perspective. *Smart Innovation, Systems and Technologies*, *203*, 151–160. https://doi.org/10.1007/978-981-15-8783-2_12

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five european countries policies and practices. *Journal of Cleaner Production*, *336*(January), 130395. https://doi.org/10.1016/j.jclepro.2022.130395

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/J.RESCONREC.2021.105617

Hjaltadóttir, R. E., & Hild, P. (2021). Circular Economy in the building industry European policy and local practices. *European Planning Studies*, *29*(12), 2226–2251. https://doi.org/10.1080/09654313.2021.1904838

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., & Ren, J. (2018). Construction and demolition waste management in China through the 3R principle. *Resources, Conservation and Recycling*, *129*, 36–44. https://doi.org/10.1016/J.RESCONREC.2017.09.029

Kanters, J. (2020). Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector. *Buildings*, *10*(77), 1–16. https://doi.org/10.3390/buildings10040077

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*(September), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability*, *13*(10), 5621. https://doi.org/10.3390/su13105621

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Schon, D. A. (1983). *The reflective practitioner: How professionals think in action.* London: Maurice Temple Smith Ltd.

Selman, A. D., & Gade, A. N. (2020). Barriers of incorporating circular economy in building design in a Danish context. *ARCOM 2020 - Association of Researchers in Construction Management, 36th Annual Conference 2020 - Proceedings*, 665–674.

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, *11*(11). https://doi.org/10.3390/buildings11110501

van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2022). *Design guidelines for circular building components based on LCA and MFA*. https://doi.org/10.1088/1755-1315/588/4/042045 van Stijn, A., & Gruis, V. (2020). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment*, *9*(4), 635–653. https://doi.org/10.1108/SASBE-05-2019-0063

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

Wouterszoon Jansen, Bas, van Stijn, A., Eberhardt, L. C. M., 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

Wouterszoon Jansen, Bas, van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

8 Conclusions

A van Stijn[1,2]

[1] Department of Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands.
[2] Amsterdam Institute for Advanced Metropolitan Solutions (AMS), Amsterdam, The Netherlands.

8.1 Introduction

The building industry plays a crucial role 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. The built environment can be made more circular by replacing building components with more circular ones during new construction, renovation and maintenance. Many circular design options are imaginable for building components. Knowledge is needed on what are the most 'ideal' – or desirable – circular building components. These are the components that reduce resource use, environmental impacts and waste generation the most. Furthermore, we need circular building components which are 'feasible' – or likely – to be implemented within projects and practice.

In this dissertation, we aimed to develop 'ideal' and 'feasible' circular building components. The components were developed focusing on renovation of Dutch, low-rise, post-war, social housing. We identified four key questions in the design(ing) of circular building components which underpinned the research goals of the four studies in this dissertation. In our first study, we investigated how to design circular building components. We developed a tool to support the integral design of circular building components. In the second study, we explored how to select the most circular building component. We developed a Life Cycle Assessment model suitable for assessing the environmental impacts of circular building components. In the third study, we explored what are the most ideal – or desirable – circular building components. We compared the environmental performance of multiple circular design options for multiple building components and derived environmental design guidelines. In the fourth study, we investigated what circular building components are feasible – or likely – to be implemented within current renovation projects and practice. We identified which stakeholder choices throughout the development of 8 circular building components led to feasible, circular building components, comparing multiple circular design options and different building components.

This concluding chapter starts by summarizing the key findings on the 4 research goals, which have been addressed in Chapters 4-7. In Section 8.3, we share our conclusions on our main goal: the development of 'ideal' and 'feasible' circular building components. In Section 8.4, we discuss the scientific contribution of our dissertation and provide recommendations for future research. In Section 8.5. we share the practice implications. By reflecting further upon our conclusions, we recommend how practice can develop and implement more circular building components.

8.2 Summary conclusions per research goal

In this section, we summarize the key results, conclusions, scientific contribution and practice implications for each of the four research goals.

8.2.1 Conclusions research goal 1: the development of a design tool for circular building components

Through systematic analysis of 36 existing circular design frameworks, we identified circular design parameters and options. Through combining these, we constructed a design tool for circular building components: the Circular Building Components (CBC) generator. The CBC-generator provides a technical, industrial and business model matrix containing relevant circular design parameters (see Table 8.1) and options. Each matrix is complemented with a design table and canvas. Different variants for circular building components can be synthesized by filling the canvasses whilst systematically "mixing and matching" design options. To illustrate and test the CBC-generator, the tool was applied in the development of an example component 'the circular kitchen' and tested in a student workshop.

TABLE 8.1 Circular design parameters included in the CBC-generator

Technical model parameters	Industrial model parameters	Business model parameters
Materials	Key partners	Key partners
Energy	Key activities	Customer segments
System architecture	Key resources	Supply chain relations
Amount	Transport	Cost structure
Time(s)	Process energy	Revenue streams
Lifecycle stage		Value propositions
Circular design strategy		Key resources
		Channels
		Take back systems
		Adoption factors

Whilst existing circular design frameworks are not comprehensive, nor specifically developed for building components, the CBC-generator provides all the circular design parameters which should be considered; second, it provides extensive circular design options per parameter; and third, through its canvases it supports systematic synthesis of design options to a cohesive and comprehensive circular design. As such, the CBC-generator could support industry in developing circular building components. However, the CBC-generator only provides support in the synthesis and not yet in the assessment of the most circular design. Furthermore, the developed tool does not show which are logical combinations of design options.

In collaboration with the researchers from Chalmers University of Technology and Delft University of Technology, the CBC-generator was further developed to a card-based game: 'Cards for Circularity' (Dokter, van Stijn, Thuvander, & Rahe, 2020). The card-game was tested in multiple workshops with students and practice to investigate how circular knowledge is adopted in design practice (see Figure 8.1)

FIG. 8.1 Cards for circularity used during the design of a circular supply-chain model

8.2.2 Conclusions research goal 2: the development of a Circular Economy Life Cycle Assessment model for building components

We elaborated on key principles of CE in building components and analysed how existing LCA standards deal with these; we identified gaps and defined requirements for LCA of circular building components. Following, we developed the Circular Economy Life Cycle Assessment (CE-LCA) model for building components. This model builds on existing LCA standards applied in the building sector: EN 15804 (2012) and EN 15978 (2011). In CE-LCA, building components are considered as a composite of parts and materials with different and multiple use cycles; the system boundary is extended to include all cycles (see Figure 8.2). Impacts can be divided between use cycles using various allocation approaches. For short-cycling parts and materials, when reuse and recycling avoids primary production of the same 'thing', applying the same processes, an equal distribution of impacts between all cycles could be reasonable (and simple). The Circular Economy Linearly Degressive (CE LD) allocation approach of Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved and Birgisdottir (2020) is suitable when the use and value of materials is not the same in each cycle. The CE-LCA model has been tested in the case of the Circular Kitchen and evaluated with 44 experts.

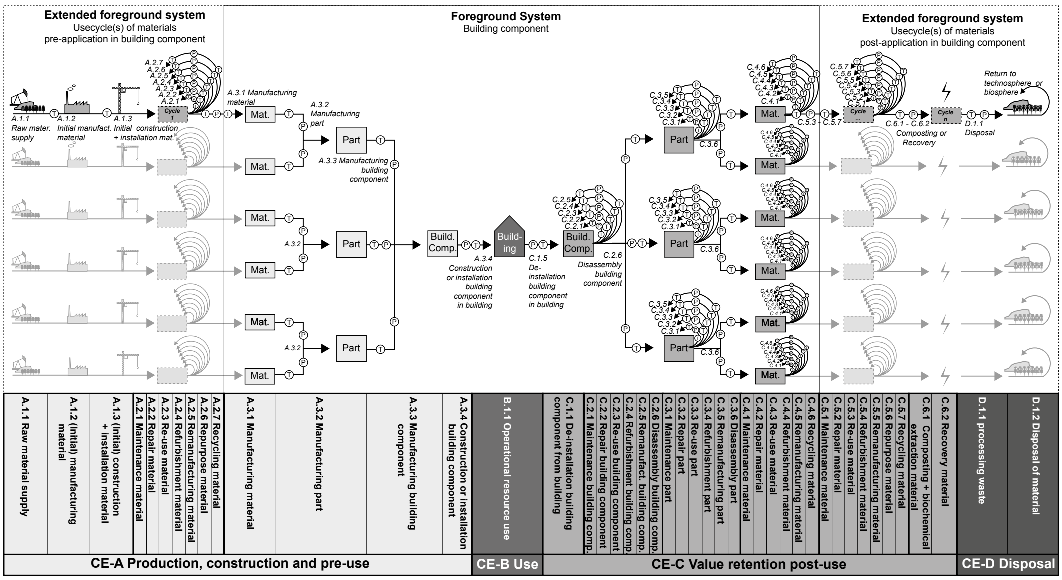


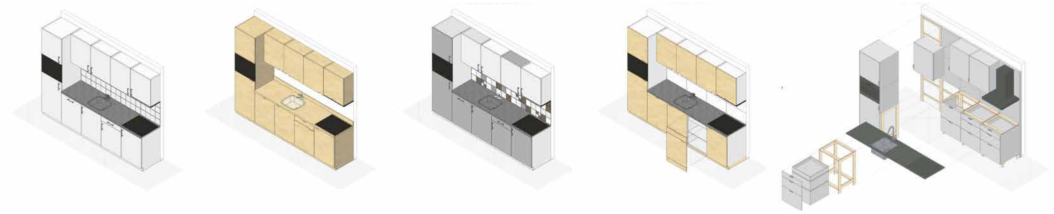
FIG. 8.2 Circular Economy Life Cycle Inventory model (see Figure 5.3 for larger image)

TOC

We found the CE-LCA approach suitable in ex-ante assessments in which scenarios are explored to identify which circular building components have the best environmental performance. The scientific contribution of this study lay in the development of a model to apply LCA on circular building components with multiple cycles and our discussion of the methodological questions which arose. Similarly to Allacker, Mathieux, Pennington and Pant (2017), De Wolf, Hoxha and Fivet (2020) and Malabi Eberhardt et al. (2020) we found that all cycles of the building component system are difficult to determine in a practice setting; this increased uncertainty, makes the approach sensitive to mis-use and could hinder reducing environmental impacts both in the short and long term. However, we suggested that applying CE-LCA, or equivalent multi-cycling LCA, is still necessary to transition to a 'truly' circular built environment. Without including all cycles in the assessment, we cannot get an accurate overview of the burdens and benefits of circularity. At the same time, the CE-LCA model could be developed further to reduce uncertainty, improve accuracy, usability and fair-use. Additionally, users should exercise awareness of the value and limitations of CE-LCA and use the model appropriately.

8.2.3 Conclusions research goal 3: the development of environmental design guidelines for circular building components

We developed environmental design guidelines by comparing the environmental performance of 4 circular design variants and a business-as-usual design for two building components: a kitchen (as an example component with a relatively short lifespan) and a renovation façade (medium lifespan). See Figure 8.3 for the design variants and the applied circular design options per variant.



Variant 1
Business as Usual
Linear design

Variant 2
BIO
Bio-based, biodegradable materials, short lifespan

Variant 3
Reclaim!
Non-virgin materials, short lifespan

Variant 4
LIFE+
Optimising lifespans, long-life materials, bio-based, biodegradable materials

Variant 5
Plug-and-play
Adjustable modular design, optimising lifespans, durable materials, facilitating repair, adjustments, reuse and recycling

Variant 6
Business as Usual
Linear design

Variant 7
BIO
Bio-based, biodegradable materials, short lifespan

Variant 8
Reclaim!
Non-virgin materials, easy to disassemble

Variant 9
Product-2-product
Easy to dis-, and re-assemble, durable materials, standard sized parts, reuse of parts

Variant 10
Plug-and-play
Adjustable modular design, standard sizes, optimising lifespans, durable materials, facilitating repair, adjustments, reuse and recycling

FIG. 8.3 Design variants for the circular kitchen and renovation façade

We compared the environmental performance of the design variants through Material Flow Analysis (MFA) and Circular Economy Life Cycle Assessment (CE-LCA) including extensive sensitivity analysis. From the analysis of 78 CE-LCAs and MFAs, we derived 8 lessons (see Table 8.2). Amongst these, we found that in both building components, the environmental performance improves most by combining circular design options to narrow, slow and close cycles. Furthermore, we concluded that different building components benefit from different combinations of circular design options: components with shorter lifespans benefit more from slowing and closing future cycles; components with a medium lifespan benefit more from reducing resource use now and slowing loops on site. We validated the environmental design guidelines with 49 experts and by comparing our guidelines to existing environmental design guidelines.

TOC

TABLE 8.2 List of lessons learned on environmental design of circular building components

1.	**Consider not only the present placement and maintenance, but consider all future cycles.** During design, do not only consider the initial placement of the building component in the project. Also consider (re) placements in the future and consider what happens after the component, parts and materials leave the building.
2.	**Consider building components as a composite of parts and materials with different and multiple use cycles.** Determine the expected lifespan, usecycle(s), and Value Retention Processes (VRPs) for each material and part applied in the building component.
3.	**Combine circular design options to facilitate multiple Value Retention Processes as opposed to focussing on a single one.** Environmental performance often improves most by combining circular design options to narrow, slow and close cycles simultaneously, instead of focusing on one.
4.	**(Re)design the technical, industrial and business model integrally and in co-creation with involved stakeholders.** The environmental performance of building components is dependent on the ability to design, determine, guarantee and realise multiple cycles.
5.	**Consider all circular design parameters in interrelation with each other.** Trade-offs and changes in assumptions can cause tipping points. Applying circular design options could also result in higher environmental impacts and resource use. For example, substituting linear materials with more circular materials (e.g., biological, low-impact, reused or recycled) does not necessarily result in a more circular building component.
6.	**Prioritize impacts from material production and recycling processes over transport.** Most of the environmental impacts are linked to material production and recycling: increasing transport to realise VRPs is preferable over placing a new building component. Unless the component is bulky or heavy, then, transport should be kept to a minimum.
7.	**Components with a shorter service life benefit from prioritizing circular design options which slow and close future cycles, and components with a longer service life from reducing resources now and slowing loops on site.** • **For a circular building component with a short service life (e.g., circular kitchen) the better environmentally performing design could apply the following circular design options:** o The component is designed (as efficient as possible) modular, facilitating partial replacements such as technical repairs and functional and aesthetic updates to keep the whole building component in use longer; o The building component applies materials with long technical lifespans; o Multiple cycles are facilitated, organised and incentivised after EoU to prolong the period of use (e.g., repair, reuse, and refurbishment), and after EoL to close the loop (e.g., biodegrading, recycling); o Non-virgin materials, and/or bio-based, biodegradable materials are applied if they show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials. • **For a circular building component with a medium service life (e.g., circular façade) the better environmentally performing design could apply the following circular design options:** o Non-virgin materials, and/or bio-based, biodegradable materials are applied which show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials; o The building component applies materials with long technical lifespans; o If it can be done efficiently, the component is designed modular, facilitating partial replacement such as technical repairs and functional and aesthetic updates to keep the whole building component in use longer; o Multiple cycles are facilitated, organised and incentivised after EoU to prolong the period of use (e.g., repair, reuse, and refurbishment), and after EoL to close the loop (e.g., biodegrading, recycling);
8.	**If future cycles cannot be organised in the supply chain and incentivised in the business model, then the best environmentally performing design for a circular building component with a short or medium service life (e.g., circular kitchen and façade) applies the following circular design options:** o The building component is an efficient, lightweight solution; o The building component is kept in use as long as possible; o Non-virgin materials, and/or bio-based, biodegradable materials are applied if they show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials; o The building component applies materials which are open-loop biodegradable or recyclable.

We do not claim that our guidelines are entirely novel: the circular design options have been proposed before and parts of our guidelines overlapped with existing guidelines. Our contribution lay in having compared the environmental performance of multiple circular design options for different building components. As such we provided a preliminary answer to what *specific* circular design option(s) would result in the most environmental savings, for different *specific* circular building components. Applying our guidelines can support designers, policy makers and other decision makers to develop more circular building components. Yet, we stress that our guidelines should be understood as 'preliminary' as applying circular design options does not always result in a better environmental performance. Tipping-points were identified based on the number of use cycles, lifespans and the assessment methods applied. Further development and testing of the presented guidelines in practice could improve their generalizability and validate their usability in practice.

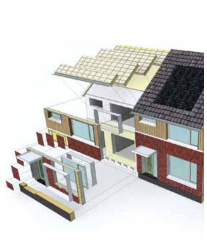
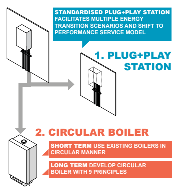
In collaboration with researchers from Delft University of Technology, the MFA and CE-LCA results from our study were compared to outcomes of an economic performance assessment using a Circular Economy Life Cycle Costing model. We found that a purposeful combination of both biological and technical materials, which can be separated after use, yielded the best economic and environmental performance. This research has been published in Wouterszoon Jansen, van Stijn, Malabi Eberhardt, Gruis and van Bortel (2022). Together with researchers from Aalborg University, we developed additional environmental design guidelines for a circular building structure as an example of a building component with a long lifespan. This research has been published in Malabi Eberhardt, van Stijn, Kristensen Stranddorf, Birkved and Birgisdottir (2021) and their findings are in line with the guidelines presented in our study. They found that building components with long lifespans benefit – even stronger – from reducing resource use now and slowing loops in on site.

8.2.4 Conclusions research goal 4: Identifying stakeholder choices that lead to circular building components which are feasible to implement in projects and practice

We presented a longitudinal study on the stakeholder choices in 5 development processes of 8 circular building components. The researchers actively co-created with stakeholders from initiative to market implementation and documented the stakeholder choices.

TOC

TABLE 8.3 Overview of developed circular building components and reasoning behind the change in applied circular design options throughout the development process

Case name	Intended circular design options during design	Realised circular design options	Most important reason for change between intended and realised	Representative image developed component
1 Circular kitchen	Modular design: long-life frames to which infill and finishing parts could be attached facilitating repair and adjustments; kitchen as a service model	Kitchen constructed with demountable panels facilitating repair	1. Frame of the kitchen not manufacturable on current machine park 2. Repairability is more important to the client than (future) adjustability	
2 Circular skin	NZEB renovation concept with modular façade and roof facilitating likely adjustments and reuse; reclaimed and biobased materials are applied	Modular renovation concept focusing initially on a modular roof facilitating likely adjustments; applying reclaimed materials where possible	1. Challenges processing reclaimed materials on machines & no technical performance guarantee 2. High initial costs façade 3. More demand for roof renovations 4. Step-by-step renovation supports client to realise energy transition	
3 Circular dwelling extension	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	Design combining reclaimed materials with standard-sized modules allowing repair, adjustments and reuse	N/A	
4 Circular NZEB-light	NZEB with exterior façade and roof insulation applying more circular materials and more demountable connections	(Re)placing less building components to achieve NZEB-level energy performance; applying more circular materials	1. Component development not role of contractors leading to focus on narrowing and closing loops now 2. Initial costs too high for NZEB with exterior skin renovation 3. Less building components are (re)placed saving costs and new material use	
5 Circular central heating boiler	Modular climate system adjustable to future heating scenarios; modular boiler facilitating future repair, adjustments and reuse of the boiler and parts	Development of circular boiler was halted after proof-of-principle phase	1. Miss-alignment incentives: costs for applying circular design options lie with manufacturer and benefits with service provider 2. Uncertainty of future use natural gas for heating	

See Table 8.3 for the developed circular building components. Through iterative process reflection and analysis, we identified the choices which influenced the perceived feasibility of different circular design options for different building components throughout their development. We validated our findings with the stakeholders involved in the development process.

We found that different combinations of circular design options were perceived as more feasible for different circular building components. For components with product-like characteristics, narrowing loops now can be combined with slowing and closing likely future cycles. Prioritizing narrowing loops now and slowing likely future loops on-site was found more feasible in building-like components. However, the particular application and context influenced the perceived feasibility of circular design options. We identified numerous trade-offs and synergies between circular design options and their perceived feasibility depending on the application(context). Furthermore, what was perceived as feasible changed throughout the development process (see Table 8.3): more ambitious combinations of circular design options were perceived feasible initially. Throughout the development process, compromises on circular design options were made to achieve a fit with the current business and supply-chain model. Finally, the perceived feasibility of circular design options was also dependent on the development process, the stakeholders and individuals involved and by choices not related to circular design options.

We do not claim that all our findings are novel. Many of the barriers we found during our literature review can be recognized throughout this study. However, we identified what *specific* choices, by which stakeholder, at what moment in the development and for what reason, influenced the perceived feasibility of different circular design options in different building components. We presented four 'key' reasons which significantly influenced the feasibility of circular design options in our study: (1) fit of the technical model to the supply-chain and business model, (2) priority given to circularity, (3) high-complexity and (4) previous experience of stakeholders. Future research and innovation can help overcome the related barriers to make more circular building components feasible. However, we are careful to claim the generalizability of our findings. Our findings remain based on situational knowledge and might not be true for all, for always, everywhere. However, the concrete knowledge presented here can already support industry stakeholders in developing more feasible circular building components.

8.3 Conclusions on the design goal: development of feasible, circular building components

In this section, we conclude upon on the design goal by bringing together the conclusions of the four studies. The main design goal of this thesis was to develop the most 'ideal' – or desirable – circular building components which are 'feasible' - or likely - to be implemented within current renovation projects and practice.

So, which circular building components were the most ideal and feasible to implement? To identify those components that reduce resource use, environmental impacts and waste generation the most, we looked to the findings of our third study (see Section 8.2.3). From the findings of our fourth study (see Section 8.2.4), we identified which circular building components are most likely to be implemented in projects and practice.

8.3.1 Between ideal and feasible

Figure 8.4 shows which circular design options led to a better environmental performance and those found more feasible to implement. We can see both similarities and differences when comparing these circular design options.

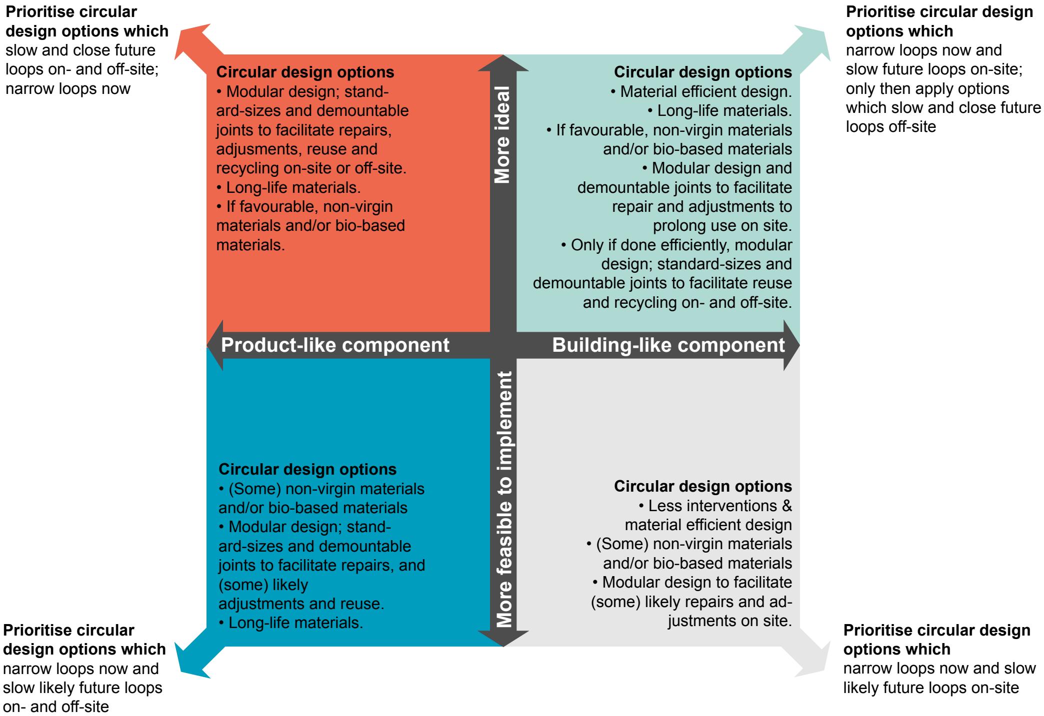


FIG. 8.4 Circular design options which were found more ideal and feasible to implement for different types of building components

Similar combinations of circular design options led a better environmental performance and were perceived as feasible to implement. For components with product-like characteristics – including a shorter service life – slowing and closing future cycles and narrowing loops now are desirable and perceived as feasible. Circular design options which narrow loops now and slow future loops on-site are both desirable and feasible in building-like components – including components with a longer service life. Notably, for building-like components, less circular design options were considered both desirable and feasible.

Second, we saw that more circular design options were considered desirable than were perceived as feasible to implement. We saw this in particular for circular design options which slow and close loops further into the future and off-site (i.e., loops taking place elsewhere than the location where the building component was placed). For example, circular design options which facilitated maintenance in the following years were perceived as more feasible than disassembly, reuse of components off-site, future adjustments and recycling. The size of the gap between more circular and more feasible was influenced by the extent to which the supply chain and business model needed to be adapted to accommodate the circular design options.

Our findings did not yet indicate a circular building component design which is 'ideally circular'. Some circular design options worsened the environmental performance of building components; the better-performing variants did not nullify resource use, environmental impacts and waste generation. Nor did we find circular building component designs which were 'feasible' in absolute. Rather we can speak of more or less circular building components – which are more or less feasible to implement – depending on how circular design options are applied in their application contexts. As such, we conclude that more circular building components can be developed and implemented in projects and practice today. However not every circular design option is desirable and not everything which is desirable is yet feasible. Implementing ideal circular building components still remains a spot on the horizon.

8.4 Scientific contribution

The scientific novelty of our research – for each of the four research goals – has already been summarized in sections 8.2.1-4. In this section, we discuss the scientific contribution of this research as a whole. Furthermore, we make recommendations for future research.

8.4.1 From consumer products to building components for housing renovation

At the start of this research, most theories on circular design originated from the field of industrial design. Theories were primarily focused on consumer products with a relatively short service life. When we used online search engines to find examples for a circular kitchen, we found just that: a circular-shaped kitchen. In our scientific background we showed that existing (pré)circular building examples applied some circular design options. However, there were few examples which combined circular design options to optimally narrow, slow and close loops; knowledge on how to do so was lacking. Our research on the development of circular building components has contributed to bringing circular design theory into the context of the built environment.

The few existing studies on circular design in the built environment focused on the macro or micro levels such as industrial parks, buildings or materials. This study focused on circular design on the building component level. We showed that 'jumping' from building to materials without redesigning the component and its parts results in a focus on applying less materials, substituting linear materials with more circular alternatives and recycling at the end of life (see Figure 8.5). Circular design options to slow future loops – such as making the building modular to facilitate repair, adjustments and reuse – require consideration of the building component and its parts (see Figure 8.6). The building component level itself is not novel and has already been described in building management theories. For example, the component level is already considered in theories on housing maintenance (e.g., Straub (2006)). Also, Habraken (1961), Duffy and Brand (1994) proposed to 'cut up' the entire building to facilitate current and future users to adjust their living environment. In line with these ideas, Kapteins (1989, p. 11) described the 'horizontal planning process' of the built environment to facilitate these adjustments. We built upon their theories, suggesting and substantiating the importance that building management models consider the building as a composite of building components, parts and materials – during all building management phases – to keep resources cycling at highest utility and value.

The majority of studies on circular design in the built environment focused on developing solutions for new construction rather than renovation and maintenance. In this study we developed circular building components focusing on housing renovation. We note that some components could be used both during maintenance, renovation and new construction, such as the circular kitchen and dwelling extension. However, for components like a renovation façade, the technical design needs to 'fit' with the existing building; the supply chain and business models are different from new construction. By researching the development of these building components, we have contributed to the – by now – growing body of knowledge on circularity in housing renovation.

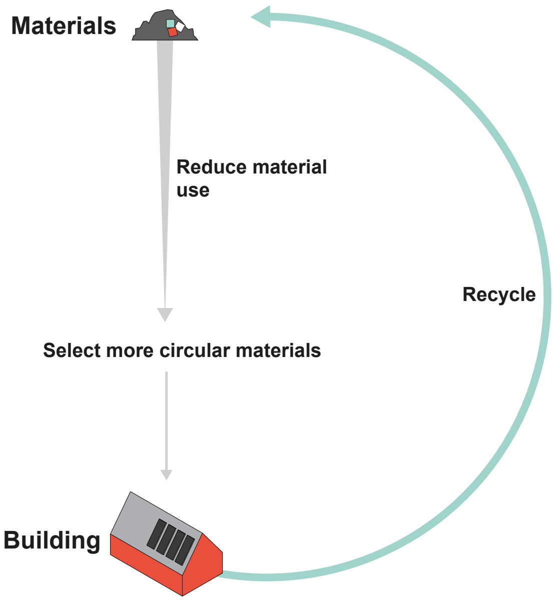


FIG. 8.5 Limited circular potential between material and building levels

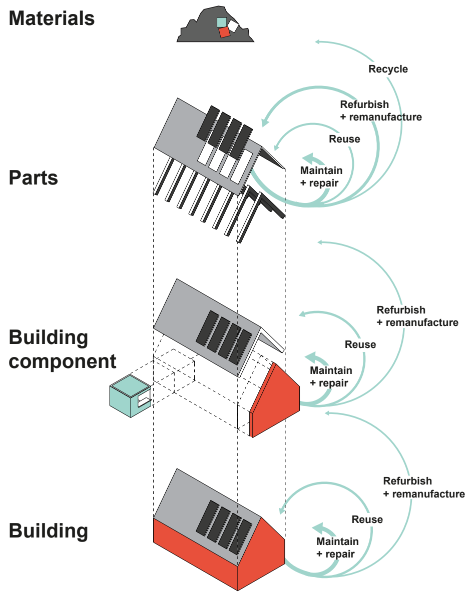


FIG. 8.6 Increased circular potential by considering the building component, its parts and materials in relation to the building

8.4.2 From carbon emissions during use to a whole life cycle perspective

Most research on sustainability in building management has focused on reducing carbon emissions from energy used during the building's operational phase (see Figure 8.7). This focus is also reflected in EU- and Dutch policy, as well as in practice. In practice, the Dutch term for making a dwelling more sustainable – 'woning verduurzaming' – can even be used as a synonym for applying energy-efficiency measures. This study contributes to shifting the understanding of- and theories on sustainability in building management by considering sustainability of the building's whole life cycle (see Figure 8.8).

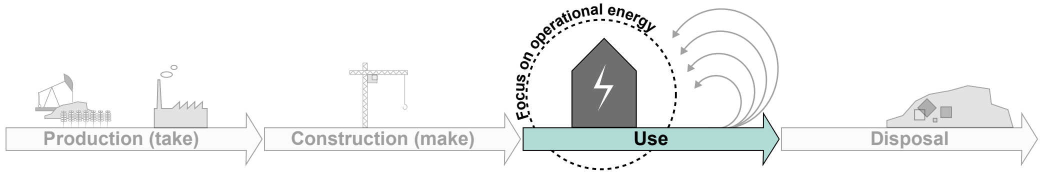


FIG. 8.7 Focus on carbon emissions from the building's operational phase

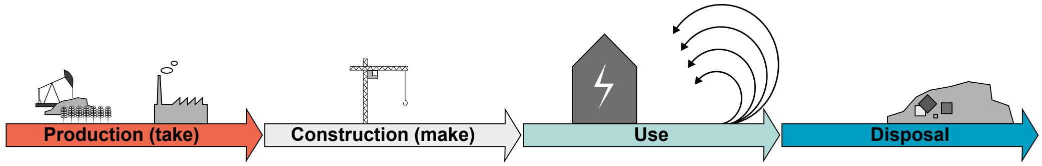


FIG. 8.8 Environmental impacts from the whole life cycle of the building

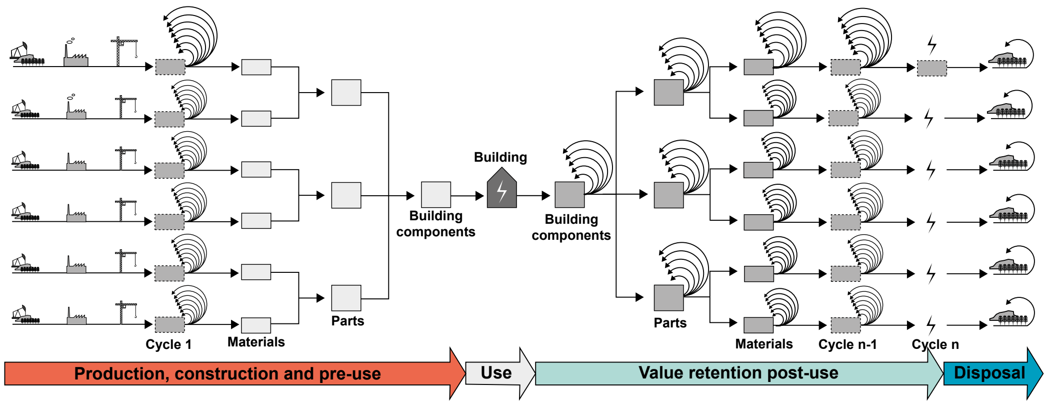


FIG. 8.9 Environmental impacts of multiple cycles in the building, building components, parts and materials

Considering the environmental impacts of a building over its whole life cycle is not novel in theory. However, in our study we go one step further by considering the embodied impacts of the building as a temporary composite of building components, parts and materials which cycle in the built environment (see Figure 8.9). We also found trade-offs between the ambitions to reduce energy use and reducing the embodied impacts. Energy-saving measures often require the use of impactful, virgin materials whilst choosing more circular alternatives, increases the project's cost. But circular design options and energy-efficiency measures also have synergies. Energy renovations became more circular and feasible by reducing the number of interventions, virgin material use and by using modularity to make step-by-step

TOC

renovations possible. Costs and benefits of energy measures are often evaluated separately from the project's material use and embodied impacts. We recommend further research on how to integrally weigh the environmental costs and benefits of circular design options and measures to reduce operational energy use.

8.4.3 Towards multi-cycle collaboration within a value network

The housing cycle (Geraedts & Wamelink, 2009) describes the four activities 'initiate', 'prepare', 'execute' and 'use'. This model lies at the basis of building management theories. Although this model essentially captures the multi-cyclic nature of buildings, we tend to study only one cycle, or a part of it, at a time (see Figure 8.10). Our second and third study showed the importance of optimizing multiple cycles to keep building components, parts and materials cycling at highest utility and value. So, our management models – on each level – should foster such a multi-cycle scope (see Figure 8.11).

The traditional ways of collaborating in the building industry are based on 'single' projects in which a fragmented supply chain gathers temporally to initiate, design, realize and use the project. To improve quality, stimulate innovation and reduce costs, new collaboration models have since been developed. These models involve stakeholders earlier into the project, involve stakeholders over multiple projects and/or involve them in finance, maintenance and operational activities. We found that loops which are realized on shorter term – such as maintenance – can be realized as they fit within these collaboration models. However, we found that loops which introduce new activities and take place in the long-term – such as disassembly, reuse, adjustments and recycling – were much harder to concretize in the scope of current collaboration models. More research is needed on how to develop collaboration models centred around continuous VRPs taking place over longer periods of time. We explicitly question if these VRPs will be realized with the stakeholders who 'exist' nowadays. Stakeholder organizations likely evolve or disappear over the decades to come. So, these models will have to accommodate the making of long-term loops whilst allowing for flexibility in who will make them. We imagine long-term collaborative frameworks in which stakeholders can plug-in and -out.

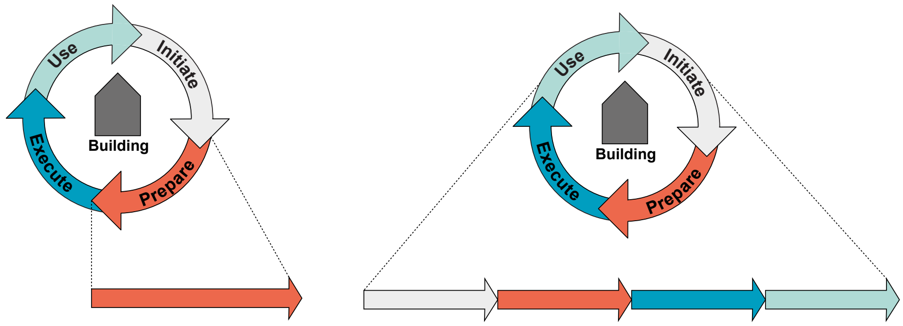


FIG. 8.10 Focus on a single cycle or part of it

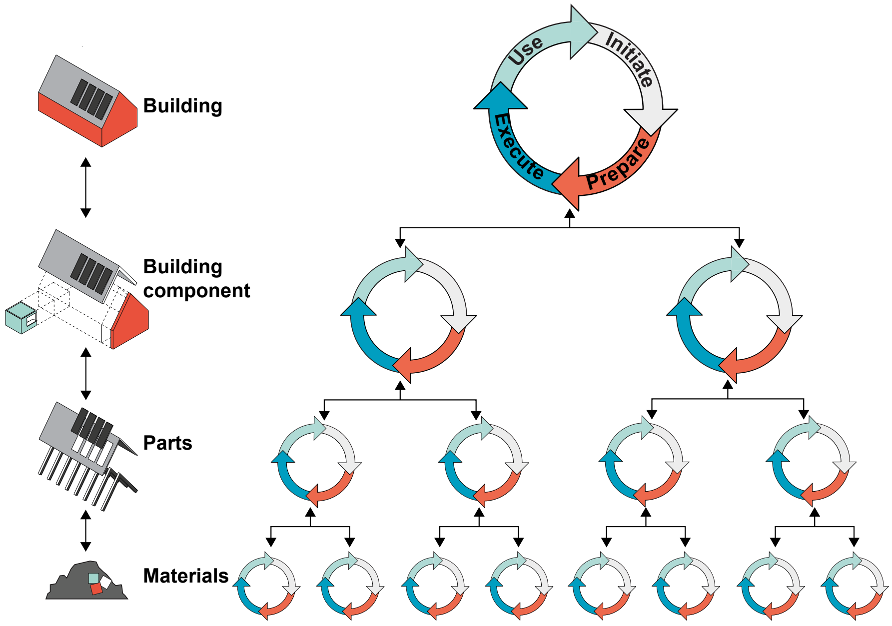


FIG. 8.11 Multi-cycle management processes on multiple building levels

A wider network of stakeholders is needed to be able to determine and optimize all the loops of circular building components, parts and materials during design, realization and use activities. We found that not all stakeholders needed to make these loops are generally involved in the design and realization phases. This means there is no opportunity to optimize their loops. Geldermans (2020) already coined the term 'ice berg principle'. Without involving all the stakeholders, parts of the design system will remain obscured under the surface. However, current theories on

TOC

collaboration in the built environment focus on collaboration between individuals, within the project team, within the organization of a single stakeholder or between a limited number of stakeholders (Figures 8.12-15). Further research is needed on how to collaborate in a larger value network both within the building supply chain as cross-sectors (Figure 8.16).

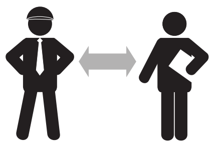


FIG. 8.12 Collaboration between individuals

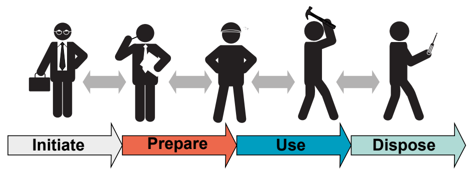


FIG. 8.13 Collaboration between members of a project team

FIG. 8.14 Collaboration within an organisation

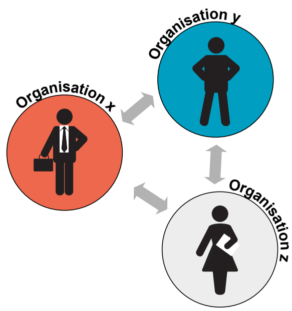


FIG. 8.15 Collaboration between several organisations

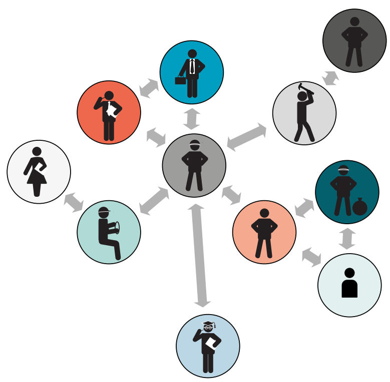


FIG. 8.16 Collaboration in a value network

8.4.4 Comparative study

Most studies look at desirability or feasibility of singular circular design options and/or look at singular building components. Our study adds a comparative perspective to the existing body of knowledge. We compared multiple circular design options and multiple building components. Furthermore, we have compared the desirability of circular design options with their feasibility to be implemented in projects and practice – including both perspectives in one research.

8.4.5 From a new research approach to a shift in academic mind-set

Finally, our research also contributes to knowledge on ‘how’ to do research, particularly for research which aims to find solutions for complex societal challenges. In our study, we further developed and exemplified the Research through Design approach. We combined Action Research with Research through Design, developing an ‘Action Research through Design’ approach. By proposing and evaluating design variants with stakeholders, more relevant and realistic knowledge could be found. Furthermore, our approach allows to move beyond researching what already exists. It allows to explore possible solutions, and compare if they are desirable and likely. As such we further articulated the concept of a transitional ontology in which multiple realities are researched in parallel. Future research is needed to investigate if this warrants its own ontological model, or if this model of reality is already described within existing research paradigms. Finally, designing solutions which are both desirable and likely to be implemented, requires knowledge on a wide range of topics. This is exemplified by the breadth of the research in this dissertation. This also requires the application of various research methods originating from different research fields. Such research requires a different academic mind-set. Rather than dividing researchers in highly specialized research groups with their own interests, the designer-researcher needs to be a generalist or even a chameleon. Their research works best in a collaborative setting, gathering researchers and practitioners from different backgrounds who work on one common goal. Similar ideas have been expressed by proponents of a transdisciplinary research approach (e.g., Doucet & Janssens (2011)).

TOC

8.5 Practice implications

The practice implications for our research – on each of the four research goals – has already been summarized in Sections 8.2.1-4. In this section we discuss the practice implications that follow from our research as a whole. We recognize the key role of the government to create policy and regulations which stimulate the development and implementation of circular building components. Undoubtedly our findings may also be food for policy implications. However, as we co-developed the circular building components with stakeholders from industry and not with policy makers, we have chosen to limit our implications to practice.

Our research can directly support practice in developing circular and feasible building components in the several ways. First, the research in this dissertation provides concrete knowledge in the form of design guidelines and tools to support practice. Second, over the course of this research, several circular building components with scaling potential have been developed. These can be replicated in other projects or can serve as inspiration for the development of other circular building components. Third, several stakeholders involved in this research indicated that the value of this research lay in the learning effect it had on those who participated. By 'just doing it together', the stakeholders internalized thinking about circularity. They indicated that they took this way of thinking to their following projects and new collaborations. In turn, they might inspire and teach others in practice.

In our fourth study we found four key reasons which influenced how circular and how feasible the developed building components were. In the remainder of this chapter we reflect on how we could change the conditions in practice to allow stakeholders to develop more circular and feasible building components in the future.

8.5.1 Changing the stakeholders' abilities: honing circular knowledge, skills and experience

Reflecting upon the development process of circular building components, we questioned to which extend stakeholders were already able to develop them. Non-circular designs processes have been aptly described as wicked problems due to the many design parameters and the 'confusing' and evolving requirements from the various stakeholders involved (Rittel & Webber, 1973). We experienced that including circularity into the development process increases the complexity of an already complex process. To develop building components which are both more circular and more feasible to implement, we recommend that additional, circular knowledge, skills and experience are needed in the supply chain.

When developing circular building components, circularity becomes another requirement to consider. New choices need to be made and previous decisions suddenly require revisiting. But how to weigh circularity to other requirements? In our research we saw that the relative importance of circularity was not a given. The priority differed per component development and evolved (un)consciously. More knowledge is needed in practice on how to weigh circularity to other requirements.

Designing more circular building components requires other knowledge and skills by practitioners. Circular design requires the designer to consider many additional circular design parameters and options. These choices relate strongly to each other. We compare it to gears gripping into each other. Particular combinations of design options – in a particular context – lead to more or less desirable circular components which are more or less feasible to implement. To keep components cycling at highest utility and value, stakeholders need to consider the 'entire' design system, multiple cycles and redesign the technical, business and supply-chain model integrally. However, having analyzed the actual development processes, we question to what extent this occurred. We saw that the focus remained primarily on the technical model. It was challenging to discuss a new supply-chain and business model without having a technical design. Utterback and Abernathy (1975) described that 'the product' is usually innovated before innovating accompanying 'processes'. However, we suspect that those working in the building industry also have more experience discussing technical models. Likewise, the stakeholders' collaboration is focused initially on getting the project done, not optimizing past, present and future resource cycles. For practitioners to be able to develop more circular building components we recommend increasing their knowledge on what circular design parameters need to be considered and which circular design options there are. We recommend to increase their skill to include multiple cycles, consider the building, component, part and material level and work integrally with the stakeholders of the entire design system.

Determining which designs were more circular is also complex. To accurately evaluate their environmental performance, multiple criteria need to be evaluated using multiple evaluation methods. We experienced that (tools applying) methods such as Life Cycle Assessment and Material Flow Analysis are difficult to use without training. Supplying all the input is an additional effort to stakeholders; the required information might not always be available in which case assumptions need to be made. Adding multiple cycles into the LCA scope – needed to accurately assess the environmental effects of slowing and closing cycles – requires even more data and more assumptions. The results of these assessments can also be hard to interpret due to multiple tipping points and trade-offs; the best performing design can differ when other decision-making methods are used or if – next to environmental performance – other criteria are also evaluated. We experienced that the numbers rolling out of assessments often get taken for 'the truth'. However, when environmental performance numbers vary for the same material or change over time it can cause confusion, frustration and mistrust in practice. We recommend practice to increase their skills to do environmental performance assessments and to understand assessment results and their value.

In our research, we found that the experience of stakeholders influences which circular design options they perceived as feasible. It might be a matter of 'unknown makes unloved' or resistance to innovations. However, it is also a matter of limiting the time-, cost-, and quality-related risks associated with the unknown. So, increasing circular experience through strategic pilots can ultimately lead to more circular designs being perceived as feasible to implement in projects and practice.

Finally, we found that what makes both desirable and implementable circular building components is highly dependent on the applicational contexts. Is will never be as simple as just applying as many circular design options as possible or even following our design guidelines. Each new design requires purposeful application depending on the application context. So, we will need practitioners with experience on which circular design option(s) will likely lead to both desirable and implementable designs in particular contexts.

To develop the abovementioned knowledge and skills, we also see a large role for universities and schools. For example, architecture students should be taught to consider materialisation, modularity, joints or future adjustments already in early conceptualization phases. Universities and schools can help develop and teach a more circular design and building tradition.

8.5.2 Make supply and demand ready for more circular designs

We concluded that the development of circular business and supply-chain models are needed to allow the implementation of more circular designs.

TOC

In section 8.4.3, we already discussed in which direction the current supply chain model should change in theory: the supply chain should collaborate with a multi-cycle perspective in a wider network of stakeholders. In practice, this will influence day-to-day activities: who does what, when, where and how? Herein we see two ways forward for practice: integrating circularity on a project basis and/or developing replicable circular solutions. Integrating circularity into projects will require different activities and stakeholders to be included into the project process. We refer to the 'practice handbook circular renovation for housing associations' (Stolker & van Stijn, 2021) in which we further explored the steps of a circular renovation process. We described which circular considerations need to be taken into account during the development of housing strategy and tactics, and the initiative, design, realization and value retention phases of a renovation project. The advantage of integrating circularity into a project approach is that it allows to develop tailor-made circular solutions for each specific design context. Furthermore, this way of working is close to the traditional building and renovation processes. However, it also requires additional efforts to integrate circularity on a case-per-case basis. Moreover, keeping resources cycling at highest utility and value is not always possible on a project-scale and in the scope of the project. To really optimize all the loops, we would recommend to focus on developing replicable circular solutions which can be implemented in projects. Both in new-built and renovation, conceptual building approaches already exist. Replicable concepts are often developed to reduce costs, risk and construction time. By making replicable circular concepts, the costs, time and risk of circular innovation can to be spread as well; all loops on each building level can be optimized step by step. Furthermore, many existing building concepts are already modular, consisting of building components. The modularity usually facilitates adjustments of concepts to different projects and prefabrication. Making an already modular concept also demountable and standard-sized to facilitate repair, reuse and adjustments is then no longer such a big step.

We recommend to reserve ample time to explore circular business model variants. In literature, different circular business models can already be found. From our research we found that implementing circular design options in different building components poses opportunities and challenges for the business model. We will give two recommendations which are vital to further circular business models in the built environment. In practice, we see that initial investment costs of components are considered – to some extent – in relation to reducing future maintenance costs and operational energy. However, balancing investment, replacements and end-value systematically is still far from common practice. A Dutch proverb speaks of real estate value as being the 'value of the bricks'. We recommend that practice should take this more literal in the appreciation of real estate. Life Cycle Costing could play an important role in testing the costs and benefits of circular business cases.

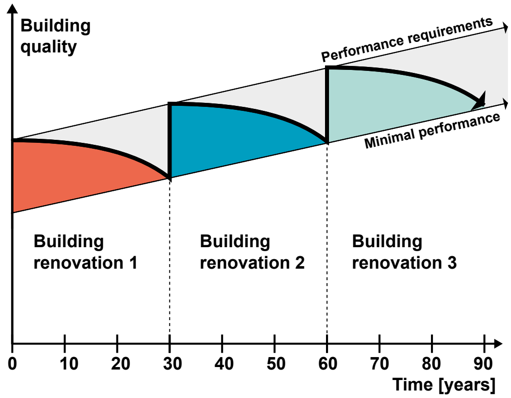


FIG. 8.17 Upkeep of dwellings through large renovations

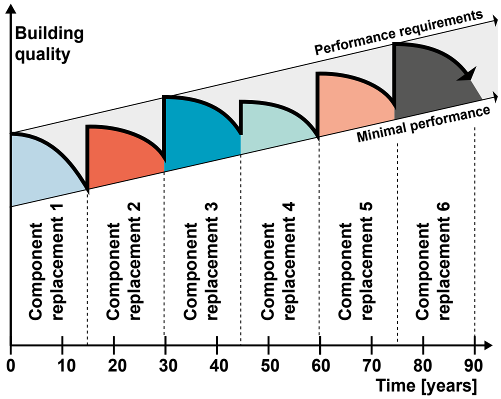


FIG. 8.18 Upkeep of buildings through building component replacements (figure adjusted from the bouwhulpgroep (van Nunen, 2014))

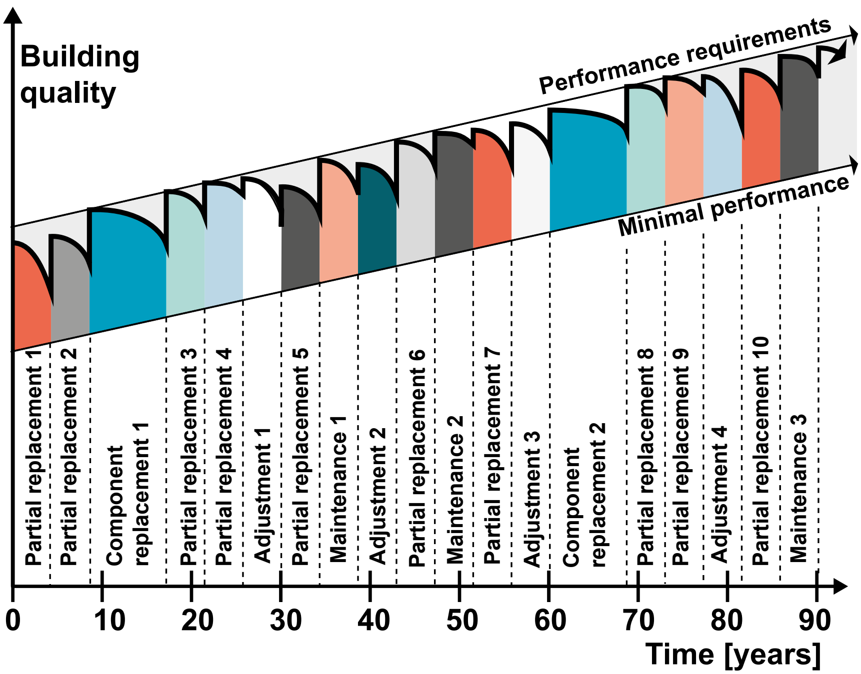


FIG. 8.19 Upkeep of buildings through continuous partial replacements and adjustments of parts and materials within a building component

We refer to Wouterszoon Jansen, van Stijn, Gruis and van Bortel (2020), who proposed a model for life cycle costing of circular building components. Second, we expect that applying circular design options will change the position of maintenance in the business model of building owners. In the current business model, we have seen a clear incentive to lower maintenance costs. Many building components are therefore made to be low-maintenance. But, after x-years these solutions require replacement as a whole. Dwellings then require a large renovation every 30 year (Brinksma, 2017) (see Figure 8.17) Circular solutions often require 'more' maintenance and partial replacements but keep the whole longer. This can create financial and environmental value over time (see also Wouterszoon Jansen, et al. (2022)), as well as keep the quality of dwellings closer to the desired performance level. This will have significant implications on how we think about investments in buildings. We could move to a more component-based renovations practice (see Figure 8.18). However, if components are also designed for repair and adjustments, an even more continuous process of partial replacements and adjustments of parts and materials within building components becomes imaginable (see Figure 8.19).

8.5.3 Start with low hanging fruit

In the recommendations above we aimed to change the abilities of practitioners and the circumstances in practice to allow for more circular design options to be implemented. However, this will likely take time and require further efforts and innovations. Furthermore, it is far from certain that those changes will become reality. Even without (waiting for) these changes, practice can already take steps on the short-term to make more circular and feasible building components. We found that certain circular design options were perceived as more challenging to implement in particular contexts than others. We recommend to start with 'low-hanging fruit'.

By keeping the technical design as simple as possible, it is easier to get a complete understanding of the supply chain and optimize all the loops. Consider, for example, a dwelling design. It is easier to make a simple tent circular than a regular, single-family home. A tent has less components, parts and materials than a full home. For everything that is added to the design system, the loops need to be optimized. So, less is more. Similarly, consider sourcing these building components, parts and materials locally. It is easier to involve local stakeholders rather than a global supply chain. Alternatively, stakeholders can consider doing more activities of production or value retention in-house. This reduces the number of stakeholders needed to slow and close all the loops.

As a first step, we recommend focussing on circular design options which narrow loops and slow loops in the near future. Circular design options focused on slowing and closing future cycles of building components, parts and materials were generally perceived as less feasible to implement without changes to the current supply chain and business model. We refer in particular to design options facilitating future adjustments, reuse of building components and parts in other dwellings and (closed-loop) material recycling. Additionally, their environmental benefits lie in the (far) future, whilst their production will cause environmental impacts now. Applying less materials, bio-based, reclaimed and/or low-impact materials and facilitating future maintenance requires less changes in the supply-chain and business models. Furthermore, these design options provide environmental benefits now or in the near future.

We recommend to focus on applying circular design options that did not increase costs compared to business-as-usual or saved costs on the short term. Think of applying less materials, affordable bio-based or and/or low-impact materials, materials reclaimed from the project which require little labour to reuse them, and facilitating future maintenance or likely adjustments on-site.

8.5.4 Towards common goals and a shared feeling of urgency

We reflected to which extend the developed circular building components solve the societal problem at the heart of this research: reducing the large share of global resource use, environmental impacts and waste generation linked to the built environment. Our third study clearly showed that not all circular design options improved the environmental performance of building components. Circular design options applied with good intentions can still increase resource use, environmental impacts and waste generation. Even in the better performing variants, we saw that resource use, environmental impacts and waste generation were not nearly nullified. Moreover, our fourth study showed that these more ambitious circular variants were not yet feasible to implement. So, realistically, making building components circular – currently – only reduces the built environment's resource use, environmental impact and waste generation to some extent.

At the same time, the global demand for new building components is expected to increase. In the Netherlands alone, the ambition is to create a million new homes in a decade. Additionally, we face a wave of renovations to make the existing building stock more energy efficient. So, even if we apply more circular building components – if the total demand for building components increases – there might

TOC

be no net-reduction in resource use, environmental impacts and waste generation at all. We stress that we are very proud of the circular building components that have been developed and realized with the stakeholders throughout this research; it took a lot of effort and we have seen a steep learning curve in all involved. However, at the same time, this research has left us rather sceptical. We question if making more circular building components will ultimately will be enough of a solution. And, we question if we will be on time. We do not claim that our study gives any definitive answers to these questions. Yet, we want to give a clear signal that further efforts are needed. So, what does this imply for practice?

We recommend practice to work towards a common understanding and set common goals. Circular economy has multiple names and definitions in practice; how circularity is understood in relation to other sustainability challenges differs. We see that circular initiatives or goals in practice remain fragmented. One group might aim to increase the use of reclaimed materials whilst others aim to increase the amount of bio-based building. We caution that application of circular design options should never be our measure of success. Ultimately circularity – and its numerous circular design options – should be considered as a means, not the goal. The environmental goals behind circular ambitions should always be about reducing resource use, environmental impacts and waste generation.

Furthermore, we urge that practice should look beyond circularity. We stress that circularity is not the same as sustainability. Depending on which definition of CE is applied, it only focusses on the planet and profit perspectives of sustainability. But other sustainability goals might not be included, for example social sustainability. Furthermore, as argued above, circularity might not be sustainable enough. To really reduce resource use, environmental impacts and waste generation in the built environment, additional sufficiency-oriented strategies may be needed. This pathway will ask for more radical changes in how we live. In this study the underlying premises was always that the building components needed to be made. Our job was to make it as circular as possible. But we never questioned if we should make the component at all. Doing nothing is usually not an appealing option. But together we need to start thinking how we as human-kind can be satisfied with less and accept the limits of growth.

Our final word of advice. Even if we have our scepticism that we will solve the environmental issues timely, we encourage no one to lose hope. If the previous years of the global pandemic have taught us anything, it is that mankind is able to change the world in a heartbeat when a feeling of urgency is shared amongst us all. We remain ever hopeful that together we can do the same for the environmental challenges we face.

References

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, *22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Brand, S. (1994). *How Buildings Learn*. New York: Viking.

Brinksma, H. (2017). *Toekomstbestendig Renoveren*. Retrieved from http://www.lesvosnews.net/articles/news-categories/politiki/dimoskopisi-gia-galino-kalogiroy-voyleytes-lesvoy-ereyna-tis-kapa

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*(102322), 1–11. https://doi.org/10.1016/j.scs.2020.102322

Dokter, G., van Stijn, A., Thuvander, L., & Rahe, U. (2020). Cards for circularity: Towards circular design in practice. *IOP Conf. Series: Earth and Environmental Science*, *588*(042043), 1–8.

Doucet, I., & Janssens, N. (2011). Transdisciplinary Knowledge Production in Architecture and Urbanism. In *Transdisciplinary Knowledge Production in Architecture and Urbanism*. https://doi.org/10.1007/978-94-007-0104-5

EN 15804. (2012). *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Retrieved from https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019

EN 15978. (2011). *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*.

Geldermans, R. J. (2020). *Securing Healthy Circular Material Flows In The Built Environment: The Case Of Indoor Partitioning*. https://doi.org/10.7480/abe.2020.6

Geraedts, R., & Wamelink, H. (2009). Het bouwproces. In H. Wamelink, R. Geraedts, F. Hobma, & L. Lousberg (Eds.), *Inleiding Bouwmanagement* (pp. 1–34). Delft: VSSD.

Habraken, N. J. (1961). *Supports: An Alternative to Mass Housing*. London: Routledge.

Kapteijs, J. (1989). *Open bouwen buurtvernieuwing: een verkennend onderzoek naar de toepassing van Open Bouwen in het kader van IOP-bouw*. Delft: Publicatieburo Bouwkunde.

Malabi Eberhardt, L. C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021). Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability*, *13*(10), 5621. https://doi.org/10.3390/su13105621

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Rittel, H., & Webber, M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169.

Stolker, M., & van Stijn, A. (2021). *Handboek Circulair Renoveren Woningcorporaties*. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjcx-tno8O31AhVNi6QKHaiFAJUQFnoECAUQAQ&url=https%3A%2F%2Fwww.ams-institute.org%2Fdocuments%2F49%2FHandboek_Circulair_Renoveren_voor_Woningcorporaties.pdf&usg=AOvVaw2dQi

Straub, A. (2006). Housing management and maintenance practise of Dutch housing associations. *ENHR 2004 Conference*, (July), 2–6. Cambridge.

Utterback, J. M., & Abernathy, W. J. (1975). A dynamic model of process and product innovation. *Omega*, *3*(6), 639–656. https://doi.org/10.1016/0305-0483(75)90068-7

van Nunen, H. (2014). Levensduur denken: woningonderhoud en oog voor milieu vragen om integratie. Retrieved September 30, 2022, from http://levensduur-denken.nl/beheer/context-bepaalt-onderhoud/

Wouterszoon Jansen, B., van Stijn, A., Eberhardt, L. C. M., Gruis, V., & van Bortel, G. A. (2022). The technical or biological loop? Economic and environmental performance of circular building components. *(In Review) Sustainable Production and Consumption.*

Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*, 104857. https://doi.org/10.1016/j.resconrec.2020.104857

Appendices

TOC

APP. A Appendix Chapter 4

APP. A.1 Technical, industrial and business model parameter-option matrices

This appendix contains the technical, industrial and business model parameter-option matrices of the CBC-generator.

TOC

TABLE APP. A.1 Technical model parameters and sub-parameters

Parameter				Sub-parameter			
Model	Numb.	Parameter	References		Numb.	Sub-parameter	References
Technical model	TP1	**Materials / resources**	1-36		TP1.1	Biological materials	2,3,5-7,9,11,13, 16-21,23-25,29,30, 33-36
					TP1.2	Technical materials	2,3,5-7,9,11,13, 16-25,29,30,33-36
	TP2	**Energy**	1-7,9-13, 15-33,35,36		TP2.1	Type of energy (in use phase)	1-7,9-11,18,19, 21, 23,27, 30, 33,35,36
	TP3	**System Architecture**	1,3,4,6,12-14, 18, 19,22, 25,29,30, 32, 33,35		TP3.1	System elements	1-4,6,8,12-14,16,18, 19,22, 25,29,30,33,35
	TP4	**Amount**	1,4-10,12,13,16-19, 21,24,25,29-34		TP4.1	Amount of elements or resources	1,4-10,12,16,18,19, 21,24,25,29-32,34
	TP5	**Time(s)**	1-23,25-30, 32-35		TP5.1	Amount of lifecycles	1-7,9-13,15-30, 32-35
					TP5.2	Expected lifespan	1-7,9-16,18-27, 29-35
	TP6	**Lifecycle stage**	3,18,24,33		TP6.1	Lifecycle stage of building component, part, material	3,18,24,33
	TP7	**Circular design strategies**	1,3-7,9-16,18-21, 23-27,29,30,32-35	Narrowing loops	TP7.1	Design for material reduction	3-5,7-10,12,13,15, 16,19-21,23-27,29, 31,33
					TP7.2	Design for energy reduction	3,4,7,9,13,16,19,20, 23,25,27,31,33
				Slowing loops	TP7.3	Design for attach-ment	3-5,9,11,12,14,16, 20-25,32,34,35
					TP7.4	Design for reliability and durability	1,3-7,9-11,13,14,16, 18,20-27,29,31-35
					TP7.5	Design for stan-dardisation and compatibility	3,5,9,11,13-15,18, 21-24,29,33-35
					TP7.6	Design for ease of maintenance and repair	1,3-7,9,14-16,18, 21-25,27,29,32-35
					TP7.7	Design for upgrades and adjustments	1,3-7,9,12-15,18, 20-25,27,29,32, 34,35
					TP7.8	Design for dis-, and re-assembly	3-5,9,11,13-15,18, 19,21-25,29,31-35
				Closing loops	TP7.9	Design for biode-grading and recycling	3-5,7,9,13,16,18-21, 23-27,29,31-35

TOC

TABLE APP. A.2 Industrial model parameters and sub-parameters

Parameter				Sub-parameter			
Model	Numb.	Parameter	References		Numb.	Sub-parameter	References
Industrial model	IP1	**Key partners**	1-11,13,15,17-28, 30-33,36		IP1.1	Partners in supply chain or value network	1-11,13,15,17-28, 30-33,36
	IP2	**Key activities**	1-10,13,15,17-22, 25-36		IP2.1	Activities	1-11,15,17-22, 25-33,36
					IP2.2	Re-loop activities	1-13,15-22,25-27, 29-36
					IP2.3	(Re-)production process per (re)activity	1-4,6,8-12,15,16,18, 20-25,27,29,31-34, 36
	IP3	**Key resources**	2,3,5,6,17-22,26-28, 30-33,36		IP3.1	Facilities for activ-ities	1,3-6,10-12,15,20, 27,32,33
					IP3.2	System elements	2,3,6,12,18, 19,29,30,33
	IP4	**Transport / logistics**	2-12,15,18,20,21, 23-25,28,30,31, 33,35		IP4.1	Mode of transport	3,6,7,15,21,23,30
					IP4.2	Distance	3-7,9,11-13,15, 18-21,23,27,29,30, 33,35
	IP5	**Process energy**	3-7,9,15,16,18-25, 27,29,30,32,33,36		IP5.1	Type of energy	3,6,7,15,16,18-23, 27,29,30,33,36

TABLE APP. A.3 Business model parameters and sub-parameters

Parameter				Sub-parameter			
Model	Numb.	Parameter	References		Numb.	Sub-parameter	References
Business model	BP1	**Key partners**	1-11,13,15,17-28, 30-33,36		BP1.1	Partners in supply chain or value network	1-11,13,15,17-28, 30-33,36
	BP2	**Customer segments**	2,3,6,17,18,20-22, 26,27,30,31,36		BP2.1	Owner	1-7,10,11,13,17-27, 30-32,34
					BP2.2	Customer	2,3,6,9,10,12,17,18, 20-22,24,26-28,30, 31,35,36
	BP3	**Supply chain relations**	1-3,6,10,17-22, 24-27,31,36		BP3.1	Primary contact customer	18,28
					BP3.2	Kind of customer relationship	1-3,6,9,11,17-22,26, 28,31,34
					BP3.3	Primary supply-chain partner / contact	1,22,28
					BP3.4	Kind of collaboration	1-3,5-8,10-12, 15-25, 27-29,31,32,34
	BP4	**Cost structure**	2,3,6,8,17,18,20,22, 26-31,34,36		BP4.1	Cost proposition	3,18
	BP5	**Revenue streams**	1-4,6,8,10,17-22, 24-28,31,32,34,36		BP5.1	Financial arrange-ment	1-4,7,10,11,15, 17-21,25-28,30-32, 34,36
					BP5.2	Income division	10,19,20,28
	BP6	**Value propositions**	2-10,12,17-28, 30-34,36		BP6.1	Product / service proposition	1-3,5-7,9,10,12, 17-28,30-32,34,36
					BP6.2	Value creation and delivery	1-3,5-7,9,12,17-21, 24,26-28,30,31,36
					BP6.3	Value capturing	1-10,12,17-22, 24-28,30,31,34
	BP7	**Key resources**	2,3,5,6,17-22,26-28, 30-33,36		BP7.1	Key resources per supply-chain partner	2,3,5,6,17-22,26-28, 30-33,36
	BP8	**Channels**	2,3,6,8,10,17-22, 26-28,31,33,34,36		BP8.1	Sale and (re)loop channels	2,3,6,8,10,17-22, 26-28,31,33,34,36
	BP9	**Take back systems**	1,2,4-6,9,10,12,16, 18-21, 23-27,32,34,36		BP9.1	Facilities for take-back	1,2,4-6,9,10,12,16, 18-21,23-27,32, 34,36
	BP10	**Adoption factors**	2,6-9,12,13,18-22, 24,25,32,34		BP10.1	Circular business model adoption factors	2,6-9,12,13,18-22, 24,25,32,34

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP1.1	**Biological materials**	
TP1.1-1	Renewable material	1,2,5-7,9,11-13,15,16,18-21,23-25,28,30,34
TP1.1-2	Bio-based material	1,3,5,6,13,16,20,23-25,27,30
TP1.1-3	Non-toxic (healthy) material	5-7,9,11,13,15,18-20,22,23,25,26,29,30,34
TP1.1-4	Safe material	2,3,5,6,11,23-25
TP1.1-5	Low-impact material	6,9,16,20,23,24,27,33
TP1.1-6	Biodegradable material	1,3,5,6,9,11-13,16-18,23-25,34,36
TP1.2	**Technological materials**	
TP1.2-1	Durable or high-quality material	3,6,7,13,16,18,20,23,25,26,29,30,34
TP1.2-2	Virgin material	1,3,6,7,12,16,19-22,26,27,32-34
TP1.2-3	Recyclable material	1,4,6-9,11-13,15,16,18-21,23-26,28,29,33,34
TP1.2-4	Non-virgin (i.e., reused, recycled) material	1-3,5-9,12,13,16,18-21,23-27,29,33,34
TP2.1	**Type of energy (in use phase)**	
TP2.1-1	Natural gas	
TP2.1-2	Grey power (i.e., electricity from fossil resources)	18,30
TP2.1-3	Diesel / petrol	18,21,30
TP2.1-4	Bio gas / biofuel	9,21
TP2.1-5	Hydrogen power	
TP2.1-6	Green alternating current (e.g., transformed electricity from PV-cells)	30
TP2.1-7	Green direct current (e.g., electricity from PV-cells)	18
TP2.1-8	Heat from thermal storage	18
TP2.1-9	On-site pre-heating (e.g., horizontal ground loop)	
TP2.1-10	City heating	
TP2.1-11	Block heating	
TP2.1-12	Off-site power (i.e., grid energy)	18,30
TP2.1-13	On-site power (i.e., independent generated power)	18,36
TP3.1	**System elements**	
TP3.1-1	Built environment	7,13,19
TP3.1-2	Building	3,7,13,19,20,32
TP3.1-3	Building component	7,13,19,20,32
TP3.1-4	Product	1-7,9-36
TP3.1-5	(Sub-)component	1,3-7,9,12-15,18-26,29,32-35
TP3.1-6	Part	1,3-7,9,12-15,18,20-22,24,26,27,29,33-35
TP3.1-7	Material	1-36
TP3.1-8	Resource	1,5,7-11,13,15-34,36

>>>

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP4.1	**Amount of elements or resources**	
TP4.1-1	Number of system elements (i.e., number of products, parts)	16,17,30,34
TP4.1-2	Amount of resources (e.g., in [kg], [m3], [kwh])	4,7-9,12,16,21,25,29,32
TP5.1	**Amount of lifecycles**	
TP5.1-1	Single lifecycle	4,19,21,23,25-28,34
TP5.1-2	Multiple lifecycles	1,3,4,6,10,16-18,20-23,25-27,33,34
TP5.2	**Expected lifespan**	
TP5.2-1	Very short	16
TP5.2-2	Short	1,3,7,11,13,16,18-20,22,23,25,32
TP5.2-3	Medium	
TP5.2-4	Long	1-5,7,9-11,13,15,16,18-22,25-27,30-32,34,35
TP5.2-5	Very long	29
TP6.1	**Lifecycle stage of building component, part, material**	
TP6.1-1	Introduction	3,18
TP6.1-2	Growth	3,18
TP6.1-3	Maturity	3,18,33
TP6.1-4	Decline	3,18
TP7.1	**Design for material reduction**	
TP7.1-1	Reduce material by making (building)component not needed or digital	7,9,20,22,24,30,33
TP7.1-2	Apply reused, recycled, or low-impact materials	6,9,13,15,16,23,24,33
TP7.1-3	Find local industrial symbiosis for needed resources	5,8,9,18,21,23
TP7.1-4	Reducing material in (re)production (e.g., less cutting losses)	7,9,13,16,19,23-25,29
TP7.1-5	Reducing packaging material (i.e., light weighting or minimisation)	9,15,23,25
TP7.1-6	Reduce material in building component (i.e., light weighting, remove redundant parts, minimise the building component)	3,5,7,9,13,16,19,21,23-25,29,32,33
TP7.1-7	Reduce use-phase material (i.e. water, consumables)	7,9,25
TP7.1-8	Use bio-inspired (biomimetic) design for biological loop designs	6,18,19,23-25
TP7.1-9	Reduction or smart-use of critical and scarce materials (e.g., critical materials only for short-cycled use)	9,17

>>>

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.2	Design for energy reduction	
TP7.2-1	Design for a lean, clean, green production process	3,7,9,16,20,21,23-25,27
TP7.2-2	Balance component lifespan with energy performance prospects	9
TP7.2-3	Minimise energy in use-phase (e.g., passive design)	3,7,9,13,23,27
TP7.2-4	Optimise energy efficiency in use-phase (e.g., insulate)	5,7,23,24,33
TP7.2-5	Recover and exchange energy	13
TP7.2-6	Use renewable energy sources in (re)production and use	6,7,11,15,18-21,23,24,28,30,33
TP7.3	**Design for attachment**	
TP7.3-1	Design for easy use	14
TP7.3-2	Design for high safety standards	4,9,14,19,29,33
TP7.3-3	Add surplus quality	3,4,7,14
TP7.3-4	Design for user trust (e.g., ensure reliability of design)	3,4,7,14,22,32
TP7.3-5	Design for comfortable use	14
TP7.3-6	Facilitate democratic or open-source design and use	3,6,13,16,20,23
TP7.3-7	Design for emotional desirability (e.g., provide emotional relevant narrative, service, information, meaning)	3,11,12,14,16,22,23,25,32,34,35
TP7.3-8	Design for strong social value (e.g., provide services and information relevant to the users social environment)	14
TP7.3-9	Make a timeless base design	3,4,23,25,35
TP7.3-10	Facilitate customisation and adjustment options to reflect user's emotional, social values, and user preferences	3,4,12,14
TP7.3-11	Balance quality with user expectations	3,14
TP7.3-12	Make a design which ages well and builds a personal patina	3,14
TP7.3-13	Make an innovative (i.e., novel, sufficiently complex) design	14
TP7.3-14	Offer upgrades to keep user interest	4,14,35
TP7.3-15	Design to facilitate interaction with user (to enhance curiosity, understanding, attractiveness, attachment)	3,14,25

>>>

TOC

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.4	Design for reliability and durability	
TP7.4-1	Consider obsolescence, growth and future scenarios	3,4,6,8,11,13,18,33,35
TP7.4-2	Select an appropriate lifespan for the component / part / material	3,13,16,25,29
TP7.4-3	Make a highly functional design	13,15,16,24,32
TP7.4-4	Anticipate on new regulations	4,13,18,29,35
TP7.4-5	Dimension for unintended / stressed use	14,23,29,35
TP7.4-6	Over-dimension or duplicate critical parts	9,13,14,35
TP7.4-7	Design out moving parts	14,35
TP7.4-8	Only include electronic parts consciously	9,18
TP7.4-9	Evaluate, and optimise the component, (sub) components and parts on quality, and design-out component failures (i.e., iterative design)	3,5,6,14,23,25
TP7.4-10	Design for resistance to wear	22,35
TP7.4-11	Use durable materials	9,13,14,16,34
TP7.4-12	Design so (sub)components and parts can withstand repetitive assembly and disassembly	3,29
TP7.4-13	Design robust interfaces (i.e., joints or touch surfaces) between components and parts	14,29
TP7.4-14	Select materials which can withstand shock and vibration impacts	13,14
TP7.4-15	Reduce coated, painted or plated materials	14,35
TP7.4-16	Prevent discolouration of materials	14,35
TP7.4-17	Avoid corrosive, toxic and aging materials	11,34,35
TP7.4-18	Use (a limited variety of) compatible base materials	14
TP7.4-19	Use compatible fastener to base materials (to prevent corrosion)	35
TP7.4-20	Design for simple use of the designed building component	14
TP7.4-21	Limit number of components, parts, and materials	3,14
TP7.4-22	Design so dirt has no chance to build up (no edges, ridges or holes)	29
TP7.4-23	Decomplexify the design of (sub)components and parts	3,14,24

>>>

TOC

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.5	**Design for standardisation and compatibility**	
TP7.5-1	Company standardisation	3,14,15,18
TP7.5-2	Industry standardisation	3,14,29
TP7.5-3	Part standardisation	3,4,9,14,18,22,24,33-35
TP7.5-4	(Sub)component standardisation	3,4,14,15,18,24,29,33,34
TP7.5-5	Product / building component standardisation	3,4,6,14,18,34
TP7.5-6	Measurement standardisation	3,13,29,33
TP7.5-7	Joint standardisation	3,13,24,29,33
TP7.5-8	Joint piece (i.e., adaptor) standardisation	3,14,29
TP7.5-9	Tool standardisation	14
TP7.5-10	Interface standardisation	4,14,22,33,35
TP7.5-11	Performance test standardisation	35
TP7.6	**Design for ease of maintenance and repair**	
TP7.6-1	Make the design easy to open / accessible	3,4,9,14,18,29,32,33,35
TP7.6-2	Position maintenance points close together	9,14,18
TP7.6-3	Indicate handling and lifting instructions on components and parts (e.g., lifting handles, eyes)	14
TP7.6-4	Large (sub)components and parts should be mounted on hinges, slides or runners to offer better access during maintenance and repair	14
TP7.6-5	Design an opening plane	35
TP7.6-6	Design for safe maintenance (e.g., avoidance of toxic materials)	9,14,18
TP7.6-7	Design maintenance points so personnel can keep a comfortable posture during maintenance.	14
TP7.6-8	Design so maintenance can be done by few, and unschooled personnel	6,14,23
TP7.6-9	Design so it can only be maintained / repaired in the right way	4,14
TP7.6-10	Design so maintenance is fast	9,14,18,21,22
TP7.6-11	Optimise sequence for maintenance and repair	14,33
TP7.6-12	Keep cleaning and repair intensive parts accessible	3,4,14,35
TP7.6-13	Standardise design fit and assembly sequence	29
TP7.6-14	Design so the ‘weakest link’ is easy (and cheap) to replace	14,18
TP7.6-15	Provide sufficient space around parts to prevent secondary damage	14,32
TP7.6-16	Design to allow on-site maintenance	3,4,23,35
TP7.6-17	Enclosed maintenance and repair instructions	1,3,9,14,23,24,32,34
TP7.6-18	Make an uncomplicated design	12,14,18
TP7.6-19	Make a modular design	1,3,4,6,7,9,12,14,17,18,20,21,23-25,29,33,35

>>>

TOC

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.6	Design for ease of maintenance and repair	
TP7.6-20	Separate parts based on technical lifespan and function	3,18,29
TP7.6-21	Align the maintenance, repair and replacement cycle of (sub)components and parts	33,35
TP7.6-22	Reduce variation in lifespans of (sub)components and parts to ease maintenance planning and prevent premature replacements	14
TP7.6-23	Minimise number of components and parts to ease repairs	9,14,33
TP7.6-24	Use standardised, universally applicable compo-nents and parts	14,33,34
TP7.6-25	Components, parts which are often replaced need to be easy to handle (i.e., standard size/weight, no sharp edges, easy to transport)	14,18
TP7.6-26	Design (and offer) spare parts	1,3,6,9,21,24,34
TP7.6-27	Make products stackable (to ease transport for repairs)	35
TP7.6-28	Use fasteners which allow fast maintenance and repair (no wet-joints)	14,18,33
TP7.6-29	Select fasteners with regard to maintenance frequency and availability of tools at replacement location	14
TP7.6-30	Minimise number of fasteners to make maintenance and repair easy	9,14,33
TP7.6-31	Design joints which do no require tools for mainte-nance and repair	14
TP7.6-32	Use smooth surfaces to ease cleaning	29,33,35
TP7.6-33	Use materials that can stand cleaning and mainte-nance	3,29,35
TP7.6-34	Use materials that can be easily repaired, replaced, touched-up	14
TP7.6-35	Apply self-healing or self-cleaning materials	3,23
TP7.6-36	Include a component and part passport	12,13,20,24,32,33
TP7.6-37	Make the product easily testable (e.g., include self-use diagnostic tools)	3,4,9,14,18,33,35
TP7.6-38	Integrate (live)monitoring of performance in design	4,6,7,12-14,18,20,24,30,31,33,35

>>>

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.7	**Design for upgrades and adjustments**	
TP7.7-1	Separate the component in sub-components and parts based on functional lifespan (e.g., building 'support' and 'infill')	3,12,13,14,15,18,23,29
TP7.7-2	Separate building components into 'shearing layers': site, structure, skin, services, space-plan, stuff	13,19
TP7.7-3	Make a modular design	1,3,4,6,7,9,10,12,14,15,17,18,20,21,23-25,29,33,35
TP7.7-4	Make to-be-updated functions independent of the base of the design	12-15,18
TP7.7-5	Design excessive functionality and performance in the component base	14
TP7.7-6	Leave room in component / product for upgrades	13
TP7.7-7	Allow for technical, functional and aesthetic customisation	3-6,7,13,14,18,22,33
TP7.7-8	Plan for scenarios of change	3,4,6,7,13,14,18,19
TP7.7-9	Design (and offer) techn., funct. or aesth. upgrades & add-ons	1,3,5,9,13,14,18,23,33,34
TP7.7-10	Design versatile parts which could perform several functions	14,24
TP7.7-11	Use standardised (sub-)components and parts to ease updates	3,14,15,18
TP7.7-12	Make products and components stackable to ease transport	3,15,35
TP7.8	**Design for dis-, and re-assembly**	
TP7.8-1	Easy (enclosed) dis-, and reassembly instructions	32,33
TP7.8-2	Provide easy access to joining, breaking, cutting points	9,14,29,33,35
TP7.8-3	Design for automated disassembly	29
TP7.8-4	Use assembly methods that allow disassembly without damage to reusable components	9,29,33,35
TP7.8-5	Minimise number of components and parts	14,24,29,33,35
TP7.8-6	Use standardised and modularised components	14,15,29,33
TP7.8-7	Keep drainage points accessible	9,14
TP7.8-8	Optimise and simplify sequence for dis-, and re-assembly	4,33,35
TP7.8-9	Design so sequence independent dis-, and re-assembly is possible	33,35
TP7.8-10	Keep one surface for grasping	14,29,33,35
TP7.8-11	Prevent the need for turning	14,35
TP7.8-12	Design for a linear and unified disassembly direction	14,33
TP7.8-13	Simplify and standardise components, and the dis-, and re-assembly fit	29,33,35
TP7.8-14	Apply a loose fit for easy re-assembly	33,35

>>>

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.8	Design for dis-, and re-assembly	
TP7.8-15	Mark and label (important) disassembly joints	14,29,33,35
TP7.8-16	Limited number of different connections	4,14,24,29,33,35
TP7.8-17	Limited number of connections	4,9,14,18,24,29,33,35
TP7.8-18	Apply (grasp fit) click connections	29,33,35
TP7.8-19	Avoid or limit non-rigid parts	14,29
TP7.8-20	Use standardised and simple joints	14,24,33
TP7.8-21	Use easy and fast dis-, and remountable connections	3,4,9,13,15,18,23,24,29,33,35
TP7.8-22	Use easy to destroy joints	35
TP7.8-23	Avoid wet joints (i.e., welded or poured)	4,14,29,35
TP7.8-24	Avoid (non-solvable) adhesives	3,4,14,15,23,29,32,33,35
TP7.8-25	Design so easy or no tools are needed for dis-, and re-assembly	4,9,18,23,24,29,33,35
TP7.8-26	Avoid metal inserts in plastic parts	14,33,35
TP7.8-27	Avoid materials which are likely to damage machinery	14
TP7.9	**Design for biodegrading and recycling**	
TP7.9-1	Make disassembly easy, or not needed for recycling	4,18,22,29
TP7.9-2	Use highly recyclable / biodegradable materials	4,6,7,13,18-20,23-25,27,29,33,34
TP7.9-3	Anticipate material recycling / biodegradation routes	4,6,8,13,18,19,25,33
TP7.9-4	Use appropriate biological or technological materials	6,7,16,20,23,25,29,34,35
TP7.9-5	Separate parts at material boundaries (mono-materials)	3-6,9,13,15,16,18,20-22,24,29,32-35
TP7.9-6	Limit number of materials	4,9,14,24,29,33,35
TP7.9-7	Use recycling (process) compatible materials	4,13,14,18,24,29,32,33,35
TP7.9-8	Use common materials (to limit the number of recycling streams)	9,13,33,35
TP7.9-9	Use break lines (for destructive recycling)	4,33,35
TP7.9-10	Use recycle compatible materials for base and fasteners	24,29,33,35
TP7.9-11	Keep parts of the same material together	14,35
TP7.9-12	Provide easy access to toxic, valuable or re-usable parts / materials	14,29,33,34
TP7.9-13	Keep toxic materials grouped together, sealed and easy to remove	14,29,35
TP7.9-14	Keep critical, valuable, re-usable parts and materials grouped together	4,33,35
TP7.9-15	Prevent secondary (non-compliant) paint and coating	4,14,29,33,35

>>>

TOC

TABLE APP. A.4 Technical model design options per (sub)-parameter

TP7.9	Design for biodegrading and recycling	
TP7.9-16	Make components, parts stackable to ease re-loops	14,25,35
TP7.9-17	Minimise product volume to ease relooping	9,14,23,25,35
TP7.9-18	Provide markings or different colours to indicate material types	4,9,14,16,18,24,26,29,33,35
TP7.9-19	Provide disposal or recycling instruction	24,32,33
TP7.9-20	Include material passport (e.g., in BIM)	6,12,13,16,19,20,26,32

TABLE APP. A.5 Industrial model design options per (sub)-parameter

IP1.1	Partners in supply chain or value network	
IP1.1-1	Government	2,3,8,9,12,17,18,20-22,24-26,29-32
IP1.1-2	Building owner	13,19
IP1.1-3	Expert (e.g., designers, consultants)	1-3,6,8,11,13,15-19,21,24-26,31-33
IP1.1-4	Third-party financier	2,6,10,13,18,31,32
IP1.1-5	Material supplier	1-3,6,17-22,26-28,32,33
IP1.1-6	Part supplier	2,3,5,7,9,14,15,17-22,28,33
IP1.1-7	Manufacturer (e.g., product, building component manufacturer)	1-7,9,10,12-18,20-22,24,26-28,30-34
IP1.1-8	Transporter	2,4,5,8,18,21,26
IP1.1-9	Specialised dealer	1-3,5,6,8-10,12,16,18,21,22,24,32
IP1.1-10	Service provider	1-7,9,10,12,14,17-22,26,27,30,31,33
IP1.1-11	Contractor	19
IP1.1-12	User	1-7,9-14,16-25,27,29-36
IP1.1-13	Maintenance specialist	3,6,14,18,21,30,33
IP1.1-14	Collector	4,5,9,12,18,21,22,26,32
IP1.1-15	Second-hand reseller	1-3,5,10,18,21,22,34
IP1.1-16	Specialised refurbisher	1,3,10,18,21,22,33,34
IP1.1-17	Specialised remanufacturer	1,3,21
IP1.1-18	Specialised recovered material reseller	1,10,21,22,27
IP1.1-19	Specialised recycler	1,3-5,10,12,18-22,26,29,30,32,33,35
IP2.1	**Activities**	
IP2.1-1	Financing	3,4,9,10,13,18,31
IP2.1-2	Manufacturing materials	1,3,4,7,9,13,18,21-23,26,27,35
IP2.1-3	Manufacturing parts	3-5,7,13,18,21,22,26,33,35
IP2.1-4	Manufacturing (e.g., product / building component)	1,3-9,11-13,15,16,18-27,29-35
IP2.1-5	Transporting	1,3,4,8,9,14,15,18,21,23,24,30,33
IP2.1-6	Selling	1-6,9-13,17-22,24-27,30-32,34,35
IP2.1-7	Installation / assembly	3,6,9,10,14,18,24,26
IP2.2	**Re-loop activities**	
IP2.2-1	After sales support	3,9,18,31,34
IP2.2-2	Maintenance	1-8,10,13-15,17-21,23-25,29-31,33-35
IP2.2-3	Refilling	6,12
IP2.2-4	De-, re-installation	3,6,13,18,33,35
IP2.2-5	Repairing	1-7,9-11,14,16,18-27,29-36
IP2.2-6	Refinancing	18
IP2.2-7	Recovering or collecting	1,3-10,12,13,15,16,18-27,29-35
IP2.2-8	Re-transporting	3,5,15,18,21,23,25,29,30,33
IP2.2-9	Sorting	4,9,12,15,18,19,21,22,29,32,34
IP2.2-10	Re-using	1-7,9-13,15-27,29,30,32-36

>>>

TABLE APP. A.5 Industrial model design options per (sub)-parameter

IP2.2	Re-loop activities	
IP2.2-11	Refurbishing	1-7,9,10,12,13,15,17-23,25,29,32-35
IP2.2-12	Remanufacturing	1-7,9,10,13,15,17,18,20-27,29,31-35
IP2.2-13	Reselling	1-3,5,9,10,12,17,18,20-24,26,27,32,34,35
IP2.2-14	Dis-, reassembly (or demolition)	3-7,9,10,12,13,15,18,19,21,23-25,29-35
IP2.2-15	Re- or upcycling	1-13,15-27,29-36
IP2.2-16	Biodegrading (e.g., composting or anaerobic digestion)	3,5-7,9,12,13,16,18,20,21,23-25,34,35
IP2.2-17	Recovering (i.e., energy recovery through combustion)	1,3,4,6-9,11-13,18,20-23,25,26,29,32-35
IP2.2-18	Monitoring, testing or informational feedback provision	1,3,4,6,7,9,10,12-14,17,18,20-22,24,26,28,30,31, 33-35
IP2.3	**(Re-)production process per (re)activity**	
IP2.3-1	(Re-)casting / (re-)melting	3,5,6,33
IP2.3-2	Imaging and (re)coating	
IP2.3-3	(Re)moulding	23,33
IP2.3-4	(Re)forming	
IP2.3-5	Machining (e.g., milling, sawing, drilling)	
IP2.3-6	Welding	
IP2.3-7	De-, and re-fastening	
IP2.3-8	Adhesive bonding	
IP2.3-9	Crushing / shredding	3,4,9,18,22,32,34
IP2.3-10	Anaerobic digestion and biochemical extraction	7,18,21
IP2.3-11	Additive manufacturing - 3D printing	3,7,11,12,15,20,21,23,34
IP3.1	**Facilities for activities**	
IP3.1-1	Mine	1
IP3.1-2	Factory or production facility	1,4-6,9-11,15,31,32
IP3.1-3	Warehouse	4
IP3.1-4	(Re)distribution centre	
IP3.1-5	Digital platform	1,3,5,6,9-12,18-22,26,27,31,32,34
IP3.1-6	Shop	3,5,9,10,12,16,18,21,22,24,31,35
IP3.1-7	(Re)makerspace	11
IP3.1-8	Home or site of user	1,3,6,9,11,21,23,30,32
IP3.1-9	(Re-)sorting centre	
IP3.1-10	Second-hand shop	5,23
IP3.1-11	Repair café or repair shop	3,5,21,31
IP3.1-12	Return street	
IP3.1-13	Re-factory	32
IP3.1-14	(Re-)print shop	
IP3.1-15	Recycling facility	1-3,5,6,9,12,32
IP3.1-16	Urban mine	

>>>

TOC

TABLE APP. A.5 Industrial model design options per (sub)-parameter

IP3.2	System elements	
IP3.2-1	Built environment	7,13,19
IP3.2-2	Building	3,7,13,19,20,32
IP3.2-3	Building component	7,13,19,20,32
IP3.2-4	Product	1-7,9-36
IP3.2-5	(Sub-)component	1,3-7,9,12-15,18-26,29,32-35
IP3.2-6	Part	1,3-7,9,12-15,18,20-22,24,26,27,29,33-35
IP3.2-7	Material	1-36
IP3.2-8	Resource	1,5,7-11,13,15-34,36
IP4.1	**Mode of transport**	
IP4.1-1	Truck	3
IP4.1-2	Van	
IP4.1-3	Car	
IP4.1-4	Freight ship	3,21,32
IP4.1-5	Freight train	
IP4.1-6	Bike	
IP4.1-7	Bulky transport	
IP4.1-8	Dense transport	3
IP4.2	**Distance**	
IP4.2-1	At home / on site (i.e., ± 0 km)	1,9,15,18,19,23,30
IP4.2-2	Local (i.e., city ± 20 km)	1,4, -7,9,11-13,15,18,19,21,25,30,35
IP4.2-3	Regional (i.e., ± 50 km)	23,30
IP4.2-4	National (i.e., ± 200-300 km)	12,18,33
IP4.2-5	Continental (i.e., ± 300-2000 km)	32
IP4.2-6	Global	4,11,17,23,30,32,33
IP5.1	**Type of energy**	
IP5.1-1	Natural gas	
IP5.1-2	Grey power (i.e., electricity from fossil resources)	18,30
IP5.1-3	Diesel / petrol	18,21,30
IP5.1-4	Bio gas / biofuel	9,21
IP5.1-5	Hydrogen power	
IP5.1-6	Green alternating current (e.g., transformed electricity from PV-cells)	30
IP5.1-7	Green direct current (e.g., electricity from PV-cells)	18
IP5.1-8	Heat from thermal storage	18
IP5.1-9	On-site pre-heating (e.g., horizontal ground loop)	
IP5.1-10	Industrial symbiosis	21
IP5.1-11	Off-site power (i.e., grid energy)	18,30
IP5.1-12	On-site power (i.e., independent generated power)	18,36

TABLE APP. A.6 Business model design options per (sub)-parameter

BP1.1	Partners in supply chain or value network	
BP1.1-1	Government	2,3,8,9,12,17,18,20-22,24-26,29-32
BP1.1-2	Building owner	13,19
BP1.1-3	Expert (e.g., designers, consultants)	1-3,6,8,11,13,15-19,21,24-26,31-33
BP1.1-4	Third-party financier	2,6,10,13,18,31,32
BP1.1-5	Material supplier	1-3,6,17-22,26-28,32,33
BP1.1-6	Part supplier	2,3,5,7,9,14,15,17-22,28,33
BP1.1-7	Manufacturer (e.g., product or building component manufacturer)	1-7,9,10,12-18,20-22,24,26-28,30-34
BP1.1-8	Transporter	2,4,5,8,18,21,26
BP1.1-9	Specialised dealer	1-3,5,6,8-10,12,16,18,21,22,24,32
BP1.1-10	Service provider	1-7,9,10,12,14,17-22,26,27,30,31,33
BP1.1-11	Contractor	19
BP1.1-12	User	1-7,9-14,16-25,27,29-36
BP1.1-13	Maintenance specialist	3,6,14,18,21,30,33
BP1.1-14	Collector	4,5,9,12,18,21,22,26,32
BP1.1-15	Second-hand reseller	1-3,5,10,18,21,22,34
BP1.1-16	Specialised refurbisher	1,3,10,18,21,22,33,34
BP1.1-17	Specialised remanufacturer	1,3,21
BP1.1-18	Specialised recovered material reseller	1,10,21,22,27
BP2.1	**Owner**	
BP2.1-1	Building owner as owner	19
BP2.1-2	Manufacturer as owner	1-4,6,10,18-20,24,25,31,32,34
BP2.1-3	User as owner	1-5,9-11,17,18,20-22,24,30,32,34
BP2.1-4	Specialised dealer as owner	18
BP2.1-5	Service provider as owner	1,3,9,10,17,18,20,22,30
BP2.1-6	Financer as owner	10
BP2.1-7	Contractor as owner	
BP2.2	**Customer**	
BP2.2-1	Building owner as customer (i.e., landlord, housing association, investor)	
BP2.2-2	User as customer (i.e., home-owner or tenant)	2,10,31
BP3.1	**Primary contact customer**	
BP3.1-1	Building owner as contact	
BP3.1-2	User as contact	10,18
BP3.2	**Kind of customer relationship**	
BP3.2-1	Dedicated personal assistance	9,17,26,31
BP3.2-2	Mixed human and auto. interaction (e.g., help-desk and online website)	31
BP3.2-3	Self-service / automated	1,3,9,17,21,26,31

>>>

TOC

TABLE APP. A.6 Business model design options per (sub)-parameter

BP3.3	Primary supply chain partner / contact	
BP3.3-1	Building owner as primary supply-chain partner / contact	
BP3.3-2	Manufacturer as primary supply-chain partner / contact	1
BP3.3-3	Specialised dealer as primary supply-chain partner / contact	1
BP3.3-4	Service provider as primary supply-chain partner / cont.	
BP3.3-5	Contractor as primary supply-chain partner / contact	
BP3.4	**Kind of collaboration**	
BP3.4-1	Buyer-supplier relationship	17,22,31
BP3.4-2	Supply-chain partner-, or customer consultation	3,18-22,24,25
BP3.4-3	Strategic alliance between (non-competing) partners	1,7,8,10,12,17,21,27,31,32
BP3.4-4	Industry association	8
BP3.4-5	Co-creation	2,3,6,10,11,16-22,28,31,32
BP3.4-6	Competition	31
BP3.4-7	Building team	19
BP3.4-8	Joint venture	6,10,18,31
BP4.1	**Cost proposition**	
BP4.1-1	Cost driven (i.e., low cost to manufacture and install)	3,4,18
BP4.1-2	Value driven (e.g., high residual value, high user value)	30
BP4.1-3	Low operational cost driven (e.g., low maintenance costs)	9
BP5.1	**Financial arrangement**	
BP5.1-1	Sale	1-6,9-12,17-22,24-27,30-32,34
BP5.1-2	Sale with warrantee	1,3,5,9,12,18,21,24,32,34
BP5.1-3	Sale and take-back guarantee	1,6,9,21,23
BP5.1-4	Sale and buy-back guarantee	1,9,10,12,18-22,27
BP5.1-5	Sale with deposit	5,9,10,21,22,32
BP5.1-6	Product-service system (PSS)	1-7,9-12,14,17,18,20-22,24,25,27,28,30,31,36
BP5.1-7	For-free	21,30
BP5.1-8	Product lease	1-3,5,9,10,17-21,24,25,27,30-32,34
BP5.1-9	Pay-per-use	1-3,5,6,9,10,17,18,20,21,31,34
BP5.1-10	Use subscription	2,6,10-12,17,18,20,26,31
BP5.1-11	Rent/hire	1,3,5,9,11,12,17,18,20-22,24,25,30,31
BP5.1-12	Pooling /sharing	1-3,5-7,9-12,18-25,27,30-32
BP5.1-13	Trading (fee)	1-3,5,6,9,12,18,21,22,25
BP5.1-14	Performance lease	1,3,4,6,10,12,17-20,31
BP5.1-15	Pay-per-service	1,5,6,9,10,12,17,18,20-22,27,31
BP5.1-16	Reward system (e.g., bonus-malus points, discount on new purchase)	5,9,10,12,18,21,22,31
BP5.1-17	Service subscription	6,10,17-19,25,27

>>>

TOC

TABLE APP. A.6 Business model design options per (sub)-parameter

BP5.2	**Income division**	
BP5.2-1	Income division per company	19
BP5.2-2	Income division in 'mini' coalitions	5,10,14
BP5.2-3	Income division over the value chain	5,10,14,19,20,22
BP6.1	**Product / service proposition**	
BP6.1-1	Building	13,19
BP6.1-2	Building components	19,34
BP6.1-3	Products	1-7,9-13,17-28,30-34
BP6.1-4	(Sub-)components or parts (e.g., for repair or updates)	1,3,5,6,9,12,18,20-22,24-27,34
BP6.1-5	Materials	1,5,9,12,18-22,25-27
BP6.1-6	Resources	1,5,9,12,18-22,25-27
BP6.1-7	Service (e.g., maintenance, advice, connecting, brokering)	1-7,9-14,17-28,30-35
BP6.1-8	Consumables	1,3,4,6,9,12,20,22,25,27,34
BP6.1-9	Use	1-6,9,12,17,18,20-22,24,25,27,30-32,34
BP6.1-10	Performance	1-6,9,12,17,18,20-24,27,31
BP6.1-11	Component use energy	12,18,20,22,25
BP6.2	**Value creation and delivery**	
BP6.2-1	Value through high service / performance / customer experience	1,5-7,9,12,17,18,21,27,30
BP6.2-2	Value through reduction of costs by encouraging sufficiency	1,5
BP6.2-3	Value through less space needed (through demate-rialisation)	12,26
BP6.2-4	Value through (green) prestige or status	12,17,18,20,30
BP6.2-5	Value through lower initial investment	3,5,9,12,17,21,22,26
BP6.2-6	Value through lower Total Cost of Ownership (TCO)	3,5,7,9-12,17-20,26,27
BP6.2-7	Value through lower energy costs	4,18,30
BP6.2-8	Value through higher level of quality of maintenance	13,18
BP6.2-9	Value through (access to) better / high-quality components	1,3-7,9,12,17,18,20-22,27,30,32
BP6.2-10	Value through less 'hassle'	3,5,6,9-12,17-21,26,27,30,32
BP6.2-11	Value through less consumption of materials / energy	5-7,10,12,18,21,22,27,30
BP6.2-12	Value through better Life Cycle Assessment (LCA) / climate performance	5-7,9,10,12,18-22,24,26,28,30
BP6.2-13	Value for risk reduction	12,17,18
BP6.2-14	Value through customisation options	3-7,9,11-13,17,18,20,21,26,30
BP6.2-15	Value though upgrade opportunities	5,12,18,20,21
BP6.2-16	Value through off-balance investment	
BP6.2-17	Value through lower waste-disposal costs	12,26
BP6.2-18	Value through higher end-value of building component / product	6,12,18,20,22,27

>>>

TOC

TABLE APP. A.6 Business model design options per (sub)-parameter

BP6.3	Value capturing	
BP6.3-1	Value through stable revenue streams	10,12,19,20
BP6.3-2	Value through supply-chain interest alignment / collaboration	1,5,9,10,18,20-22,24,27,31,33
BP6.3-3	Value through green reputation for company	9,12,18,20,21
BP6.3-4	Value through becoming market leader	1,24
BP6.3-5	Value through lower risk	1,5,6,9,12,13,18,31,32
BP6.3-6	Value through efficiency by integration of systems (e.g., train-metro)	7,10,18,22,31
BP6.3-7	Lower overall costs	1,5,6,9,10,18,21,33
BP6.3-8	Value through long-term client relations	3,9,10,12,19-21,25,27,31,32
BP6.3-9	Value through increased (process) efficiency	1,8-10,12,18,20,21,27
BP6.3-10	Value through additional / untapped market share and revenue streams	1-3,5,8,9,12,18,20,21,25-27,30,31,34
BP6.3-11	Value through lower resource costs	1,5,9,10,12,20,21,26
BP6.3-12	Value through consistent resource supply	1,3,6,9,12,18,20,21,25,27,31-33
BP6.3-13	Value through less consumption of materials	1,2,5,6,9,10,12,13,21-28,30
BP6.3-14	Value through better Life Cycle Assessment (LCA) / climate performance	5-7,9,10,12,18-22,24,26,28,30
BP6.3-15	Value through lower logistic costs	8,10,12
BP6.3-16	Value through 'premium' cost price or higher margins (for quality product)	1,5,9,12,18,21,25,27
BP6.3-17	Additional revenues from long lifespan of component	1-5,10,12,13,18,20,21,25,26,34
BP6.3-18	Increased profit from reparability of component / part	1-3,5,10,12,18,20,21,26,27
BP6.3-19	Long-term customer loyalty / lock-in (i.e., repeat sales of consumables)	3,5,6,9,10,12,20,22,25,32
BP6.3-20	Increased profit from end-value product / part (i.e., reusability)	1-6,9,10,12,18-22,25-27,29,32-34
BP6.3-21	Increased profit from end-value material (i.e., reuse and recyclability)	1,3-8,10,12,18-22,25-27,29,31,33,34
BP6.3-22	Increased profit from energy savings	5,7,9,20
BP6.3-23	Increased profit by saving on recycle costs	1,8,9,12,20,21,27,29
BP6.3-24	Value through job / company growth	2,9,12,13,20,21
BP6.3-25	Higher profit margins through service proposition	1,3,5,9,10,12,18,21,25,27,32
BP7.1	**Key resources per supply chain partner**	
BP7.1-1	Physical resources (i.e., system elements and facilities for activities)	3,6,17,18,21,22,24,26,28,30,31
BP7.1-2	Intellectual resources (e.g., partnership / IP / brand)	3,6,17,18,21,22,26,31
BP7.1-3	Human resources (e.g., skilled / unskilled employees)	3,6,17,18,26,31,36
BP7.1-4	Financial resources (e.g., cash / finance capacity)	3,6,17,21,26,31

>>>

TABLE APP. A.6 Business model design options per (sub)-parameter

BP8.1	Sale and (re)loop channels	
BP8.1-1	Online (re)store	1,2,9,10,12,18,20,21,31
BP8.1-2	Customer community	3,31
BP8.1-3	Post-purchase customer support	3,31
BP8.1-4	Online (second-hand) marketplace or platform	1,3,5,6,9-12,18-22,26,27,31,32,34
BP8.1-5	(Re)store	3,5,9,10,12,16,18,21,22,24,31,35
BP8.1-6	On phone sale	
BP8.1-7	Online repair website	32
BP8.1-8	(Social) media advertisement	20
BP8.1-9	(Social media) sales team or influencers	20
BP9.1	**Facilities for take-back**	
BP9.1-1	(Nation-wide) collection points	5,10,12,21,32
BP9.1-2	At home pick-up	9,12,18,32
BP9.1-3	In store drop-off	9,12,21
BP9.1-5	Postal return	9,12
BP10.1	**Circular business model adoption factors**	
BP10.1-1	Circular leadership present	1,4,18-20,28
BP10.1-2	Work from circular ambitions for a project and process	19,33
BP10.1-3	Expertise for developing and implementing circular innovations	6,7,9,18-21,24,25,28,31-33
BP10.1-4	Need for change (in society and businesses)	2,18,20,21,25,28,30
BP10.1-5	CE concept accepted by society	13,17,20,21
BP10.1-6	Consistency in / long-term commitment by the supply-chain partners	19,30
BP10.1-7	Trust between supply-chain partners	1,9,10,18,19,22,31
BP10.1-8	Supply-chain acceptance and motivation	4,9,10,13,17-20,22-25,28
BP10.1-9	Certainty of benefit for supply-chain partners	1,2,9,17-20,22,24,32
BP10.1-10	Supply-chain alignment or collaboration possible	4,9,10,18-20,22,24,25,27,28
BP10.1-11	Customer is aware of circular offer	4,18,23,26,30,31
BP10.1-12	Customer acceptance and demand	2,3,9,10,11,18,20-26,30,31,34
BP10.1-13	Customer behaviour	4,7,9-11,20,21,28,30-33
BP10.1-14	Political acceptance	6,20
BP10.1-15	Driving policy and legislation	2,5,6,8-10,12,13,15,17,18,20,21,24-26,28,30,32
BP10.1-16	Resource availability	2,9,18,20,21,24,26,28
BP10.1-17	Geographical proximity	9,20,21
BP10.1-18	Technical ability	1,2,4,7,11,16-18,20,21,23,28,34

References

[1] Achterberg, E., Hinfelaar, J., & Bocken, N. (2016). *Master circular business with the value hill*. Retrieved from https://www.circle-economy.com/wp-content/uploads/2016/09/finance-white-paper-20160923.pdf

[2] Antikainen, M., & Valkokari, K. (2016). A framework for sustainable circular business model innovation. *Technology Innovation Management Review*, *6*(7), 5–12. https://doi.org/http://timreview.ca/article/1000

[3] Bakker, Conny, den Hollander, M., van Hinte, E., & Zijlstra, Y. (2014). *Products That Last*. Delft: TU Delft Library & Marcel den Hollander IDRC.

[4] Balkenende, R., & Bakker, C. A. (2015). Developments and challenges in design for sustainability of electronics. In R. Curran, N. Wognum, M. Borsato, J. Stjepandić, & W. J. C. Verhagen (Eds.), *Transdisciplinary Lifecycle Analysis of Systems: Proceedings of the 22nd ISPE Inc. International Conference on Concurrent Engineering*. https://doi.org/10.3233/978-1-61499-544-9-3

[5] Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

[6] Ellen MacArthur Foundation, & IDEO. (2017). The circular design guide. Retrieved August 27, 2018, from https://www.circulardesignguide.com/

[7] Ellen MacArthur Foundation. (2015). *Growth within: a circular economy vision for a competitive europe*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf

[8] Ellen MacArthur Foundation. (2013). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Retrieved from https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

[9] Evans, J., & Bocken, N. M. P. (2013). Circular Economy Toolkit. Retrieved August 22, 2018, from http://circulareconomytoolkit.org/ and Evans, J. L., & Bocken, N. M. P. (2014). A tool for manufacturers to find opportunity in the circular economy: www.circulareconomytoolkit.org. In R. Setchi, R. J. Howlett, M. Naim, & H. Seinz (Eds.), *KES Transactions on Sustainable Design and Manufacturing I* (pp. 303–320). England, UK: Future Technology Press.

[10] Fischer, A., & Achterberg, E. (2016). *Create a financeable circular business in 10 steps*. The Netherlands: Circle Economy & Sustainable Finance Lab.

[11] Forum for the Future, & Novelis. (n.d.). Design for Demand. Retrieved August 28, 2018, from http://designfordemand.forumforthefuture.org/

[12] Forum for the Future, & Unilever. (n.d.). Circular business models. https://doi.org/10.1007/978-3-319-71791-3

[13] Geldermans, R. J. (2016). Design for change and circularity - Accommodating circular material & product flows in construction. *Energy Procedia*, *96*, 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

[14] Gerritsen, M. (2015). *Circular Design Checklist*. The Netherlands: Reversed Concepts.

[15] Gispen. (n.d.). Design framework. Retrieved August 24, 2018, from https://www.gispen.com/nl/circulaire-economie/het-ontwerpproces-circulaire-economie

[16] Goldsworthy, K. (2017). The Speedcycle: A design-led framework for fast and slow circular fashion lifecycles. *The Design Journal*, *20*(sup1), S1960–S1970. https://doi.org/10.1080/14606925.2017.1352714

[17] Hofmann, F., Marwede, M., F, N., & D, K. (2017). Circular added value: Business model design in the circular economy. In C. Bakker & R. Mugge (Eds.), *PLATE Product Lifetimes And The Environment 2017* (pp. 171–177). https://doi.org/10.3233/978-1-61499-820-4-171

[18] Joustra, D. J., de Jong, E., & Engelaer, F. (2013). *Guided choices towards a circular business model*. Retrieved from http://www.opai.eu/uploads/Guided_Choices_towards_a_Circular_Business_Model_pdf11.pdf

[19] Leising, E., Quist, J., & Bocken, N. (2018). Circular economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

[20] Lewandowski, M. (2016). Designing the business models for circular economy - Towards the conceptual framework. *Sustainability*, *8*(43), 1–28. https://doi.org/10.3390/su8010043
[21] Lüdeke-Freund, F., Gold, S., & Bocken, N. M. P. (2018). A review and typology of circular economy business model patterns. *Journal of Industrial and Production Engineering*, *23*(1). https://doi.org/10.1111/jiec.12763
[22] Mentink, B. (2014). Circular Business Model Innovation: A process framework and a tool for business model innovation in a circular economy. Delft University of Technology & Leiden University.
[23] Mestre, A., & Cooper, T. (2017). Circular product design: A multiple loops life cycle design approach for the circular economy. *The Design Journal*, *20*(sup1), S1620–S1635. https://doi.org/10.1080/14606925.2017.1352686
[24] Mendoza, J. M. F., Sharmina, M., Gallego-Schmid, A., Heyes, G., & Azapagic, A. (2017). Integrating backcasting and eco-design for the circular economy: The BECE framework. *Journal of Industrial Ecology*, *21*(3), 526–544. https://doi.org/10.1111/jiec.12590
[25] Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. *Sustainability*, *8*(937), 1–15. https://doi.org/10.3390/su8090937
[26] Nußholz, J. (2017a). Circular Business Model Framework : Mapping value creation architectures along the product lifecycle. In C. A. Bakker & R. Mugge (Eds.), *PLATE Product Lifetimes And The Environment 2017*. Delft: IOS press.
[27] Nußholz, J. (2017b). Circular business models: Defining a concept and framing an emerging research field. *Sustainability*, *9*(1810), 2–16. https://doi.org/10.3390/su9101810
[28] Pádua, M. De, Pigosso, D. C. A., & Mcaloone, T. C. (2018). Sustainable qualifying criteria for designing circular business models. *Procedia CIRP*, *69*(May), 799–804. https://doi.org/10.1016/j.procir.2017.11.014
[29] Poppelaars, F. (2014). Designing for a circular economy: The conceptual design of a circular mobile device. Delft University of Technology.
[30] Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *Journal of Cleaner Production*, *114*, 257–268. https://doi.org/10.1016/j.jclepro.2015.05.075
[31] Sempels, C. (2014). Implementing a circular and performance economy through business model innovation. In Ellen MacArthur Foundation (Ed.), *A new dynamics: Effective business in a circular economy*. Cowes, UK: Ellen MacArthur Foundation.
[32] The Great Recovery, & RSA. (2013). *Investigating the role of design in the circular economy*. UK: The Great Recovery & RSA.
[33] Toxopeus, M. E., van den Hout, N. B., & van Diepen, B. G. D. (2018). Supporting product development with a practical tool for applying the strategy of resource circulation. *Procedia CIRP*, *69*, 680–685. https://doi.org/10.1016/j.procir.2017.11.033
[34] van Dam, S. S., Bakker, C. A., De Pauw, I., & Van Der Grinten, B. (2017). The circular pathfinder: development and evaluation of a practice-based tool for selecting circular design strategies. *PLATE Product Lifetimes And The Environment 2017*, 102–107. https://doi.org/10.3233/978-1-61499-820-4-102
[35] van den Berg, M. R., & Bakker, C. A. (2015). A product design framework for a circular economy. *PLATE Product Lifetimes And The Environment 2015*, 365–379. Nottingham: Nottingham Trent University.
[36] WIITHAA. (n.d.). Tools - Circulab board, the business game to activate your circular business model. Retrieved August 27, 2018, from https://circulab.eu/tools/#board

APP. B Appendix Chapter 5

APP. B.1 Determining the allocation fraction in CE-LCA using an equal distribution or CE LD allocation approach

In this appendix we explain how to determine the allocation fraction – parameter Af – in a Circular Economy Life Cycle Assessment (CE-LCA) of a building component following an equal distribution approach or using the Circular Economy Linearly Degressive (CE LD) approach (Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020). As discussed in Section 5.4.3, Af determines the fraction of impact of the building component system that is allocated to the assessed building component. In CE-LCA, the impacts are calculated on material level using equation 5.3. There, the Af specifies how much impact of each lifecycle stage within a material's life cycle is allocated to the use cycle where the material is applied in the assessed building component.

APP. B.1.1 Equal distribution approach

Af is influenced by the total number of use cycles within a material's lifecycle, captured by parameter N_{cycles}. For example, before wood is applied in the assessed building component – a façade – it had a previous use cycle in another building (use cycle 1); after use in the façade (use cycle 2), the wood is chipped for OSB production (use cycle 3); after that use cycle, the wood is incinerated for energy production (use cycle 4). In this case the number of use cycles within the wood lifecycle (N_{cycles}) is 4. If impacts are distributed equally between cycles and we assume the cycles are of equal length, the value of Af equals a fraction of N_{cycles} (see equation B.1a):

$$Af = \frac{1}{N_{cycles}} \quad \text{(B.1a)}$$

If impacts are distributed equally and the cycles are not of equal length, the length of the current cycle $(\Delta t_{current\ cycle})$ can be divided by the length of all use cycles within the material's lifecycle $(\Delta t_{all\ cycles})$ using equation B.1b.

$$Af = \frac{\Delta t_{current\ cycle}}{\Delta t_{all\ cycles}} \quad \text{(B.1b)}$$

APP. B.1.2 Circular Economy Linearly Degressive approach

The CE LD approach divides impacts from initial production and construction (all life cycle stages before the first use), VRPs (all life cycle stages after first use and prior to disposal), and disposal differently. The majority share of the impact is allocated to the use cycle where the impacts occur. For the initial production and construction this is cycle number (C_{number}) 1. The share of impact allocated to subsequent cycles decreases linearly (see Figure App.B.1). For disposal impacts the majority share is allocated to the last cycle and impacts are allocated to previous cycles in a linearly degressive manner. The impacts of VRPs are allocated equally over all use cycles. Note that the impacts from initial production and construction, VRPs and disposal allocated per use cycles should add up to 100% of the impacts generated throughout the entire lifecycle (represented by the grey area in Figure App.B.1). In other words, impacts over the entire lifecycle do not 'disappear'.

The CE LD approach consists of a series of equations: how the impacts are divided between cycles depends on two parameters. First, on the total number of use cycles within the materials lifecycle - parameter N_{cycles}. Second, a factor (F) determining how much more impact of initial production and construction should be allocated to the first cycle versus the last cycle; vice versa for the disposal impacts. To apply the CE LD approach in the CE-LCA of a building component, the Af of initial production and construction, VRPs and disposal of each material (with different use cycles) applied in the building component needs to be determined.

Determining the allocation fraction of initial production and construction impacts for a material

To calculate the amount of initial production and construction impacts allocated to each use cycle of a material (see Figure App.B.1), equations B.2-5 can be applied. These equations were derived from Malabi Eberhardt et al. (2020, pp. 9 & Supplementary material S3).

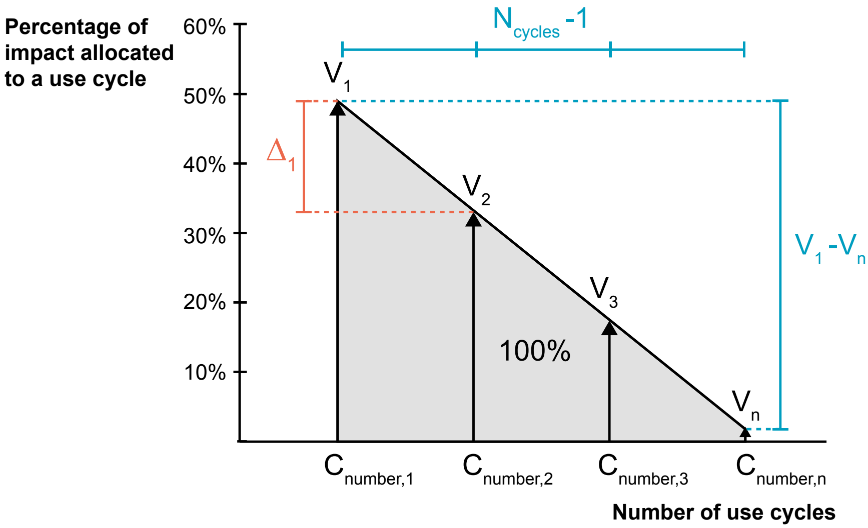


FIG. APP. B.1 Explanatory figure illustrating the CE LD equations to determine the percentage of impact of initial production and construction impacts allocated to each use cycle of a material (adapted from Malabi Eberhardt et al. (2020))

The percentage of initial production and construction impacts of a materials allocated to its first use cycle (V_1) can be calculated using equation B.2:

$$V_1 = \frac{2 \cdot F}{N_{cycles} \cdot (F+1)} \cdot 100\% \qquad \text{(B.2)}$$

Where F is the factor determining how much more impact is allocated to the first use cycle versus the last use cycle. Malabi Eberhardt et al. (2020) propose in their CE LD approach to set the F on 50; we applied this in the case of the circular kitchen. The value for N_{cycles} is determined by the number of use cycles for the material, represented by $C_{number,\,n}$ in Figure App.B.1. This value should be found in the CE-LCI of the building material. Please note that VRPs indicate the start of a new use cycle, for example, reuse, remanufacturing, recycling, composting, or recovery; we do not consider the final disposal of a material as a use cycle.

Likewise, the percentage of initial production and construction impacts of a material allocated to its last use cycle (V_n) can be calculated using equation B.3:

$$V_n = \frac{2}{N_{cycles} \cdot (F+1)} \cdot 100\% \tag{B.3}$$

To determine the amount of the initial production and construction impacts allocated to intermediate use cycles, we first need to calculate the Δ_1 (shown in orange in Figure App.B.1). Δ_1 expresses the decrease in percentage of impacts allocated between cycle 1 and cycle 2 (represented by $C_{number,1}$ and $C_{number,2}$, respectively, in Figure App.B.1). The Δ_1 can be calculated using equation B.4:

$$\Delta_1 = \frac{V_1 - V_n}{N_{cycles} - 1} \tag{B.4}$$

in which we subtract V_n from V_1 and divide this by the number of cycles (N_{cycles}) minus 1 (i.e., the number of spaces between the cycles). These expressions are shown in blue in Figure App.B.1. The percentage of impact of initial production and construction allocated to use cycles 2 of a material can be calculated using equation B.5:

$$\mathrm{V}_2 = \mathrm{V}_1 - \Delta_1 \tag{B.5}$$

TOC

In which the Δ_1 is subtracted from the percentage of impact of initial production and construction allocated to use cycle 1 (V_1). Likewise, the impacts allocated to cycle 3 can be calculated by subtracting Δ_1 from V_2 and so on. Now that the percentage of impacts of initial production and construction allocated to each use cycle is determined (i.e., V_1 to V_n), the Af value for use in the CE-LCA can be selected. The Af can be V_1, V_2, $V_{...}$ to V_n depending on the cycle number (C_{number}) in which the material is when applied in the assessed building component. So, for virgin material the Af is V_1. But for non-virgin material it could be values V_2 to V_n. Which cycle number the material is in should be found in the CE-LCI of the building component.

Determining the allocation fraction of disposal impacts for a material

To determine the Af of disposal impacts of each material (with different use cycles) applied in the building component, equations B.2-5 can be applied in a similar manner. Only, in this case V_1 refers to the impacts allocated to the last use cycle (i.e., where disposal occurs) and V_n refers to the first use cycle (i.e., cycle furthest from disposal).

Determining the allocation fraction of VRP impacts for a material

To determine the Af of VRP impacts of each material (with different use cycles) applied in the building component, the fraction of VRP impacts allocated to each use cycle of a material (V_{VRP}) should be calculated using equation B.6:

$$V_{VRP} = \frac{1}{N_{cycles}} \quad \text{(B..6)}$$

To support the ease of use of the CE LD approach in the CE-LCA model, we provided the allocation fractions for initial production and construction, VRPs, and disposal impacts for an F of 50 and N_{cycles} values between 1-20 in Table App.B.1.

For more information on the background, development and evaluation of the CE LD allocation approach we refer to Malabi Eberhardt et al. (2020, pp. 9 & Supplementary material S3).

TABLE APP. B.1 Precalculated CE LD allocation fractions for F=50

Number of cycles (N_{cycles})	Cycle number (C_{number})	Allocation fraction *(Af)* for initial production and construction impacts [%]	Allocation fraction *(Af)* for VRP impacts [%]	Allocation fraction *(Af)* for disposal impacts [%]
1	1	100%	N/A	100%
2	1	98%	50%	2%
	2	2%	50%	98%
3	1	65%	33%	1%
	2	33%	33%	33%
	3	1%	33%	65%
4	1	49%	25%	1%
	2	33%	25%	17%
	3	17%	25%	33%
	4	1%	25%	49%
5	1	39%	20%	1%
	2	30%	20%	10%
	3	20%	20%	20%
	4	10%	20%	30%
	5	1%	20%	39%
6	1	33%	17%	1%
	2	26%	17%	17%
	3	20%	17%	13%
	4	13%	17%	20%
	5	7%	17%	26%
	6	1%	17%	33%
7	1	28%	14%	1%
	2	23%	14%	5%
	3	19%	14%	10%
	4	14%	14%	14%
	5	10%	14%	19%
	6	5%	14%	23%
	7	1%	14%	28%
8	1	25%	13%	0%
	2	21%	13%	4%
	3	18%	13%	7%
	4	14%	13%	11%
	5	11%	13%	14%
	6	7%	13%	18%
	7	4%	13%	21%
	8	0%	13%	25%

>>>

TOC

TABLE APP. B.1 Precalculated CE LD allocation fractions for F=50

Number of cycles (N_{cycles})	Cycle number (C_{number})	Allocation fraction *(Af)* for initial production and construction impacts [%]	Allocation fraction *(Af)* for VRP impacts [%]	Allocation fraction *(Af)* for disposal impacts [%]
9	1	22%	11%	0%
	2	19%	11%	3%
	3	16%	11%	6%
	4	14%	11%	8%
	5	11%	11%	11%
	6	8%	11%	14%
	7	6%	11%	16%
	8	3%	11%	19%
	9	0%	11%	22%
10	1	20%	10%	0%
	2	17%	10%	3%
	3	15%	10%	5%
	4	13%	10%	7%
	5	11%	10%	9%
	6	9%	10%	11%
	7	7%	10%	13%
	8	5%	10%	15%
	9	3%	10%	17%
	10	0%	10%	20%

The percentages in this table have been rounded of to the nearest whole number

References

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

APP. B.2 Detailed CE-LCI of the kitchen variants

In this appendix we have provided the detailed CE-LCI of the kitchen variants.

TABLE APP. B.2 Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
BAU kitchen	Lower kitchen cabinet		Panels	Particle board	$M_{1.1.1}$	A.1.1-A1.2	Particle board production	0.037	m3
					$T_{1.1.1}$	A.3.2	Lorry from material supplier to panel coater	24.01*200	kg*km
					$T_{1.1.2}$	A.3.3	Lorry from panel coater to kitchen manufacturer	24.01*50	kg*km
					$T_{1.1.3}$	A.3.4	Lorry from kitchen manufacturer to user	24.01*200	kg*km
					$T_{1.1.4}+P_{1.1.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	24.01	kg
				Melamine coating	$M_{1.2.1}$	A.1.1-A1.2	Coating with melamine paper	2.41	m2
					$T_{1.2.1}$	A.3.2	Lorry from material supplier to panel coater	4.72*200	kg*km
					$T_{1.2.2}$	A.3.3	Lorry from panel coater to kitchen manufacturer	4.72*50	kg*km
					$T_{1.2.3}$	A.3.4	Lorry from kitchen manufacturer to user	4.72*200	kg*km
					$T_{1.2.4}+P_{1.2.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	4.72	kg
			Back-panel	MDF	$M_{1.3.1}$	A.1.1-A1.2	MDF board production	0.0014	m3
					$T_{1.3.1}$	A.3.2	Lorry from material supplier to panel coater	0.9*200	kg*km
					$T_{1.3.2}$	A.3.3	Lorry from panel coater to kitchen manufacturer	0.9*50	kg*km
					$T_{1.3.3}$	A.3.4	Lorry from kitchen manufacturer to user	0.9*200	kg*km
					$T_{1.3.4}+P_{1.3.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.9	kg

>>>

TABLE APP. B.2 Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
BAU kitchen	Lower kitchen cabinet			Melamine coating	$M_{1.4.1}$	A.1.1-A1.2	Coating with melamine paper	0.23	m2
					$T_{1.4.1}$	A.3.2	Lorry from material supplier to panel coater	0.45*200	kg*km
					$T_{1.4.2}$	A.3.3	Lorry from panel coater to kitchen manufac-turer	0.45*50	kg*km
					$T_{1.4.3}$	A.3.4	Lorry from kitchen manufacturer to user	0.45*200	kg*km
					$T_{1.4.4}+P_{1.4.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.45	kg
			Structural lath	Spruce	$M_{1.5.1}$	A.1.1-A1.2	Spruce lath production	0.52	kg
					$T_{1.5.1}$	A.3.2	Lorry from material supplier to kitchen manufacturer	0.52*200	kg*km
					$T_{1.5.2}$	A.3.4	Lorry from kitchen manufacturer to user	0.52*200	kg*km
					$T_{1.5.3}+P_{1.5.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.52	kg

>>>

TOC

TABLE APP. B.2 Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
BAU kitchen	Lower kitchen cabinet		Feet	Poly-propylene	$M_{1.6.1}$	A.1.1-A1.2	PP production	0.40	kg
					$T_{1.6.1}$	A.3.2	Lorry material supplier to part manufacturer	0.40*400	kg*km
					$P_{1.6.1}$	A.3.2	Part production using injection moulding	0.40	kg
					$T_{1.6.2}$	A.3.3	Lorry from part man-ufacturer to kitchen manufacturer	0.40*200	kg*km
					$T_{1.6.3}$	A.3.4	Lorry from kitchen manufacturer to user	0.40*200	kg*km
					$T_{1.6.4}$	C.5.7	Lorry from user to material recycler	0.40*400	kg*km
					$P_{1.6.2}$	C.5.7	Recycling plastics	0.40	kg
					$T_{1.6.5}$	C.5.7	Lorry from material recycler to user	0.40*400	kg*km
					$T_{1.6.6}$+$P_{1.6.3}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.40	kg
			Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{1.7.1}$	A.1.1-A1.2	Production hot rolled stainless steel	1.83	kg
					$T_{1.7.1}$	A.3.2	Container ship from material supplier to part manufacturer	1.83*2500	kg*km
					$T_{1.7.2}$	A.3.2	Lorry material supplier to part manufacturer	1.83*400	kg*km
					$T_{1.7.3}$	A.3.3	Lorry from part man-ufacturer to kitchen manufacturer	1.83*200	kg*km
					$T_{1.7.4}$	A.3.4	Lorry from kitchen manufacturer to user	1.83*200	kg*km
					$T_{1.7.5}$	C.5.7	(10 times) Lorry from user to material recycler	10*1.83*400	kg*km
					$P_{1.7.1}$ $T_{1.7.6}$	C.5.7	(10 times) Recycling metals + transport from recycler to user (in dataset)	10*1.83	kg

>>>

TOC

TABLE APP. B.2 Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
BAU kitchen	Lower kitchen cabinet		Glue	PVAC	$M_{1.8.1}$	A.1.1-A1.2	PVAC production	0.10	kg
					$T_{1.8.1}$	A.3.2	Lorry material supplier to kitchen manufac-turer	0.10*200	kg*km
					$T_{1.8.2}$	A.3.4	Lorry from kitchen manufacturer to user	0.10*200	kg*km
					$T_{1.8.3}+P_{1.8.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.10	kg

TABLE APP. B.3 (continued) Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$M_{1.1.1}$	particle board production, uncoated, average glue mix | particleboard, uncoated | APOS, S - RER	Initial production and con-struction
$T_{1.1.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.1.4}+P_{1.1.1}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{1.2.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and con-struction
$T_{1.2.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{1.2.4}+P_{1.2.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{1.3.1}$	medium density fibre board production, uncoated | medium density fibreboard | APOS, S - RER	Initial production and con-struction

>>>

TOC

TABLE APP. B.3 (continued) Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$T_{1.3.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.3.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.3.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.3.4}+P_{1.3.1}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{1.4.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and construction
$T_{1.4.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.4.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.4.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.4.4}+P_{1.4.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{1.5.1}$	planing, lath, softwood, u=10% | sawnwood, lath, softwood, dried (u=10%), planed | APOS, S - CH	Initial production and construction
$T_{1.5.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.5.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.5.3}+P_{1.5.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{1.6.1}$	polypropylene production, granulate | polypropylene, granulate | APOS, S - RER	Initial production and construction
$T_{1.6.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$P_{1.6.1}$	injection moulding | injection moulding | APOS, S - RER	Initial production and construction
$T_{1.6.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.6.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.6.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$P_{1.6.2}$	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | APOS, S - Europe without Switzerland	Value retention processes

>>>

TOC

TABLE APP. B.3 (continued) Detailed CE-LCI for the Business-As-Usual (BAU) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$T_{1.6.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{1.6.6}+P_{1.6.3}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{1.7.1}$	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | APOS, S - RER	Initial production and construction
$T_{1.7.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{1.7.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.7.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.7.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.7.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$P_{1.7.1}$ $T_{1.7.6}$	steel production, converter, unalloyed | steel, unalloyed | APOS, S - RER	Value retention processes
$M_{1.8.1}$	polyurethane production, flexible foam | polyurethane, flexible foam | APOS, S - RER	Initial production and construction
$T_{1.8.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.8.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{1.8.3}+P_{1.8.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes

TABLE APP. B.4 Detailed CE-LCI for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
Recclaim! kitchen	Lower kitchen cabinet		Panels	Particle board	$M_{2.1.1}$	A.1.1	Particle board production	0.037	m3
					$T_{2.1.1}$	A.1.2	Lorry from material supplier to panel coater	24.01*200	kg*km
					$T_{2.1.2}$	A.1.2	Lorry from panel coater to kitchen manufacturer	24.01*50	kg*km
					$T_{2.1.3}$	A.1.3	Lorry from kitchen manufacturer to user	24.01*200	kg*km
					$T_{2.1.4}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	24.01*200	kg*km
					$T_{2.1.5}$	A.3.4	Lorry from kitchen manufacturer to user	24.01*200	kg*km
					$T_{2.1.6}+P_{2.1.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	24.01	kg
				Melamine coating	$M_{2.2.1}$	A.1.1	Coating with melamine paper	2.41	m2
					$T_{2.2.1}$	A.1.2	Lorry from material supplier to panel coater	4.72*200	kg*km
					$T_{2.2.2}$	A.1.2	Lorry from panel coater to kitchen manufacturer	4.72*50	kg*km
					$T_{2.2.3}$	A.1.3	Lorry from kitchen manufacturer to user	4.72*200	kg*km
					$T_{2.2.4}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	4.72*200	kg*km
					$T_{2.2.5}$	A.3.4	Lorry from kitchen manufacturer to user	4.72*200	kg*km
					$T_{2.2.6}+P_{2.2.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	4.72	kg

>>>

TOC

TABLE APP. B.4 Detailed CE-LCI for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
Recclaim! kitchen	Lower kitchen cabinet		Back-panel	MDF	$M_{2.3.1}$	A.1.1	MDF board production	0.0014	m3
					$T_{2.3.1}$	A.1.2	Lorry from material supplier to panel coater	0.9*200	kg*km
					$T_{2.3.2}$	A.1.2	Lorry from panel coater to kitchen manufac-turer	0.9*50	kg*km
					$T_{2.3.3}$	A.1.3	Lorry from kitchen manufacturer to user	0.9*200	kg*km
					$T_{2.3.4}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	0.9*200	kg*km
					$T_{2.3.5}$	A.3.4	Lorry from kitchen manufacturer to user	0.9*200	kg*km
					$T_{2.3.6}+P_{2.3.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.9	kg
				Melamine coating	$M_{2.4.1}$	A.1.1	Coating with melamine paper	0.23	m2
					$T_{2.4.1}$	A.1.2	Lorry from material supplier to panel coater	0.45*200	kg*km
					$T_{2.4.2}$	A.1.2	Lorry from panel coater to kitchen manufac-turer	0.45*50	kg*km
					$T_{2.4.3}$	A.1.3	Lorry from kitchen manufacturer to user	0.45*200	kg*km
					$T_{2.4.4}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	0.45*200	kg*km
					$T_{2.4.5}$	A.3.4	Lorry from kitchen manufacturer to user	0.45*200	kg*km
					$T_{2.4.6}+P_{2.4.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.45	kg

>>>

TOC

TABLE APP. B.4 Detailed CE-LCI for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
Recclaim! kitchen	Lower kitchen cabinet		Structural lath	Spruce	$M_{2.5.1}$	A.1.1	Spruce lath production	0.52	kg
					$T_{2.5.1}$	A.1.2	Lorry from material supplier to kitchen manufacturer	0.52*200	kg*km
					$T_{2.5.2}$	A.1.3	Lorry from kitchen manufacturer to user	0.52*200	kg*km
					$T_{2.5.3}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	0.52*200	kg*km
					$T_{2.5.4}$	A.3.4	Lorry from kitchen manufacturer to user	0.52*200	kg*km
					$T_{2.5.5}+P_{2.5.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.52	kg
			Feet	Poly-propylene	$M_{2.6.1}$	A.1.1	PP production	0.40	kg
					$T_{2.6.1}$	A.1.2	Lorry material supplier to part manufacturer	0.40*400	kg*km
					$P_{1.6.1}$	A.1.2	Part production using injection moulding	0.40	kg
					$T_{2.6.2}$	A.1.2	Lorry from part man-ufacturer to kitchen manufacturer	0.40*200	kg*km
					$T_{2.6.3}$	A.1.3	Lorry from kitchen manufacturer to user	0.40*200	kg*km
					$T_{2.6.4}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	0.40*200	kg*km
					$T_{2.6.5}$	A.3.4	Lorry from kitchen manufacturer to user	0.40*200	kg*km
					$T_{2.6.6}$	C.5.7	Lorry from user to material recycler	0.40*400	kg*km
					$P_{2.6.2}$	C.5.7	Recycling plastics	0.40	kg
					$T_{2.6.7}$	C.5.7	Lorry from material recycler to user	0.40*400	kg*km
					$T_{2.6.8}+P_{2.6.3}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.40	kg

>>>

TABLE APP. B.4 Detailed CE-LCI for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
Recclaim! kitchen	Lower kitchen cabinet		Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{2.7.1}$	A.1.1	Production hot rolled stainless steel	1.83	kg
					$T_{2.7.1}$	A.1.2	Container ship from material supplier to part manufacturer	1.83*2500	kg*km
					$T_{2.7.2}$	A.1.2	Lorry material supplier to part manufacturer	1.83*400	kg*km
					$T_{2.7.3}$	A.1.2	Lorry from part manufacturer to kitchen manufacturer	1.83*200	kg*km
					$T_{2.7.4}$	A.1.3	Lorry from kitchen manufacturer to user	1.83*200	kg*km
					$T_{2.7.5}$	A.2.3	Lorry from user to kitchen manufacturer for reuse materials	1.83*200	kg*km
					$T_{2.7.6}$	A.3.4	Lorry from kitchen manufacturer to user	1.83*200	kg*km
					$T_{2.7.7}$	C.5.7	(10 times) Lorry from user to material recycler	10*1.83*400	kg*km
					$T_{2.7.8}+P_{2.7.1}$	C.5.7	(10 times) Recycling metals + transport from recycler to user (in dataset)	10*1.83	kg
			Glue	PVAC	$M_{2.8.1}$	A.1.1-A1.2	PVAC production	0.10	kg
					$T_{2.8.1}$	A.3.2	Lorry material supplier to kitchen manufacturer	0.10*200	kg*km
					$T_{2.8.2}$	A.3.4	Lorry from kitchen manufacturer to user	0.10*200	kg*km
					$T_{2.8.3}+P_{2.8.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.10	kg

TABLE APP. B.5 (continued) Detailed CE-LCI for the Reclaim! kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$M_{2.1.1}$	particle board production, uncoated, average glue mix | particleboard, uncoated | APOS, S - RER	Initial production and construction
$T_{2.1.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.1.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.1.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.1.6}+P_{2.1.1}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{2.2.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and construction
$T_{2.2.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.2.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.2.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.2.6}+P_{2.2.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{2.3.1}$	medium density fibre board production, uncoated | medium density fibreboard | APOS, S - RER	Initial production and construction
$T_{2.3.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.3.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.3.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.3.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.3.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.3.6}+P_{2.3.1}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes

>>>

TABLE APP. B.5 (continued) Detailed CE-LCI for the Reclaim! kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$M_{2.4.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and construction
$T_{2.4.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.4.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.4.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.4.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.4.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.4.6}$+$P_{2.4.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{2.5.1}$	planing, lath, softwood, u=10% | sawnwood, lath, softwood, dried (u=10%), planed | APOS, S - CH	Initial production and construction
$T_{2.5.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.5.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.5.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.5.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.5.5}$+$P_{2.5.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{2.6.1}$	polypropylene production, granulate | polypropylene, granulate | APOS, S - RER	Initial production and construction
$T_{2.6.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$P_{1.6.1}$	injection moulding | injection moulding | APOS, S - RER	Initial production and construction
$T_{2.6.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.6.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{2.6.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.6.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.6.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes

>>>

TOC

TABLE APP. B.5 (continued) Detailed CE-LCI for the Reclaim! kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$P_{2.6.2}$	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | APOS, S - Europe without Switzerland	Value retention processes
$T_{2.6.7}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.6.8}+P_{2.6.3}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{2.7.1}$	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | APOS, S - RER	Initial production and con-struction
$T_{2.7.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, trans-oceanic ship | APOS, S - GLO	Initial production and con-struction
$T_{2.7.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{2.7.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{2.7.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{2.7.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.7.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.7.7}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{2.7.8}+P_{2.7.1}$	steel production, converter, unalloyed | steel, unalloyed | APOS, S - RER	Value retention processes
$M_{2.8.1}$	polyurethane production, flexible foam | polyurethane, flexible foam | APOS, S - RER	Initial production and con-struction
$T_{2.8.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{2.8.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and con-struction
$T_{2.8.3}+P_{2.8.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	Lower kitchen module	Construction	Frame & feet	Plywood	$M_{3.1.1.1}$	A.1.1-A1.2	Plywood production	0.011	m3
					$T_{3.1.1.1}$	A.3.2	Freight ship from material supplier to kitchen manufacturer	7.86*2500	kg*km
					$T_{3.1.1.2}$	A.3.2	Lorry from material supplier to kitchen manufacturer	7.86*800	kg*km
					$T_{3.1.1.3}$	A.3.4	Lorry from kitchen manufacturer to user	7.86*200	kg*km
					$T_{3.1.1.4}$	C.2.6	Lorry from user to kitchen manufacturer	7.86*200	kg*km
					$T_{3.1.1.5}+P_{3.1.1.1}$	C.5.7	Transport kitchen manuf. to recycler (incl. in data) + chipping for OSB production	7.86	kg
					$T_{3.1.1.6}$	C.5.7	Lorry from OSB producer to user	7.86*400	kg*km
					$T_{3.1.1.7}+P_{3.1.1.2}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	7.86	kg
			Feet extender	Stainless steel	$M_{3.1.2.1}$	A.1.1-A1.2	Production hot rolled stainless steel	0.13	kg
					$T_{3.1.2.1}$	A.3.2	Container ship from material supplier to part manufacturer	0.13*2500	kg*km
					$T_{3.1.2.2}$	A.3.2	Lorry material supplier to part manufacturer	0.13*400	kg*km
					$T_{3.1.2.3}$	A.3.3	Lorry from part man-ufacturer to kitchen manufacturer	0.13*200	kg*km
					$T_{3.1.2.4}$	A.3.4	Lorry from kitchen manufacturer to user	0.13*200	kg*km
					$T_{3.1.2.5}$	C.2.6	Lorry from user to kitchen manufacturer	0.13*200	kg*km
					$T_{3.1.2.6}$	C.5.7	(10 times) Lorry from kitchen manufacturer to material recycler	10*0.13*400	kg*km
					$T_{3.1.2.7}+P_{3.1.2.1}$	C.5.7	(10 times) Recycling metals + transport from recycler to user (in dataset)	10*0.13	kg

>>>

TOC

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	Lower kitchen module	Infill	Back and side panels (thin)	Triplex	$M_{3.2.1.1}$	A.1.1-A1.2	Triplex board production	0.003	m3
					$T_{3.2.1.1}$	A.3.2	Freight ship from material supplier to panel supplier	2.24*2500	kg*km
					$T_{3.2.1.2}$	A.3.2	Lorry from material supplier to panel supplier	2.24*800	kg*km
					$T_{3.2.1.3}$	A.3.3	Lorry from panel supplier to kitchen manufacturer	2.24*50	kg*km
					$T_{3.2.1.4}$	A.3.4	Lorry from kitchen manufacturer to user	2.24*200	kg*km
					$T_{3.2.1.5}$	C.2.6	Lorry from user to kitchen manufacturer	2.24*200	kg*km
					$T_{3.2.1.6}+P_{3.2.1.1}$	C.5.7	Transport kitchen manuf. to recycler (included in dataset) + chipping for OSB pr.	9.68	kg
					$T_{3.2.1.7}$	C.5.7	Lorry from OSB producer to user	9.68*400	kg*km
					$T_{3.2.1.8}+P_{3.2.1.2}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	2.24	kg
			Bottom panel, shelve & drawer panels (thick)	Plywood	$M_{3.2.2.1}$	A.1.1-A1.2	Triplex board production	0.013	m3
					$T_{3.2.2.1}$	A.3.2	Freight ship from material supplier to panel coater	9.68*2500	kg*km
					$T_{3.2.2.2}$	A.3.2	Lorry from material supplier to panel coater	9.68*800	kg*km
					$T_{3.2.2.3}$	A.3.3	Lorry from panel coater to kitchen manufacturer	9.68*50	kg*km
					$T_{3.2.2.4}$	A.3.4	Lorry from kitchen manufacturer to user	9.68*200	kg*km
					$T_{3.2.2.5}$	C.2.6	Lorry from user to kitchen manufacturer	9.68*200	kg*km

>>>

TOC

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	Lower kitchen module	Infill	Bottom panel, shelve & drawer panels (thick)	Plywood	$T_{3.2.2.6}$	C.4.4	Lorry from kitchen manufacturer to refurbisher	9.68*50	kg*km
					$T_{3.2.2.7}$	C.4.4	Lorry from refurbisher to user	9.68*200	kg*km
					$T_{3.2.2.8}$+$P_{3.2.2.1}$	C.5.7	Transport user to recycler (included in dataset) + chipping for OSB production	9.68	kg
					$T_{3.2.2.9}$	C.5.7	Lorry from OSB producer to user	9.68*400	kg*km
					$T_{3.2.2.10}$+$P_{3.2.2.2}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	9.68	kg
				HPL coating	$M_{3.2.3.1}$	A.1.1-A1.2	Coating with melamine paper	0.71	m2
					$T_{3.2.3.1}$	A.3.2	Lorry from material supplier to panel coater	2.11*200	kg*km
					$T_{3.2.3.2}$	A.3.3	Lorry from panel coater to kitchen manufacturer	2.11*50	kg*km
					$T_{3.2.3.3}$	A.3.4	Lorry from kitchen manufacturer to user	2.11*200	kg*km
					$T_{3.2.3.4}$	C.2.6	Lorry from user to kitchen manufacturer	2.11*200	kg*km
					$T_{3.2.3.5}$+$P_{3.2.3.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	2.11	kg
		Finishing	Fronts, side panels & plints	Plywood	$M_{3.3.1.1}$	A.1.1-A1.2	Triplex board production	0.016	m3
					$T_{3.3.1.1}$	A.3.2	Freight ship from material supplier to panel coater	12.1*2500	kg*km
					$T_{3.3.1.2}$	A.3.2	Lorry from material supplier to panel coater	12.1*800	kg*km
					$T_{3.3.1.3}$	A.3.3	Lorry from panel coater to kitchen manufacturer	12.1*50	kg*km

>>>

TOC

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	Lower kitchen module	Finishing	Fronts, side panels & plints	Plywood	$T_{3.3.1.4}$	A.3.4	Lorry from kitchen manufacturer to user	12.1*200	kg*km
					$T_{3.3.1.5}$	C.2.6	Lorry from user to kitchen manufacturer	12.1*200	kg*km
					$T_{3.3.1.6}$	C.4.4	Lorry from kitchen manufacturer to refur-bisher	12.1*50	kg*km
					$T_{3.3.1.7}$	C.4.4	Lorry from refurbisher to user	12.1*200	kg*km
					$T_{3.3.1.8}$+$P_{3.3.1.1}$	C.5.7	Transport user to recycler (included in dataset) + chipping for OSB production	12.1	kg
					$T_{3.3.1.9}$	C.5.7	Lorry from OSB producer to user	12.1*400	kg*km
					$T_{3.3.1.10}$+$P_{3.3.1.2}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	12.1	kg
				HPL coating	$M_{3.3.2.1}$	A.1.1-A1.2	Coating with melamine paper	1.03	m2
					$T_{3.3.2.1}$	A.3.2	Lorry from material supplier to panel coater	2.023*200	kg*km
					$T_{3.3.2.2}$	A.3.3	Lorry from panel coater to kitchen manufac-turer	2.023*50	kg*km
					$T_{3.3.2.3}$	A.3.4	Lorry from kitchen manufacturer to user	2.023*200	kg*km
					$T_{3.3.2.4}$	C.2.6	Lorry from user to kitchen manufacturer	2.023*200	kg*km
					$T_{3.3.2.5}$+$P_{3.3.2.1}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	2.023	kg

>>>

TOC

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	**Lower kitchen module**	**Connectors**	Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{3.4.1.1}$	A.1.1-A1.2	Production hot rolled stainless steel	1.83	kg
					$T_{3.4.1.1}$	A.3.2	Container ship from material supplier to part manufacturer	1.83*2500	kg*km
					$T_{3.4.1.2}$	A.3.2	Lorry material supplier to part manufacturer	1.83*400	kg*km
				Stainless steel	$T_{3.4.1.3}$	A.3.3	Lorry from part manufacturer to kitchen manufacturer	1.83*200	kg*km
					$T_{3.4.1.4}$	A.3.4	Lorry from kitchen manufacturer to user	1.83*200	kg*km
					$T_{3.4.1.5}$	C.2.6	Lorry from user to kitchen manufacturer	1.83*400	kg*km
					$T_{3.4.1.6}$	C.5.7	(10 times) Lorry from kitchen manufacturer to material recycler	10*1.83*400	kg*km
					$T_{3.4.1.7}+P_{3.4.1.1}$	C.5.7	(10 times) Recycling metals + transport from recycler to user (in dataset)	10*1.83	kg

>>>

TOC

TABLE APP. B.6 Detailed CE-LCI for the Plug-and-play (P&P) kitchen

	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	CE-LCA Life cycle stage	Description	Amount	Unit
P&P kitchen	Lower kitchen module	Connectors	Click connector	Poly-propylene	$M_{3.4.2.1}$	A.1.1-A1.2	PE production	0.064	kg
					$T_{3.4.2.1}$	A.3.2	Lorry material supplier to part manufacturer	0.064*400	kg*km
					$T_{3.4.2.2}$	A.3.3	Lorry from part manufacturer to kitchen manufacturer	0.064*200	kg*km
					$T_{3.4.2.3}$	A.3.4	Lorry from kitchen manufacturer to user	0.064*200	kg*km
					$T_{3.4.2.4}$	C.2.6	Lorry from user to kitchen manufacturer	0.064*200	kg*km
					$T_{3.4.2.5}$	C.5.7	(2 times) Lorry from kitchen manufacturer to part manufacturer	2*0.064*200	kg*km
					$P_{3.4.2.1}$	C.5.7	(2 times) Closed loop recycling PE	2*0.064	kg
					$T_{3.4.2.6}$	C.5.7	(2 times) Lorry from part manufacturer to user	2*0.064*200	kg*km
					$T_{3.4.2.7}+P_{3.4.2.2}$	C.6.2	Transport user to incineration plant + Incineration for energy recovery	0.064	kg

TABLE APP. B.7 (continued) Detailed CE-LCI for the Plug-and-Play (P&P) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$M_{3.1.1.1}$	plywood production, for indoor use | plywood, for indoor use | APOS, S - RER	Initial production and construction
$T_{3.1.1.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.1.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.1.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.1.1.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.1.1.5}$+$P_{3.1.1.1}$	treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | APOS, S - CH	Value retention processes
$T_{3.1.1.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.1.1.7}$+$P_{3.1.1.2}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{3.1.2.1}$	steel production, converter, chromium steel 18/8 | steel, chromium steel 18/8 | APOS, S - RER	Initial production and construction
$T_{3.1.2.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.1.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.1.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.1.2.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.1.2.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.1.2.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.1.2.7}$+$P_{3.1.2.1}$	steel production, converter, unalloyed | steel, unalloyed | APOS, S - RER	Value retention processes
$M_{3.2.1.1}$	plywood production, for indoor use | plywood, for indoor use | APOS, S - RER	Initial production and construction
$T_{3.2.1.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.2.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.1.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction

>>>

TABLE APP. B.7 (continued) Detailed CE-LCI for the Plug-and-Play (P&P) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$T_{3.2.1.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.1.6}$+$P_{3.2.1.1}$	treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | APOS, S - CH	Value retention processes
$T_{3.2.1.7}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.1.8}$+$P_{3.2.1.2}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{3.2.2.1}$	plywood production, for indoor use | plywood, for indoor use | APOS, S - RER	Initial production and construction
$T_{3.2.2.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.2.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.2.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.2.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.2.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.2.7}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.2.8}$+$P_{3.2.2.1}$	treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | APOS, S - CH	Value retention processes
$T_{3.2.2.9}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.2.10}$+$P_{3.2.2.2}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{3.2.3.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and construction
$T_{3.2.3.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.3.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.3.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.2.3.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.2.3.5}$+$P_{3.2.3.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes

>>>

TABLE APP. B.7 (continued) Detailed CE-LCI for the Plug-and-Play (P&P) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$M_{3.3.1.1}$	plywood production, for indoor use | plywood, for indoor use | APOS, S - RER	Initial production and construction
$T_{3.3.1.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.3.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.1.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.1.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.3.1.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.3.1.7}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.3.1.8}+P_{3.3.1.1}$	treatment of waste wood, post-consumer, sorting and shredding | wood chips, from post-consumer wood, measured as dry mass | APOS, S - CH	Value retention processes
$T_{3.3.1.9}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.3.1.10}+P_{3.3.1.2}$	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | APOS, S - CH	Value retention processes
$M_{3.3.2.1}$	coating service, melamine impregnated paper, double-sided | coating, with melamine impregnated paper | APOS, S - RER	Initial production and construction
$T_{3.3.2.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.3.2.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.3.2.5}+P_{3.3.2.1}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes
$M_{3.4.1.1}$	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | APOS, S - RER	Initial production and construction
$T_{3.4.1.1}$	transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | APOS, S - GLO	Initial production and construction
$T_{3.4.1.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.4.1.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction

>>>

TOC

TABLE APP. B.7 (continued) Detailed CE-LCI for the Plug-and-Play (P&P) kitchen

Code in LCI flowchart	Ecoinvent dataset (For processes not available in the Ecoinvent Database, we selected the closest available process)	Impact part of allocation: initial production & construction / VRPs / disposal
$T_{3.4.1.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.4.1.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.4.1.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.4.1.7}+P_{3.4.1.1}$	steel production, converter, unalloyed | steel, unalloyed | APOS, S - RER	Value retention processes
$M_{3.4.2.1}$	polyethylene production, low density, granulate | polyethylene, low density, granulate | APOS, S - RER	Initial production and construction
$T_{3.4.2.1}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.4.2.2}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.4.2.3}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Initial production and construction
$T_{3.4.2.4}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.4.2.5}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$P_{3.4.2.1}$	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | APOS, S - Europe without Switzerland	Value retention processes
$T_{3.4.2.6}$	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, S - RER	Value retention processes
$T_{3.4.2.7}+P_{3.4.2.2}$	treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, S - Europe without Switzerland	Value retention processes

APP. B.3 Detailed overview CE-LCIA parameters of kitchen variants

In this appendix we have provided the CE-LCIA parameters for the baseline and all sensitivity scenarios of the kitchen variants. For a further clarification on the sensitivity analysis scenarios, we refer to Appendix B.5.

Note that, in the P&P kitchen variant, when finishing and infill parts with reuse cycles are (re)placed, we assume virgin and reused parts are alternated. As the C_{number} of the virgin and reused parts vary, these parts have multiple sets of CE-LCIA parameters.

TABLE APP. B.8 Detailed CE-LCIA for the Business-As-Usual (BAU) kitchen

						Baseline					
Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
BAU kitchen	Lower kitchen cabinet		Panels	Particle board	$M_{1.1.1}$	1	2	1	80/20	98%	
					$T_{1.1.1}$	1	2	1	80/20	98%	
					$T_{1.1.2}$	1	2	1	80/20	98%	
					$T_{1.1.3}$	1	2	1	80/20	98%	
					$T_{1.1.4}+P_{1.1.1}$	1	2	1	80/20		50%
				Melamine coating	$M_{1.2.1}$	1	2	1	80/20	98%	
					$T_{1.2.1}$	1	2	1	80/20	98%	
					$T_{1.2.2}$	1	2	1	80/20	98%	
					$T_{1.2.3}$	1	2	1	80/20	98%	
					$T_{1.2.4}+P_{1.2.1}$	1	2	1	80/20		50%
			Back-panel	MDF	$M_{1.3.1}$	1	2	1	80/20	98%	
					$T_{1.3.1}$	1	2	1	80/20	98%	
					$T_{1.3.2}$	1	2	1	80/20	98%	
					$T_{1.3.3}$	1	2	1	80/20	98%	
					$T_{1.3.4}+P_{1.3.1}$	1	2	1	80/20		50%
				Melamine coating	$M_{1.4.1}$	1	2	1	80/20	98%	
					$T_{1.4.1}$	1	2	1	80/20	98%	
					$T_{1.4.2}$	1	2	1	80/20	98%	
					$T_{1.4.3}$	1	2	1	80/20	98%	
					$T_{1.4.4}+P_{1.4.1}$	1	2	1	80/20		50%
			Structural lath	Spruce	$M_{1.5.1}$	1	2	1	80/20	98%	
					$T_{1.5.1}$	1	2	1	80/20	98%	
					$T_{1.5.2}$	1	2	1	80/20	98%	
					$T_{1.5.3}+P_{1.5.1}$	1	2	1	80/20		50%

	N_{cycles} | C+1						N_{cycles} | C+2					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%

>>>

TOC

TABLE APP. B.8 Detailed CE-LCIA for the Business-As-Usual (BAU) kitchen

						Baseline					
Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
BAU kitchen	Lower kitchen cabinet		Feet	Poly-propylene	$M_{1.6.1}$	1	3	1	80/20	65%	
					$T_{1.6.1}$	1	3	1	80/20	65%	
					$P_{1.6.1}$	1	3	1	80/20	65%	
					$T_{1.6.2}$	1	3	1	80/20	65%	
					$T_{1.6.3}$	1	3	1	80/20	65%	
					$T_{1.6.4}$	1	3	1	80/20		33%
					$P_{1.6.2}$	1	3	1	80/20		33%
					$T_{1.6.5}$	1	3	1	80/20		33%
					$T_{1.6.6}+P_{1.6.3}$	1	3	1	80/20		33%
			Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{1.7.1}$	1	11	1	80/20	18%	
					$T_{1.7.1}$	1	11	1	80/20	18%	
					$T_{1.7.2}$	1	11	1	80/20	18%	
					$T_{1.7.3}$	1	11	1	80/20	18%	
					$T_{1.7.4}$	1	11	1	80/20	18%	
					$T_{1.7.5}$	1	11	1	80/20		9%
					$P_{1.7.1}$ $T_{1.7.6}$	1	11	1	80/20		9%
			Glue	PVAC	$M_{1.8.1}$	1	2	1	80/20	98%	
					$T_{1.8.1}$	1	2	1	80/20	98%	
					$T_{1.8.2}$	1	2	1	80/20	98%	
					$T_{1.8.3}+P_{1.8.1}$	1	2	1	80/20		50%

	N_{cycles} | C+1						N_{cycles} | C+2					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	4	1	80/20	49%		1	5	1	80/20	39%	
	1	4	1	80/20	49%		1	5	1	80/20	39%	
	1	4	1	80/20	49%		1	5	1	80/20	39%	
	1	4	1	80/20	49%		1	5	1	80/20	39%	
	1	4	1	80/20	49%		1	5	1	80/20	39%	
	1	4	1	80/20		25%	1	5	1	80/20		20%
	1	4	1	80/20		25%	1	5	1	80/20		20%
	1	4	1	80/20		25%	1	5	1	80/20		20%
	1	4	1	80/20		25%	1	5	1	80/20		20%
	1	12	1	80/20	16%		1	13	1	80/20	15%	
	1	12	1	80/20	16%		1	13	1	80/20	15%	
	1	12	1	80/20	16%		1	13	1	80/20	15%	
	1	12	1	80/20	16%		1	13	1	80/20	15%	
	1	12	1	80/20	16%		1	13	1	80/20	15%	
	1	12	1	80/20		8%	1	13	1	80/20		8%
	1	12	1	80/20		8%	1	13	1	80/20		8%
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20	65%		1	4	1	80/20	49%	
	1	3	1	80/20		33%	1	4	1	80/20		25%

TABLE APP. B.9 (continued) Detailed CE-LCIA for the Business-As-Usual (BAU) kitchen

	$L_{technical}$ - $L_{functional}$ | L7						$L_{technical}$ - $L_{functional}$ | L40					
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
$M_{1.1.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.1.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.1.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.1.3}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.1.4}+P_{1.1.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%
$M_{1.2.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.2.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.2.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.2.3}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.2.4}+P_{1.2.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%
$M_{1.3.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.3.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.3.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.3.3}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.3.4}+P_{1.3.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%
$M_{1.4.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.4.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.4.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.4.3}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.4.4}+P_{1.4.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%
$M_{1.5.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.5.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.5.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%	
$T_{1.5.3}+P_{1.5.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%

	$L_{technical}$ - $L_{functional}$ | L80					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%

>>>

TOC

TABLE APP. B.9 (continued) Detailed CE-LCIA for the Business-As-Usual (BAU) kitchen

	$L_{technical}$ - $L_{functional}$ | L7						$L_{technical}$ - $L_{functional}$ | L40						
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	
$M_{1.6.1}$	1	3	1	80/6,7	65%		1	3	1	80/40	65%		
$T_{1.6.1}$	1	3	1	80/6,7	65%		1	3	1	80/40	65%		
$P_{1.6.1}$	1	3	1	80/6,7	65%		1	3	1	80/40	65%		
$T_{1.6.2}$	1	3	1	80/6,7	65%		1	3	1	80/40	65%		
$T_{1.6.3}$	1	3	1	80/6,7	65%		1	3	1	80/40	65%		
$T_{1.6.4}$	1	3	1	80/6,7		33%	1	3	1	80/40		33%	
$P_{1.6.2}$	1	3	1	80/6,7		33%	1	3	1	80/40		33%	
$T_{1.6.5}$	1	3	1	80/6,7		33%	1	3	1	80/40		33%	
$T_{1.6.6}$+$P_{1.6.3}$	1	3	1	80/6,7		33%	1	3	1	80/40		33%	
$M_{1.7.1}$	1	11	1	80/6,7	18%		1	11	1	80/40	18%		
$T_{1.7.1}$	1	11	1	80/6,7	18%		1	11	1	80/40	18%		
$T_{1.7.2}$	1	11	1	80/6,7	18%		1	11	1	80/40	18%		
$T_{1.7.3}$	1	11	1	80/6,7	18%		1	11	1	80/40	18%		
$T_{1.7.4}$	1	11	1	80/6,7	18%		1	11	1	80/40	18%		
$T_{1.7.5}$	1	11	1	80/6,7		9%	1	11	1	80/40		9%	
$P_{1.7.1}$ $T_{1.7.6}$	1	11	1	80/6,7		9%	1	11	1	80/40		9%	
$M_{1.8.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%		
$T_{1.8.1}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%		
$T_{1.8.2}$	1	2	1	80/6,7	98%		1	2	1	80/40	98%		
$T_{1.8.3}$+$P_{1.8.1}$	1	2	1	80/6,7		50%	1	2	1	80/40		50%	

	$L_{technical}$ - $L_{functional}$ | L80					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	3	1	80/80	65%	
	1	3	1	80/80	65%	
	1	3	1	80/80	65%	
	1	3	1	80/80	65%	
	1	3	1	80/80	65%	
	1	3	1	80/80		33%
	1	3	1	80/80		33%
	1	3	1	80/80		33%
	1	3	1	80/80		33%
	1	11	1	80/80	18%	
	1	11	1	80/80	18%	
	1	11	1	80/80	18%	
	1	11	1	80/80	18%	
	1	11	1	80/80	18%	
	1	11	1	80/80		9%
	1	11	1	80/80		9%
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80	98%	
	1	2	1	80/80		50%

TABLE APP. B.10 Detailed CE-LCIA for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	Baseline					
						P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
Reclaim! kitchen	Lower kitchen cabinet		Panels	Particle board	$M_{2.1.1}$	1	3	2	80/10	33%	
					$T_{2.1.1}$	1	3	2	80/10	33%	
					$T_{2.1.2}$	1	3	2	80/10	33%	
					$T_{2.1.3}$	1	3	2	80/10	33%	
					$T_{2.1.4}$	1	3	2	80/10		33%
					$T_{2.1.5}$	1	3	2	80/10		33%
					$T_{2.1.6}+P_{2.1.1}$	1	3	2	80/10		33%
				Melamine coating	$M_{2.2.1}$	1	3	2	80/10	33%	
					$T_{2.2.1}$	1	3	2	80/10	33%	
					$T_{2.2.2}$	1	3	2	80/10	33%	
					$T_{2.2.3}$	1	3	2	80/10	33%	
					$T_{2.2.4}$	1	3	2	80/10		33%
					$T_{2.2.5}$	1	3	2	80/10		33%
					$T_{2.2.6}+P_{2.2.1}$	1	3	2	80/10		33%
			Back-panel	MDF	$M_{2.3.1}$	1	3	2	80/10	33%	
					$T_{2.3.1}$	1	3	2	80/10	33%	
					$T_{2.3.2}$	1	3	2	80/10	33%	
					$T_{2.3.3}$	1	3	2	80/10	33%	
					$T_{2.3.4}$	1	3	2	80/10		33%
					$T_{2.3.5}$	1	3	2	80/10		33%
					$T_{2.3.6}+P_{2.3.1}$	1	3	2	80/10		33%
				Melamine coating	$M_{2.4.1}$	1	3	2	80/10	33%	
					$T_{2.4.1}$	1	3	2	80/10	33%	
					$T_{2.4.2}$	1	3	2	80/10	33%	
					$T_{2.4.3}$	1	3	2	80/10	33%	
					$T_{2.4.4}$	1	3	2	80/10		33%
					$T_{2.4.5}$	1	3	2	80/10		33%
					$T_{2.4.6}+P_{2.4.1}$	1	3	2	80/10		33%
			Structural lath	Spruce	$M_{2.5.1}$	1	3	2	80/10	33%	
					$T_{2.5.1}$	1	3	2	80/10	33%	
					$T_{2.5.2}$	1	3	2	80/10	33%	
					$T_{2.5.3}$	1	3	2	80/10		33%
					$T_{2.5.4}$	1	3	2	80/10		33%
					$T_{2.5.5}+P_{2.5.1}$	1	3	2	80/10		33%

	N_{cycles} | C+1						N_{cycles} | C+2					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10	33%		1	5	2	80/10	30%	
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%
	1	4	2	80/10		25%	1	5	2	80/10		20%

>>>

TABLE APP. B.10 Detailed CE-LCIA for the Reclaim! kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	Baseline					
						P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
Reclaim! kitchen	Lower kitchen cabinet		Feet	Poly-propylene	$M_{2.6.1}$	1	4	2	80/10	33%	
					$T_{2.6.1}$	1	4	2	80/10	33%	
					$P_{1.6.1}$	1	4	2	80/10	33%	
					$T_{2.6.2}$	1	4	2	80/10	33%	
					$T_{2.6.3}$	1	4	2	80/10	33%	
					$T_{2.6.4}$	1	4	2	80/10		25%
					$T_{2.6.5}$	1	4	2	80/10		25%
					$T_{2.6.6}$	1	4	2	80/10		25%
					$P_{2.6.2}$	1	4	2	80/10		25%
					$T_{2.6.7}$	1	4	2	80/10		25%
					$T_{2.6.8}+P_{2.6.3}$	1	4	2	80/10		25%
			Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{2.7.1}$	1	12	2	80/10	15%	
					$T_{2.7.1}$	1	12	2	80/10	15%	
					$T_{2.7.2}$	1	12	2	80/10	15%	
					$T_{2.7.3}$	1	12	2	80/10	15%	
					$T_{2.7.4}$	1	12	2	80/10	15%	
					$T_{2.7.5}$	1	12	2	80/10		8%
					$T_{2.7.6}$	1	12	2	80/10		8%
					$T_{2.7.7}$	1	12	2	80/10		8%
					$T_{2.7.8}+P_{2.7.1}$	1	12	2	80/10		8%
			Glue	PVAC	$M_{2.8.1}$	1	2	1	80/10	98%	
					$T_{2.8.1}$	1	2	1	80/10	98%	
					$T_{2.8.2}$	1	2	1	80/10	98%	
					$T_{2.8.3}+P_{2.8.1}$	1	2	1	80/10		50%

	N_{cycles} | C+1						N_{cycles} | C+2					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	5	2	80/10	30%		1	6	2	80/10	26%	
	1	5	2	80/10	30%		1	6	2	80/10	26%	
	1	5	2	80/10	30%		1	6	2	80/10	26%	
	1	5	2	80/10	30%		1	6	2	80/10	26%	
	1	5	2	80/10	30%		1	6	2	80/10	26%	
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	5	2	80/10		20%	1	6	2	80/10		17%
	1	13	2	80/10	14%		1	14	2	80/10	13%	
	1	13	2	80/10	14%		1	14	2	80/10	13%	
	1	13	2	80/10	14%		1	14	2	80/10	13%	
	1	13	2	80/10	14%		1	14	2	80/10	13%	
	1	13	2	80/10	14%		1	14	2	80/10	13%	
	1	13	2	80/10		8%	1	14	2	80/10		7%
	1	13	2	80/10		8%	1	14	2	80/10		7%
	1	13	2	80/10		8%	1	14	2	80/10		7%
	1	13	2	80/10		8%	1	14	2	80/10		7%
	1	3	1	80/10	65%		1	4	1	80/10	49%	
	1	3	1	80/10	65%		1	4	1	80/10	49%	
	1	3	1	80/10	65%		1	4	1	80/10	49%	
	1	3	1	80/10		33%	1	4	1	80/10		25%

TABLE APP. B.11 (continued) Detailed CE-LCIA for the Reclaim! kitchen

Code in LCI flowchart	$L_{technical}$ - $L_{functional}$ | L7						$L_{technical}$ - $L_{functional}$ | L20					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
$M_{2.1.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.1.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.1.2}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.1.3}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.1.4}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.1.5}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.1.6}+P_{2.1.1}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$M_{2.2.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.2.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.2.2}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.2.3}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.2.4}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.2.5}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.2.6}+P_{2.2.1}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$M_{2.3.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.3.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.3.2}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.3.3}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.3.4}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.3.5}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.3.6}+P_{2.3.1}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$M_{2.4.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.4.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.4.2}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.4.3}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.4.4}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.4.5}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.4.6}+P_{2.4.1}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$M_{2.5.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.5.1}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.5.2}$	1	3	2	80/6,7	33%		1	3	2	80/20	33%	
$T_{2.5.3}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.5.4}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%
$T_{2.5.5}+P_{2.5.1}$	1	3	2	80/6,7		33%	1	3	2	80/20		33%

	$L_{technical}$ - $L_{functional}$ | L40						$L_{technical}$ - $L_{functional}$ | L80					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40	33%		1	3	2	80/80	33%	
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%
	1	3	2	80/40		33%	1	3	2	80/80		33%

>>>

TOC

TABLE APP. B.11 (continued) Detailed CE-LCIA for the Reclaim! kitchen

	$L_{technical}$ - $L_{functional}$ | L7						$L_{technical}$ - $L_{functional}$ | L20					
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
$M_{2.6.1}$	1	4	2	80/6,7	33%		1	4	2	80/20	33%	
$T_{2.6.1}$	1	4	2	80/6,7	33%		1	4	2	80/20	33%	
$P_{1.6.1}$	1	4	2	80/6,7	33%		1	4	2	80/20	33%	
$T_{2.6.2}$	1	4	2	80/6,7	33%		1	4	2	80/20	33%	
$T_{2.6.3}$	1	4	2	80/6,7	33%		1	4	2	80/20	33%	
$T_{2.6.4}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$T_{2.6.5}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$T_{2.6.6}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$P_{2.6.2}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$T_{2.6.7}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$T_{2.6.8}+P_{2.6.3}$	1	4	2	80/6,7		25%	1	4	2	80/20		25%
$M_{2.7.1}$	1	12	2	80/6,7	15%		1	12	2	80/20	15%	
$T_{2.7.1}$	1	12	2	80/6,7	15%		1	12	2	80/20	15%	
$T_{2.7.2}$	1	12	2	80/6,7	15%		1	12	2	80/20	15%	
$T_{2.7.3}$	1	12	2	80/6,7	15%		1	12	2	80/20	15%	
$T_{2.7.4}$	1	12	2	80/6,7	15%		1	12	2	80/20	15%	
$T_{2.7.5}$	1	12	2	80/6,7		8%	1	12	2	80/20		8%
$T_{2.7.6}$	1	12	2	80/6,7		8%	1	12	2	80/20		8%
$T_{2.7.7}$	1	12	2	80/6,7		8%	1	12	2	80/20		8%
$T_{2.7.8}+P_{2.7.1}$	1	12	2	80/6,7		8%	1	12	2	80/20		8%
$M_{2.8.1}$	1	2	1	80/6,7	98%		1	2	1	80/20	98%	
$T_{2.8.1}$	1	2	1	80/6,7	98%		1	2	1	80/20	98%	
$T_{2.8.2}$	1	2	1	80/6,7	98%		1	2	1	80/20	98%	
$T_{2.8.3}+P_{2.8.1}$	1	2	1	80/6,7		50%	1	2	1	80/20		50%

	$L_{technical}$ - $L_{functional}$ | L40						$L_{technical}$ - $L_{functional}$ | L80					
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	4	2	80/40	33%		1	4	2	80/80	33%	
	1	4	2	80/40	33%		1	4	2	80/80	33%	
	1	4	2	80/40	33%		1	4	2	80/80	33%	
	1	4	2	80/40	33%		1	4	2	80/80	33%	
	1	4	2	80/40	33%		1	4	2	80/80	33%	
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	4	2	80/40		25%	1	4	2	80/80		25%
	1	12	2	80/40	15%		1	12	2	80/80	15%	
	1	12	2	80/40	15%		1	12	2	80/80	15%	
	1	12	2	80/40	15%		1	12	2	80/80	15%	
	1	12	2	80/40	15%		1	12	2	80/80	15%	
	1	12	2	80/40	15%		1	12	2	80/80	15%	
	1	12	2	80/40		8%	1	12	2	80/80		8%
	1	12	2	80/40		8%	1	12	2	80/80		8%
	1	12	2	80/40		8%	1	12	2	80/80		8%
	1	12	2	80/40		8%	1	12	2	80/80		8%
	1	2	1	80/40	98%		1	2	1	80/80	98%	
	1	2	1	80/40	98%		1	2	1	80/80	98%	
	1	2	1	80/40	98%		1	2	1	80/80	98%	
	1	2	1	80/40		50%	1	2	1	80/80		50%

TABLE APP. B.12 Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

						Baseline						
Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	
P&P kitchen	Lower kitchen module	Construction	Frame & feet	Plywood	$M_{3.1.1.1}$	1	3	1	80/80	65%		
					$T_{3.1.1.1}$	1	3	1	80/80	65%		
					$T_{3.1.1.2}$	1	3	1	80/80	65%		
					$T_{3.1.1.3}$	1	3	1	80/80	65%		
					$T_{3.1.1.4}$	1	3	1	80/80		33%	
					$T_{3.1.1.5}+P_{3.1.1.1}$	1	3	1	80/80		33%	
					$T_{3.1.1.6}$	1	3	1	80/80		33%	
					$T_{3.1.1.7}+P_{3.1.1.2}$	1	3	1	80/80		33%	
			Feet extender	Stainless steel	$M_{3.1.2.1}$	1	11	1	80/80	18%		
					$T_{3.1.2.1}$	1	11	1	80/80	18%		
					$T_{3.1.2.2}$	1	11	1	80/80	18%		
					$T_{3.1.2.3}$	1	11	1	80/80	18%		
					$T_{3.1.2.4}$	1	11	1	80/80	18%		
					$T_{3.1.2.5}$	1	11	1	80/80		9%	
					$T_{3.1.2.6}$	1	11	1	80/80		9%	
					$T_{3.1.2.7}+P_{3.1.2.1}$	1	11	1	80/80		9%	
		Infill	Back and side panels (thin)	Triplex	$M_{3.2.1.1}$	1	3	1	80/20	65%		
					$T_{3.2.1.1}$	1	3	1	80/20	65%		
					$T_{3.2.1.2}$	1	3	1	80/20	65%		
					$T_{3.2.1.3}$	1	3	1	80/20	65%		
					$T_{3.2.1.4}$	1	3	1	80/20	65%		
					$T_{3.2.1.5}$	1	3	1	80/20		33%	
					$T_{3.2.1.6}+P_{3.2.1.1}$	1	3	1	80/20		33%	
					$T_{3.2.1.7}$	1	3	1	80/20		33%	
					$T_{3.2.1.8}+P_{3.2.1.2}$	1	3	1	80/20		33%	

							N_{cycles} | C-3					
	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
							1	2	1	80/80	98%	
							1	2	1	80/80	98%	
							1	2	1	80/80	98%	
							1	2	1	80/80	98%	
							1	2	1	80/80		50%
							1	2	1	80/80		50%
							1	11	1	80/80	18%	
							1	11	1	80/80	18%	
							1	11	1	80/80	18%	
							1	11	1	80/80	18%	
							1	11	1	80/80	18%	
							1	11	1	80/80		9%
							1	11	1	80/80		9%
							1	11	1	80/80		9%
							1	2	1	80/20	98%	
							1	2	1	80/20	98%	
							1	2	1	80/20	98%	
							1	2	1	80/20	98%	
							1	2	1	80/20	98%	
							1	2	1	80/20		50%
							1	2	1	80/20		50%

>>>

TABLE APP. B.12 Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

						Baseline					
Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
P&P kitchen	Lower kitchen module	Infill	Bottom panel, shelve & drawer panels (thick)	Plywood	$M_{3.2.2.1}$	1	4	1	80/80	49%	
					$T_{3.2.2.1}$	1	4	1	80/80	49%	
					$T_{3.2.2.2}$	1	4	1	80/80	49%	
					$T_{3.2.2.3}$	1	4	1	80/80	49%	
					$T_{3.2.2.4}$	1	4	1	80/80	49%	
					$T_{3.2.2.5}$	1	4	1	80/80		25%
					$T_{3.2.2.6}$	1	4	1	80/80		25%
					$T_{3.2.2.7}$	1	4	1	80/80		25%
					$T_{3.2.2.8}+P_{3.2.2.1}$	1	4	1	80/80		25%
					$T_{3.2.2.9}$	1	4	1	80/80		25%
					$T_{3.2.2.10}+P_{3.2.2.2}$	1	4	1	80/80		25%
				HPL coating	$M_{3.2.3.1}$	1	2	1	80/40	98%	
					$T_{3.2.3.1}$	1	2	1	80/40	98%	
					$T_{3.2.3.2}$	1	2	1	80/40	98%	
					$T_{3.2.3.3}$	1	2	1	80/40	98%	
					$T_{3.2.3.4}$	1	2	1	80/40		50%
					$T_{3.2.3.5}+P_{3.2.3.1}$	1	2	1	80/40		50%
		Finishing	Fronts, side panels & plints	Plywood	$M_{3.3.1.1}$	1	5	1	80/40	39%	
					$T_{3.3.1.1}$	1	5	1	80/40	39%	
					$T_{3.3.1.2}$	1	5	1	80/40	39%	
					$T_{3.3.1.3}$	1	5	1	80/40	39%	
					$T_{3.3.1.4}$	1	5	1	80/40	39%	
					$T_{3.3.1.5}$	1	5	1	80/40		20%
					$T_{3.3.1.6}$	1	5	1	80/40		20%
					$T_{3.3.1.7}$	1	5	1	80/40		20%
					$T_{3.3.1.8}+P_{3.3.1.1}$	1	5	1	80/40		20%
					$T_{3.3.1.9}$	1	5	1	80/40		20%
					$T_{3.3.1.10}+P_{3.3.1.2}$	1	5	1	80/40		20%
				HPL coating	$M_{3.3.2.1}$	1	3	1	80/40	65%	
					$T_{3.3.2.1}$	1	3	1	80/40	65%	
					$T_{3.3.2.2}$	1	3	1	80/40	65%	
					$T_{3.3.2.3}$	1	3	1	80/40	65%	
					$T_{3.3.2.4}$	1	3	1	80/40		33%
					$T_{3.3.2.5}+P_{3.3.2.1}$	1	3	1	80/40		33%

							N_{cycles} | C-3					
	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
	1	4	2	80/80	33%		1	2	1	80/40	98%	
	1	4	2	80/80	33%		1	2	1	80/40	98%	
	1	4	2	80/80	33%		1	2	1	80/40	98%	
	1	4	2	80/80	33%		1	2	1	80/40	98%	
	1	4	2	80/80	33%		1	2	1	80/40	98%	
	1	4	2	80/80		25%	1	2	1	80/40		50%
	1	4	2	80/80		25%						
	1	4	2	80/80		25%						
	1	4	2	80/80		25%						
	1	4	2	80/80		25%						
	1	4	2	80/80		25%	1	2	1	80/40		50%
							1	2	1	80/40	98%	
							1	2	1	80/40	98%	
							1	2	1	80/40	98%	
							1	2	1	80/40	98%	
							1	2	1	80/40		50%
							1	2	1	80/40		50%
	1	5	2	80/40	30%		1	2	1	80/20	98%	
	1	5	2	80/40	30%		1	2	1	80/20	98%	
	1	5	2	80/40	30%		1	2	1	80/20	98%	
	1	5	2	80/40	30%		1	2	1	80/20	98%	
	1	5	2	80/40	30%		1	2	1	80/20	98%	
	1	5	2	80/40		20%	1	2	1	80/20		50%
	1	5	2	80/40		20%						
	1	5	2	80/40		20%						
	1	5	2	80/40		20%						
	1	5	2	80/40		20%						
	1	5	2	80/40		20%	1	2	1	80/20		50%
	1	3	2	80/40	33%		1	2	1	80/20	98%	
	1	3	2	80/40	33%		1	2	1	80/20	98%	
	1	3	2	80/40	33%		1	2	1	80/20	98%	
	1	3	2	80/40	33%		1	2	1	80/20	98%	
	1	3	2	80/40		33%	1	2	1	80/20		50%
	1	3	2	80/40		33%	1	2	1	80/20		50%

>>>

TABLE APP. B.12 Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

Design variant	Sub-components	Sub-sub components	Parts	Materials	Code in LCI flowchart	Baseline					
						P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
P&P kitchen	Lower kitchen module	Connectors	Connectors (shelve carrier, hinges & drawer slides)	Stainless steel	$M_{3.4.1.1}$	1	11	1	80/40	18%	
					$T_{3.4.1.1}$	1	11	1	80/40	18%	
					$T_{3.4.1.2}$	1	11	1	80/40	18%	
					$T_{3.4.1.3}$	1	11	1	80/40	18%	
					$T_{3.4.1.4}$	1	11	1	80/40	18%	
					$T_{3.4.1.5}$	1	11	1	80/40		9%
					$T_{3.4.1.6}$	1	11	1	80/40		9%
					$T_{3.4.1.7}+P_{3.4.1.1}$	1	11	1	80/40		9%
			Click connector	Poly-propylene	$M_{3.4.2.1}$	1	4	1	80/40	49%	
					$T_{3.4.2.1}$	1	4	1	80/40	49%	
					$T_{3.4.2.2}$	1	4	1	80/40	49%	
					$T_{3.4.2.3}$	1	4	1	80/40	49%	
					$T_{3.4.2.4}$	1	4	1	80/40		25%
					$T_{3.4.2.5}$	1	4	1	80/40		25%
					$P_{3.4.2.1}$	1	4	1	80/40		25%
					$T_{3.4.2.6}$	1	4	1	80/40		25%
					$T_{3.4.2.7}+P_{3.4.2.2}$	1	4	1	80/40		25%

**Note that, in the P&P kitchen variant, when finishing and infill parts with reuse cycles are (re)placed, we assume virgin and reused parts are alternated. As the Cnumber of the virgin and reused parts vary, these parts have multiple sets of CE-LCIA parameters.*

TOC

							N_{cycles} | C-3					
	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$
							1	11	1	80/40	18%	
							1	11	1	80/40	18%	
							1	11	1	80/40	18%	
							1	11	1	80/40	18%	
							1	11	1	80/40	18%	
							1	11	1	80/40		9%
							1	11	1	80/40		9%
							1	11	1	80/40		9%
							1	4	1	80/40	49%	
							1	4	1	80/40	49%	
							1	4	1	80/40	49%	
							1	4	1	80/40	49%	
							1	4	1	80/40		25%
							1	4	1	80/40		25%
							1	4	1	80/40		25%
							1	4	1	80/40		25%
							1	4	1	80/40		25%

TABLE APP. B.13 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C-2											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.1.1.1}$	1	2	1	80/80	98%							
$T_{3.1.1.1}$	1	2	1	80/80	98%							
$T_{3.1.1.2}$	1	2	1	80/80	98%							
$T_{3.1.1.3}$	1	2	1	80/80	98%							
$T_{3.1.1.4}$	1	2	1	80/80		50%						
$T_{3.1.1.5}+P_{3.1.1.1}$												
$T_{3.1.1.6}$												
$T_{3.1.1.7}+P_{3.1.1.2}$	1	2	1	80/80		50%						
$M_{3.1.2.1}$	1	11	1	80/80	18%							
$T_{3.1.2.1}$	1	11	1	80/80	18%							
$T_{3.1.2.2}$	1	11	1	80/80	18%							
$T_{3.1.2.3}$	1	11	1	80/80	18%							
$T_{3.1.2.4}$	1	11	1	80/80	18%							
$T_{3.1.2.5}$	1	11	1	80/80		9%						
$T_{3.1.2.6}$	1	11	1	80/80		9%						
$T_{3.1.2.7}+P_{3.1.2.1}$	1	11	1	80/80		9%						
$M_{3.2.1.1}$	1	2	1	80/20	98%							
$T_{3.2.1.1}$	1	2	1	80/20	98%							
$T_{3.2.1.2}$	1	2	1	80/20	98%							
$T_{3.2.1.3}$	1	2	1	80/20	98%							
$T_{3.2.1.4}$	1	2	1	80/20	98%							
$T_{3.2.1.5}$	1	2	1	80/20		50%						
$T_{3.2.1.6}+P_{3.2.1.1}$												
$T_{3.2.1.7}$												
$T_{3.2.1.8}+P_{3.2.1.2}$	1	2	1	80/20		50%						

	N_{cycles} | C-1											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial}$ production and construction,1	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial}$ production and construction,2	$Af_{VRPs,2}$
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80		50%						
	1	2	1	80/80		50%						
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20		50%						
	1	2	1	80/20		50%						

>>>

TABLE APP. B.13 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C-2											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.2.2.1}$	1	2	1	80/40	98%							
$T_{3.2.2.1}$	1	2	1	80/40	98%							
$T_{3.2.2.2}$	1	2	1	80/40	98%							
$T_{3.2.2.3}$	1	2	1	80/40	98%							
$T_{3.2.2.4}$	1	2	1	80/40	98%							
$T_{3.2.2.5}$	1	2	1	80/40		50%						
$T_{3.2.2.6}$												
$T_{3.2.2.7}$												
$T_{3.2.2.8}+P_{3.2.2.1}$												
$T_{3.2.2.9}$												
$T_{3.2.2.10}+P_{3.2.2.2}$	1	2	1	80/40		50%						
$M_{3.2.3.1}$	1	2	1	80/40	98%							
$T_{3.2.3.1}$	1	2	1	80/40	98%							
$T_{3.2.3.2}$	1	2	1	80/40	98%							
$T_{3.2.3.3}$	1	2	1	80/40	98%							
$T_{3.2.3.4}$	1	2	1	80/40		50%						
$T_{3.2.3.5}+P_{3.2.3.1}$	1	2	1	80/40		50%						
$M_{3.3.1.1}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.1.1}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.1.2}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.1.3}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.1.4}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.1.5}$	1	3	1	80/40		33%	1	3	2	80/40		33%
$T_{3.3.1.6}$												
$T_{3.3.1.7}$												
$T_{3.3.1.8}+P_{3.3.1.1}$												
$T_{3.3.1.9}$												
$T_{3.3.1.10}+P_{3.3.1.2}$	1	3	1	80/40		33%	1	3	2	80/40		33%
$M_{3.3.2.1}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.2.1}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.2.2}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.2.3}$	1	3	1	80/40	65%		1	3	2	80/40	33%	
$T_{3.3.2.4}$	1	3	1	80/40		33%	1	3	2	80/40		33%
$T_{3.3.2.5}+P_{3.3.2.1}$	1	3	1	80/40		33%	1	3	2	80/40		33%

	N_{cycles} | C-1											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial}$ production and construction,1	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial}$ production and construction,2	$Af_{VRPs,2}$
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80		33%	1	3	2	80/80		33%
	1	3	1	80/80		33%	1	3	2	80/80		33%
	1	3	1	80/80		33%	1	3	2	80/80		33%
	1	3	1	80/80		33%	1	3	2	80/80		33%
	1	2	1	80/40	98%							
	1	2	1	80/40	98%							
	1	2	1	80/40	98%							
	1	2	1	80/40	98%							
	1	2	1	80/40		50%						
	1	2	1	80/40		50%						
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	3	1	80/40	65%		1	3	2	80/40	33%	
	1	3	1	80/40	65%		1	3	2	80/40	33%	
	1	3	1	80/40	65%		1	3	2	80/40	33%	
	1	3	1	80/40	65%		1	3	2	80/40	33%	
	1	3	1	80/40		33%	1	3	2	80/40		33%
	1	3	1	80/40		33%	1	3	2	80/40		33%

>>>

TABLE APP. B.13 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C-2												
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	
$M_{3.4.1.1}$	1	11	1	80/40	18%								
$T_{3.4.1.1}$	1	11	1	80/40	18%								
$T_{3.4.1.2}$	1	11	1	80/40	18%								
$T_{3.4.1.3}$	1	11	1	80/40	18%								
$T_{3.4.1.4}$	1	11	1	80/40	18%								
$T_{3.4.1.5}$	1	11	1	80/40		9%							
$T_{3.4.1.6}$	1	11	1	80/40		9%							
$T_{3.4.1.7}$+$P_{3.4.1.1}$	1	11	1	80/40		9%							
$M_{3.4.2.1}$	1	4	1	80/40	49%								
$T_{3.4.2.1}$	1	4	1	80/40	49%								
$T_{3.4.2.2}$	1	4	1	80/40	49%								
$T_{3.4.2.3}$	1	4	1	80/40	49%								
$T_{3.4.2.4}$	1	4	1	80/40		25%							
$T_{3.4.2.5}$	1	4	1	80/40		25%							
$P_{3.4.2.1}$	1	4	1	80/40		25%							
$T_{3.4.2.6}$	1	4	1	80/40		25%							
$T_{3.4.2.7}$+$P_{3.4.2.2}$	1	4	1	80/40		25%							

TOC

	N_{cycles} | C-1											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	11	1	80/40	18%							
	1	11	1	80/40	18%							
	1	11	1	80/40	18%							
	1	11	1	80/40	18%							
	1	11	1	80/40	18%							
	1	11	1	80/40		9%						
	1	11	1	80/40		9%						
	1	11	1	80/40		9%						
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40		25%						
	1	4	1	80/40		25%						
	1	4	1	80/40		25%						
	1	4	1	80/40		25%						
	1	4	1	80/40		25%						

TABLE APP. B.14 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C+1											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.1.1.1}$	1	4	1	80/80	49%							
$T_{3.1.1.1}$	1	4	1	80/80	49%							
$T_{3.1.1.2}$	1	4	1	80/80	49%							
$T_{3.1.1.3}$	1	4	1	80/80	49%							
$T_{3.1.1.4}$	1	4	1	80/80		25%						
$T_{3.1.1.5}+P_{3.1.1.1}$	1	4	1	80/80		25%						
$T_{3.1.1.6}$	1	4	1	80/80		25%						
$T_{3.1.1.7}+P_{3.1.1.2}$	1	4	1	80/80		25%						
$M_{3.1.2.1}$	1	12	1	80/80	16%							
$T_{3.1.2.1}$	1	12	1	80/80	16%							
$T_{3.1.2.2}$	1	12	1	80/80	16%							
$T_{3.1.2.3}$	1	12	1	80/80	16%							
$T_{3.1.2.4}$	1	12	1	80/80	16%							
$T_{3.1.2.5}$	1	12	1	80/80		8%						
$T_{3.1.2.6}$	1	12	1	80/80		8%						
$T_{3.1.2.7}+P_{3.1.2.1}$	1	12	1	80/80		8%						
$M_{3.2.1.1}$	1	4	1	80/20	49%							
$T_{3.2.1.1}$	1	4	1	80/20	49%							
$T_{3.2.1.2}$	1	4	1	80/20	49%							
$T_{3.2.1.3}$	1	4	1	80/20	49%							
$T_{3.2.1.4}$	1	4	1	80/20	49%							
$T_{3.2.1.5}$	1	4	1	80/20		25%						
$T_{3.2.1.6}+P_{3.2.1.1}$	1	4	1	80/20		25%						
$T_{3.2.1.7}$	1	4	1	80/20		25%						
$T_{3.2.1.8}+P_{3.2.1.2}$	1	4	1	80/20		25%						

	N_{cycles} | C+2											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial}$ production and construction,1	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial}$ production and construction,2	$Af_{VRPs,2}$
	1	5	1	80/80	39%							
	1	5	1	80/80	39%							
	1	5	1	80/80	39%							
	1	5	1	80/80	39%							
	1	5	1	80/80		20%						
	1	5	1	80/80		20%						
	1	5	1	80/80		20%						
	1	5	1	80/80		20%						
	1	13	1	80/80	15%							
	1	13	1	80/80	15%							
	1	13	1	80/80	15%							
	1	13	1	80/80	15%							
	1	13	1	80/80	15%							
	1	13	1	80/80		8%						
	1	13	1	80/80		8%						
	1	13	1	80/80		8%						
	1	5	1	80/20	39%							
	1	5	1	80/20	39%							
	1	5	1	80/20	39%							
	1	5	1	80/20	39%							
	1	5	1	80/20	39%							
	1	5	1	80/20		20%						
	1	5	1	80/20		20%						
	1	5	1	80/20		20%						
	1	5	1	80/20		20%						

>>>

TABLE APP. B.14 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C+1											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.2.2.1}$	1	5	1	80/80	39%		1	5	2	80/80	30%	
$T_{3.2.2.1}$	1	5	1	80/80	39%		1	5	2	80/80	30%	
$T_{3.2.2.2}$	1	5	1	80/80	39%		1	5	2	80/80	30%	
$T_{3.2.2.3}$	1	5	1	80/80	39%		1	5	2	80/80	30%	
$T_{3.2.2.4}$	1	5	1	80/80	39%		1	5	2	80/80	30%	
$T_{3.2.2.5}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$T_{3.2.2.6}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$T_{3.2.2.7}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$T_{3.2.2.8}+P_{3.2.2.1}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$T_{3.2.2.9}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$T_{3.2.2.10}+P_{3.2.2.2}$	1	5	1	80/80		20%	1	5	2	80/80		20%
$M_{3.2.3.1}$	1	3	1	80/40	65%							
$T_{3.2.3.1}$	1	3	1	80/40	65%							
$T_{3.2.3.2}$	1	3	1	80/40	65%							
$T_{3.2.3.3}$	1	3	1	80/40	65%							
$T_{3.2.3.4}$	1	3	1	80/40		33%						
$T_{3.2.3.5}+P_{3.2.3.1}$	1	3	1	80/40		33%						
$M_{3.3.1.1}$	1	6	1	80/40	33%		1	6	2	80/40	26%	
$T_{3.3.1.1}$	1	6	1	80/40	33%		1	6	2	80/40	26%	
$T_{3.3.1.2}$	1	6	1	80/40	33%		1	6	2	80/40	26%	
$T_{3.3.1.3}$	1	6	1	80/40	33%		1	6	2	80/40	26%	
$T_{3.3.1.4}$	1	6	1	80/40	33%		1	6	2	80/40	26%	
$T_{3.3.1.5}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$T_{3.3.1.6}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$T_{3.3.1.7}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$T_{3.3.1.8}+P_{3.3.1.1}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$T_{3.3.1.9}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$T_{3.3.1.10}+P_{3.3.1.2}$	1	6	1	80/40		17%	1	6	2	80/40		17%
$M_{3.3.2.1}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.3.2.1}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.3.2.2}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.3.2.3}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.3.2.4}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.3.2.5}+P_{3.3.2.1}$	1	4	1	80/40		25%	1	4	2	80/40		25%

	N_{cycles} | C+2											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	6	1	80/80	33%		1	6	2	80/80	26%	
	1	6	1	80/80	33%		1	6	2	80/80	26%	
	1	6	1	80/80	33%		1	6	2	80/80	26%	
	1	6	1	80/80	33%		1	6	2	80/80	26%	
	1	6	1	80/80	33%		1	6	2	80/80	26%	
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	6	1	80/80		17%	1	6	2	80/80		17%
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40	49%							
	1	4	1	80/40		17%						
	1	4	1	80/40		17%						
	1	7	1	80/40	28%		1	7	2	80/40	23%	
	1	7	1	80/40	28%		1	7	2	80/40	23%	
	1	7	1	80/40	28%		1	7	2	80/40	23%	
	1	7	1	80/40	28%		1	7	2	80/40	23%	
	1	7	1	80/40	28%		1	7	2	80/40	23%	
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	7	1	80/40		14%	1	7	2	80/40		14%
	1	5	1	80/40	39%		1	5	2	80/40	30%	
	1	5	1	80/40	39%		1	5	2	80/40	30%	
	1	5	1	80/40	39%		1	5	2	80/40	30%	
	1	5	1	80/40	39%		1	5	2	80/40	30%	
	1	5	1	80/40		20%	1	5	2	80/40		20%
	1	5	1	80/40		20%	1	5	2	80/40		20%

>>>

TOC

TABLE APP. B.14 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	N_{cycles} | C+1											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.4.1.1}$	1	12	1	80/40	16%							
$T_{3.4.1.1}$	1	12	1	80/40	16%							
$T_{3.4.1.2}$	1	12	1	80/40	16%							
$T_{3.4.1.3}$	1	12	1	80/40	16%							
$T_{3.4.1.4}$	1	12	1	80/40	16%							
$T_{3.4.1.5}$	1	12	1	80/40		8%						
$T_{3.4.1.6}$	1	12	1	80/40		8%						
$T_{3.4.1.7}+P_{3.4.1.1}$	1	12	1	80/40		8%						
$M_{3.4.2.1}$	1	5	1	80/40	39%							
$T_{3.4.2.1}$	1	5	1	80/40	39%							
$T_{3.4.2.2}$	1	5	1	80/40	39%							
$T_{3.4.2.3}$	1	5	1	80/40	39%							
$T_{3.4.2.4}$	1	5	1	80/40		20%						
$T_{3.4.2.5}$	1	5	1	80/40		20%						
$P_{3.4.2.1}$	1	5	1	80/40		20%						
$T_{3.4.2.6}$	1	5	1	80/40		20%						
$T_{3.4.2.7}+P_{3.4.2.2}$	1	5	1	80/40		20%						

	N_{cycles} | C+2											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	13	1	80/40	15%							
	1	13	1	80/40	15%							
	1	13	1	80/40	15%							
	1	13	1	80/40	15%							
	1	13	1	80/40	15%							
	1	13	1	80/40		8%						
	1	13	1	80/40		8%						
	1	13	1	80/40		8%						
	1	6	1	80/40	33%							
	1	6	1	80/40	33%							
	1	6	1	80/40	33%							
	1	6	1	80/40	33%							
	1	6	1	80/40		17%						
	1	6	1	80/40		17%						
	1	6	1	80/40		17%						
	1	6	1	80/40		17%						
	1	6	1	80/40		17%						

TABLE APP. B.15 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{functional}$ (finishing parts) | Lf=80-40-7-40, Lt=80-40-40-40														
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_3	$N_{cycles,3}$	$C_{number,3}$
$M_{3.1.1.1}$	1	3	1	80/80	65%										
$T_{3.1.1.1}$	1	3	1	80/80	65%										
$T_{3.1.1.2}$	1	3	1	80/80	65%										
$T_{3.1.1.3}$	1	3	1	80/80	65%										
$T_{3.1.1.4}$	1	3	1	80/80		33%									
$T_{3.1.1.5}+P_{3.1.1.1}$	1	3	1	80/80		33%									
$T_{3.1.1.6}$	1	3	1	80/80		33%									
$T_{3.1.1.7}+P_{3.1.1.2}$	1	3	1	80/80		33%									
$M_{3.1.2.1}$	1	11	1	80/80	18%										
$T_{3.1.2.1}$	1	11	1	80/80	18%										
$T_{3.1.2.2}$	1	11	1	80/80	18%										
$T_{3.1.2.3}$	1	11	1	80/80	18%										
$T_{3.1.2.4}$	1	11	1	80/80	18%										
$T_{3.1.2.5}$	1	11	1	80/80		9%									
$T_{3.1.2.6}$	1	11	1	80/80		9%									
$T_{3.1.2.7}+P_{3.1.2.1}$	1	11	1	80/80		9%									
$M_{3.2.1.1}$	1	3	1	80/20	65%										
$T_{3.2.1.1}$	1	3	1	80/20	65%										
$T_{3.2.1.2}$	1	3	1	80/20	65%										
$T_{3.2.1.3}$	1	3	1	80/20	65%										
$T_{3.2.1.4}$	1	3	1	80/20	65%										
$T_{3.2.1.5}$	1	3	1	80/20		33%									
$T_{3.2.1.6}+P_{3.2.1.1}$	1	3	1	80/20		33%									
$T_{3.2.1.7}$	1	3	1	80/20		33%									
$T_{3.2.1.8}+P_{3.2.1.2}$	1	3	1	80/20		33%									

				$L_{functional}$ | Lf=80-40-40-40, Lt=80-40-40-40											
	R_3	$Af_{Initial\ production\ and\ construction,3}$	$Af_{VRPs,3}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
				1	3	1	80/80	65%							
				1	3	1	80/80	65%							
				1	3	1	80/80	65%							
				1	3	1	80/80	65%							
				1	3	1	80/80		33%						
				1	3	1	80/80		33%						
				1	3	1	80/80		33%						
				1	3	1	80/80		33%						
				1	11	1	80/80	18%							
				1	11	1	80/80	18%							
				1	11	1	80/80	18%							
				1	11	1	80/80	18%							
				1	11	1	80/80	18%							
				1	11	1	80/80		9%						
				1	11	1	80/80		9%						
				1	11	1	80/80		9%						
				1	3	1	80/20	65%							
				1	3	1	80/20	65%							
				1	3	1	80/20	65%							
				1	3	1	80/20	65%							
				1	3	1	80/20	65%							
				1	3	1	80/20		33%						
				1	3	1	80/20		33%						
				1	3	1	80/20		33%						
				1	3	1	80/20		33%						

>>>

TOC

TABLE APP. B.15 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{functional}$ (finishing parts) | Lf=80-40-7-40, Lt=80-40-40-40														
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_3	$N_{cycles,3}$	$C_{number,3}$
$M_{3.2.2.1}$	1	4	1	80/80	49%		1	4	2	80/80	33%				
$T_{3.2.2.1}$	1	4	1	80/80	49%		1	4	2	80/80	33%				
$T_{3.2.2.2}$	1	4	1	80/80	49%		1	4	2	80/80	33%				
$T_{3.2.2.3}$	1	4	1	80/80	49%		1	4	2	80/80	33%				
$T_{3.2.2.4}$	1	4	1	80/80	49%		1	4	2	80/80	33%				
$T_{3.2.2.5}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$T_{3.2.2.6}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$T_{3.2.2.7}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$T_{3.2.2.8}+P_{3.2.2.1}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$T_{3.2.2.9}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$T_{3.2.2.10}+P_{3.2.2.2}$	1	4	1	80/80		25%	1	4	2	80/80		25%			
$M_{3.2.3.1}$	1	2	1	80/40	98%										
$T_{3.2.3.1}$	1	2	1	80/40	98%										
$T_{3.2.3.2}$	1	2	1	80/40	98%										
$T_{3.2.3.3}$	1	2	1	80/40	98%										
$T_{3.2.3.4}$	1	2	1	80/40		50%									
$T_{3.2.3.5}+P_{3.2.3.1}$	1	2	1	80/40		50%									
$M_{3.3.1.1}$	1	8	1	80/20	25%		1	8	2	80/20	18%		1	8	2
$T_{3.3.1.1}$	1	8	1	80/20	25%		1	8	2	80/20	18%		1	8	2
$T_{3.3.1.2}$	1	8	1	80/20	25%		1	8	2	80/20	18%		1	8	2
$T_{3.3.1.3}$	1	8	1	80/20	25%		1	8	2	80/20	18%		1	8	2
$T_{3.3.1.4}$	1	8	1	80/20	25%		1	8	2	80/20	18%		1	8	2
$T_{3.3.1.5}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$T_{3.3.1.6}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$T_{3.3.1.7}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$T_{3.3.1.8}+P_{3.3.1.1}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$T_{3.3.1.9}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$T_{3.3.1.10}+P_{3.3.1.2}$	1	8	1	80/20		13%	1	8	2	80/20		13%	1	8	2
$M_{3.3.2.1}$	1	6	1	80/20	33%		1	6	2	80/20	20%		1	6	2
$T_{3.3.2.1}$	1	6	1	80/20	33%		1	6	2	80/20	20%		1	6	2
$T_{3.3.2.2}$	1	6	1	80/20	33%		1	6	2	80/20	20%		1	6	2
$T_{3.3.2.3}$	1	6	1	80/20	33%		1	6	2	80/20	20%		1	6	2
$T_{3.3.2.4}$	1	6	1	80/20		17%	1	6	2	80/20		17%	1	6	2
$T_{3.3.2.5}+P_{3.3.2.1}$	1	6	1	80/20		17%	1	6	2	80/20		17%	1	6	2

R_3	$Af_{Initial\ production\ and\ construction,3}$	$Af_{VRPs,3}$	$L_{functional}$ | Lf=80-40-40-40, Lt=80-40-40-40											
			P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
			1	4	1	80/80	49%		1	4	2	80/80	33%	
			1	4	1	80/80	49%		1	4	2	80/80	33%	
			1	4	1	80/80	49%		1	4	2	80/80	33%	
			1	4	1	80/80	49%		1	4	2	80/80	33%	
			1	4	1	80/80	49%		1	4	2	80/80	33%	
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	4	1	80/80		25%	1	4	2	80/80		25%
			1	2	1	80/40	98%							
			1	2	1	80/40	98%							
			1	2	1	80/40	98%							
			1	2	1	80/40	98%							
			1	2	1	80/40		50%						
			1	2	1	80/40		50%						
80/20	11%		1	4	1	80/40	49%							
80/20	11%		1	4	1	80/40	49%							
80/20	11%		1	4	1	80/40	49%							
80/20	11%		1	4	1	80/40	49%							
80/20	11%		1	4	1	80/40	49%							
80/20		13%	1	4	1	80/40		25%						
80/20		13%	1	4	1	80/40		25%						
80/20		13%	1	4	1	80/40		25%						
80/20		13%	1	4	1	80/40		25%						
80/20		13%	1	4	1	80/40		25%						
80/20		13%	1	4	1	80/40		25%						
80/20	7%		1	2	1	80/40	98%							
80/20	7%		1	2	1	80/40	98%							
80/20	7%		1	2	1	80/40	98%							
80/20	7%		1	2	1	80/40	98%							
80/20		17%	1	2	1	80/40		50%						
80/20		17%	1	2	1	80/40		50%						

>>>

TOC

TABLE APP. B.15 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{functional}$ (finishing parts) | Lf=80-40-7-40, Lt=80-40-40-40														
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	P_3	$N_{cycles,3}$	$C_{number,3}$
$M_{3.4.1.1}$	1	11	1	80/40	18%										
$T_{3.4.1.1}$	1	11	1	80/40	18%										
$T_{3.4.1.2}$	1	11	1	80/40	18%										
$T_{3.4.1.3}$	1	11	1	80/40	18%										
$T_{3.4.1.4}$	1	11	1	80/40	18%										
$T_{3.4.1.5}$	1	11	1	80/40		9%									
$T_{3.4.1.6}$	1	11	1	80/40		9%									
$T_{3.4.1.7}+P_{3.4.1.1}$	1	11	1	80/40		9%									
$M_{3.4.2.1}$	1	4	1	80/40	49%										
$T_{3.4.2.1}$	1	4	1	80/40	49%										
$T_{3.4.2.2}$	1	4	1	80/40	49%										
$T_{3.4.2.3}$	1	4	1	80/40	49%										
$T_{3.4.2.4}$	1	4	1	80/40		25%									
$T_{3.4.2.5}$	1	4	1	80/40		25%									
$P_{3.4.2.1}$	1	4	1	80/40		25%									
$T_{3.4.2.6}$	1	4	1	80/40		25%									
$T_{3.4.2.7}+P_{3.4.2.2}$	1	4	1	80/40		25%									

				$L_{functional}$ | Lf=80-40-40-40, Lt=80-40-40-40											
	R_3	$Af_{Initial\ production\ and\ construction,3}$	$Af_{VRPs,3}$	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
				1	11	1	80/40	18%							
				1	11	1	80/40	18%							
				1	11	1	80/40	18%							
				1	11	1	80/40	18%							
				1	11	1	80/40	18%							
				1	11	1	80/40		9%						
				1	11	1	80/40		9%						
				1	11	1	80/40		9%						
				1	4	1	80/40	49%							
				1	4	1	80/40	49%							
				1	4	1	80/40	49%							
				1	4	1	80/40	49%							
				1	4	1	80/40		25%						
				1	4	1	80/40		25%						
				1	4	1	80/40		25%						
				1	4	1	80/40		25%						
				1	4	1	80/40		25%						

TABLE APP. B.16 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=7-7-7-7, Lf=7-7-3,5-7											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.1.1.1}$	1	3	1	80/6.7	65%							
$T_{3.1.1.1}$	1	3	1	80/6.7	65%							
$T_{3.1.1.2}$	1	3	1	80/6.7	65%							
$T_{3.1.1.3}$	1	3	1	80/6.7	65%							
$T_{3.1.1.4}$	1	3	1	80/6.7		33%						
$T_{3.1.1.5}+P_{3.1.1.1}$	1	3	1	80/6.7		33%						
$T_{3.1.1.6}$	1	3	1	80/6.7		33%						
$T_{3.1.1.7}+P_{3.1.1.2}$	1	3	1	80/6.7		33%						
$M_{3.1.2.1}$	1	11	1	80/6.7	18%							
$T_{3.1.2.1}$	1	11	1	80/6.7	18%							
$T_{3.1.2.2}$	1	11	1	80/6.7	18%							
$T_{3.1.2.3}$	1	11	1	80/6.7	18%							
$T_{3.1.2.4}$	1	11	1	80/6.7	18%							
$T_{3.1.2.5}$	1	11	1	80/6.7		9%						
$T_{3.1.2.6}$	1	11	1	80/6.7		9%						
$T_{3.1.2.7}+P_{3.1.2.1}$	1	11	1	80/6.7		9%						
$M_{3.2.1.1}$	1	3	1	80/6.7	65%							
$T_{3.2.1.1}$	1	3	1	80/6.7	65%							
$T_{3.2.1.2}$	1	3	1	80/6.7	65%							
$T_{3.2.1.3}$	1	3	1	80/6.7	65%							
$T_{3.2.1.4}$	1	3	1	80/6.7	65%							
$T_{3.2.1.5}$	1	3	1	80/6.7		33%						
$T_{3.2.1.6}+P_{3.2.1.1}$	1	3	1	80/6.7		33%						
$T_{3.2.1.7}$	1	3	1	80/6.7		33%						
$T_{3.2.1.8}+P_{3.2.1.2}$	1	3	1	80/6.7		33%						

	$L_{technical}$ - $L_{functional}$ | Lt=20-20-20-20, Lf=20-20-10-20											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20		9%						
	1	11	1	80/20		9%						
	1	11	1	80/20		9%						
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20	65%							
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						
	1	3	1	80/20		33%						

>>>

TOC

TABLE APP. B.16 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=7-7-7-7, Lf=7-7-3,5-7											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.2.2.1}$	1	4	1	80/133	49%		1	4	2	80/133	33%	
$T_{3.2.2.1}$	1	4	1	80/133	49%		1	4	2	80/133	33%	
$T_{3.2.2.2}$	1	4	1	80/133	49%		1	4	2	80/133	33%	
$T_{3.2.2.3}$	1	4	1	80/133	49%		1	4	2	80/133	33%	
$T_{3.2.2.4}$	1	4	1	80/133	49%		1	4	2	80/133	33%	
$T_{3.2.2.5}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$T_{3.2.2.6}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$T_{3.2.2.7}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$T_{3.2.2.8}+P_{3.2.2.1}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$T_{3.2.2.9}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$T_{3.2.2.10}+P_{3.2.2.2}$	1	4	1	80/133		25%	1	4	2	80/133		25%
$M_{3.2.3.1}$	1	2	1	80/6.7	98%							
$T_{3.2.3.1}$	1	2	1	80/6.7	98%							
$T_{3.2.3.2}$	1	2	1	80/6.7	98%							
$T_{3.2.3.3}$	1	2	1	80/6.7	98%							
$T_{3.2.3.4}$	1	2	1	80/6.7		50%						
$T_{3.2.3.5}+P_{3.2.3.1}$	1	2	1	80/6.7		50%						
$M_{3.3.1.1}$	1	5	1	80/6.7	39%		1	5	2	80/6.7	30%	
$T_{3.3.1.1}$	1	5	1	80/6.7	39%		1	5	2	80/6.7	30%	
$T_{3.3.1.2}$	1	5	1	80/6.7	39%		1	5	2	80/6.7	30%	
$T_{3.3.1.3}$	1	5	1	80/6.7	39%		1	5	2	80/6.7	30%	
$T_{3.3.1.4}$	1	5	1	80/6.7	39%		1	5	2	80/6.7	30%	
$T_{3.3.1.5}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$T_{3.3.1.6}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$T_{3.3.1.7}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$T_{3.3.1.8}+P_{3.3.1.1}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$T_{3.3.1.9}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$T_{3.3.1.10}+P_{3.3.1.2}$	1	5	1	80/6.7		20%	1	5	2	80/6.7		20%
$M_{3.3.2.1}$	1	3	1	80/6.7	65%		1	3	2	80/6.7	33%	
$T_{3.3.2.1}$	1	3	1	80/6.7	65%		1	3	2	80/6.7	33%	
$T_{3.3.2.2}$	1	3	1	80/6.7	65%		1	3	2	80/6.7	33%	
$T_{3.3.2.3}$	1	3	1	80/6.7	65%		1	3	2	80/6.7	33%	
$T_{3.3.2.4}$	1	3	1	80/6.7		33%	1	3	2	80/6.7		33%
$T_{3.3.2.5}+P_{3.3.2.1}$	1	3	1	80/6.7		33%	1	3	2	80/6.7		33%

	$L_{technical}$ - $L_{functional}$ | Lt=20-20-20-20, Lf=20-20-10-20											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40	49%		1	4	2	80/40	33%	
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	4	1	80/40		25%	1	4	2	80/40		25%
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20	98%							
	1	2	1	80/20		50%						
	1	2	1	80/20		50%						
	1	5	1	80/20	39%		1	5	2	80/20	30%	
	1	5	1	80/20	39%		1	5	2	80/20	30%	
	1	5	1	80/20	39%		1	5	2	80/20	30%	
	1	5	1	80/20	39%		1	5	2	80/20	30%	
	1	5	1	80/20	39%		1	5	2	80/20	30%	
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	5	1	80/20		20%	1	5	2	80/20		20%
	1	3	1	80/20	65%		1	3	2	80/20	33%	
	1	3	1	80/20	65%		1	3	2	80/20	33%	
	1	3	1	80/20	65%		1	3	2	80/20	33%	
	1	3	1	80/20	65%		1	3	2	80/20	33%	
	1	3	1	80/20		33%	1	3	2	80/20		33%
	1	3	1	80/20		33%	1	3	2	80/20		33%

>>>

TABLE APP. B.16 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=7-7-7-7, Lf=7-7-3,5-7											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.4.1.1}$	1	11	1	80/6.7	18%							
$T_{3.4.1.1}$	1	11	1	80/6.7	18%							
$T_{3.4.1.2}$	1	11	1	80/6.7	18%							
$T_{3.4.1.3}$	1	11	1	80/6.7	18%							
$T_{3.4.1.4}$	1	11	1	80/6.7	18%							
$T_{3.4.1.5}$	1	11	1	80/6.7		9%						
$T_{3.4.1.6}$	1	11	1	80/6.7		9%						
$T_{3.4.1.7}+P_{3.4.1.1}$	1	11	1	80/6.7		9%						
$M_{3.4.2.1}$	1	4	1	80/6.7	49%							
$T_{3.4.2.1}$	1	4	1	80/6.7	49%							
$T_{3.4.2.2}$	1	4	1	80/6.7	49%							
$T_{3.4.2.3}$	1	4	1	80/6.7	49%							
$T_{3.4.2.4}$	1	4	1	80/6.7		25%						
$T_{3.4.2.5}$	1	4	1	80/6.7		25%						
$P_{3.4.2.1}$	1	4	1	80/6.7		25%						
$T_{3.4.2.6}$	1	4	1	80/6.7		25%						
$T_{3.4.2.7}+P_{3.4.2.2}$	1	4	1	80/6.7		25%						

	$L_{technical}$ - $L_{functional}$ | Lt=20-20-20-20, Lf=20-20-10-20											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20	18%							
	1	11	1	80/20		9%						
	1	11	1	80/20		9%						
	1	11	1	80/20		9%						
	1	4	1	80/20	49%							
	1	4	1	80/20	49%							
	1	4	1	80/20	49%							
	1	4	1	80/20	49%							
	1	4	1	80/20		25%						
	1	4	1	80/20		25%						
	1	4	1	80/20		25%						
	1	4	1	80/20		25%						
	1	4	1	80/20		25%						

TABLE APP. B.17 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=40-20-20-20, Lf=40-20-10-20												
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$	
$M_{3.1.1.1}$	1	3	1	80/40	65%								
$T_{3.1.1.1}$	1	3	1	80/40	65%								
$T_{3.1.1.2}$	1	3	1	80/40	65%								
$T_{3.1.1.3}$	1	3	1	80/40	65%								
$T_{3.1.1.4}$	1	3	1	80/40		33%							
$T_{3.1.1.5}$+$P_{3.1.1.1}$	1	3	1	80/40		33%							
$T_{3.1.1.6}$	1	3	1	80/40		33%							
$T_{3.1.1.7}$+$P_{3.1.1.2}$	1	3	1	80/40		33%							
$M_{3.1.2.1}$	1	11	1	80/40	18%								
$T_{3.1.2.1}$	1	11	1	80/40	18%								
$T_{3.1.2.2}$	1	11	1	80/40	18%								
$T_{3.1.2.3}$	1	11	1	80/40	18%								
$T_{3.1.2.4}$	1	11	1	80/40	18%								
$T_{3.1.2.5}$	1	11	1	80/40		9%							
$T_{3.1.2.6}$	1	11	1	80/40		9%							
$T_{3.1.2.7}$+$P_{3.1.2.1}$	1	11	1	80/40		9%							
$M_{3.2.1.1}$	1	3	1	80/10	65%								
$T_{3.2.1.1}$	1	3	1	80/10	65%								
$T_{3.2.1.2}$	1	3	1	80/10	65%								
$T_{3.2.1.3}$	1	3	1	80/10	65%								
$T_{3.2.1.4}$	1	3	1	80/10	65%								
$T_{3.2.1.5}$	1	3	1	80/10		33%							
$T_{3.2.1.6}$+$P_{3.2.1.1}$	1	3	1	80/10		33%							
$T_{3.2.1.7}$	1	3	1	80/10		33%							
$T_{3.2.1.8}$+$P_{3.2.1.2}$	1	3	1	80/10		33%							

	$L_{technical}$ - $L_{functional}$ | Lt=80-80-80-80, Lf=80-80-40-80											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80	65%							
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						
	1	3	1	80/80		33%						

>>>

TABLE APP. B.17 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=40-20-20-20, Lf=40-20-10-20											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.2.2.1}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.2.2.1}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.2.2.2}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.2.2.3}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.2.2.4}$	1	4	1	80/40	49%		1	4	2	80/40	33%	
$T_{3.2.2.5}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.2.2.6}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.2.2.7}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.2.2.8}+P_{3.2.2.1}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.2.2.9}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$T_{3.2.2.10}+P_{3.2.2.2}$	1	4	1	80/40		25%	1	4	2	80/40		25%
$M_{3.2.3.1}$	1	2	1	80/20	98%							
$T_{3.2.3.1}$	1	2	1	80/20	98%							
$T_{3.2.3.2}$	1	2	1	80/20	98%							
$T_{3.2.3.3}$	1	2	1	80/20	98%							
$T_{3.2.3.4}$	1	2	1	80/20		50%						
$T_{3.2.3.5}+P_{3.2.3.1}$	1	2	1	80/20		50%						
$M_{3.3.1.1}$	1	5	1	80/20	39%		1	5	2	80/20	30%	
$T_{3.3.1.1}$	1	5	1	80/20	39%		1	5	2	80/20	30%	
$T_{3.3.1.2}$	1	5	1	80/20	39%		1	5	2	80/20	30%	
$T_{3.3.1.3}$	1	5	1	80/20	39%		1	5	2	80/20	30%	
$T_{3.3.1.4}$	1	5	1	80/20	39%		1	5	2	80/20	30%	
$T_{3.3.1.5}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$T_{3.3.1.6}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$T_{3.3.1.7}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$T_{3.3.1.8}+P_{3.3.1.1}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$T_{3.3.1.9}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$T_{3.3.1.10}+P_{3.3.1.2}$	1	5	1	80/20		20%	1	5	2	80/20		20%
$M_{3.3.2.1}$	1	3	1	80/20	65%		1	3	2	80/20	33%	
$T_{3.3.2.1}$	1	3	1	80/20	65%		1	3	2	80/20	33%	
$T_{3.3.2.2}$	1	3	1	80/20	65%		1	3	2	80/20	33%	
$T_{3.3.2.3}$	1	3	1	80/20	65%		1	3	2	80/20	33%	
$T_{3.3.2.4}$	1	3	1	80/20		33%	1	3	2	80/20		33%
$T_{3.3.2.5}+P_{3.3.2.1}$	1	3	1	80/20		33%	1	3	2	80/20		33%

	$L_{technical}$ - $L_{functional}$ | Lt=80-80-80-80, Lf=80-80-40-80											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80	98%							
	1	2	1	80/80		50%						
	1	2	1	80/80		50%						
	1	5	1	80/80	39%		1	5	2	80/80	30%	
	1	5	1	80/80	39%		1	5	2	80/80	30%	
	1	5	1	80/80	39%		1	5	2	80/80	30%	
	1	5	1	80/80	39%		1	5	2	80/80	30%	
	1	5	1	80/80	39%		1	5	2	80/80	30%	
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	5	1	80/80		20%	1	5	2	80/80		20%
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80	65%		1	3	2	80/80	33%	
	1	3	1	80/80		33%	1	3	2	80/80		33%
	1	3	1	80/80		33%	1	3	2	80/80		33%

>>>

TABLE APP. B.17 (continued) Detailed CE-LCIA for the Plug-and-Play (P&P) kitchen

	$L_{technical}$ - $L_{functional}$ | Lt=40-20-20-20, Lf=40-20-10-20											
Code in LCI flowchart	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
$M_{3.4.1.1}$	1	11	1	80/20	18%							
$T_{3.4.1.1}$	1	11	1	80/20	18%							
$T_{3.4.1.2}$	1	11	1	80/20	18%							
$T_{3.4.1.3}$	1	11	1	80/20	18%							
$T_{3.4.1.4}$	1	11	1	80/20	18%							
$T_{3.4.1.5}$	1	11	1	80/20		9%						
$T_{3.4.1.6}$	1	11	1	80/20		9%						
$T_{3.4.1.7}$+$P_{3.4.1.1}$	1	11	1	80/20		9%						
$M_{3.4.2.1}$	1	4	1	80/20	49%							
$T_{3.4.2.1}$	1	4	1	80/20	49%							
$T_{3.4.2.2}$	1	4	1	80/20	49%							
$T_{3.4.2.3}$	1	4	1	80/20	49%							
$T_{3.4.2.4}$	1	4	1	80/20		25%						
$T_{3.4.2.5}$	1	4	1	80/20		25%						
$P_{3.4.2.1}$	1	4	1	80/20		25%						
$T_{3.4.2.6}$	1	4	1	80/20		25%						
$T_{3.4.2.7}$+$P_{3.4.2.2}$	1	4	1	80/20		25%						

	$L_{technical}$ - $L_{functional}$ | Lt=80-80-80-80, Lf=80-80-40-80											
	P_1	$N_{cycles,1}$	$C_{number,1}$	R_1	$Af_{Initial\ production\ and\ construction,1}$	$Af_{VRPs,1}$	P_2	$N_{cycles,2}$	$C_{number,2}$	R_2	$Af_{Initial\ production\ and\ construction,2}$	$Af_{VRPs,2}$
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80	18%							
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	11	1	80/80		9%						
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80	49%							
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						
	1	4	1	80/80		25%						

APP. B.4 Analysis of the CE-LCIA results

This appendix includes a deeper analysis of the CE-LCIA results of the BAU, Reclaim! and P&P kitchen variants.

APP. B.4.1 Impact distribution between 'production, construction and pre-use' and 'value retention post-use' for the lower kitchen cabinet and its subcomponents

Table App.B18 shows the impact distribution between modules CE-A (i.e., production, construction and pre-use) and CE-C (i.e., value retention post-use) for the lower kitchen cabinet and its subcomponents per impact category in percentage.

Which life cycle stages contribute most to the results varies per design variant and impact category. In the BAU kitchen the materials have a low number of use cycles; a higher share of impacts originates from production, construction and pre-use, namely between 71%-99%. In the Reclaim! kitchen, materials have one more use cycle than in the BAU kitchen: between 59%-98% of impacts originate from production, construction and pre-use. Introducing multiple use cycles results in higher shares of impact originating from 'value retention post-use': in the P&P kitchen, only 53-79% of impacts originate from production, construction and pre-use. An exception is the 'abiotic depletion for elements' category, where only 23% are production, construction and pre-use impacts. This is due to the high abiotic depletion potential of 'wood chipping for OSB production' during recycling of wooden parts. The effect of including multiple cycles is also visible in the stainless-steel connectors: the assumed 10 recycling cycles for virgin stainless steel result in an Af of 0.18 for initial production and construction impacts and an Af of 0.09 for impacts of each recycling cycle. As such the share of impacts of value retention post-use is larger than the share of impacts of production, construction and pre-use: double or triple for the first five impact categories. However, the distribution of impacts also greatly depends on impacts emanating from production versus recycling processes. For example, in the toxicity categories, the impacts from initial production and construction of stainless steel still contribute the majority share.

Which materials or processes contribute most to the results varies per impact category. From the CE-LCI, we see that the panels form the bulk of the material in the BAU and Reclaim! kitchens and the infill and finishing parts in the P&P kitchen.

Their initial production and construction contribute significantly in nearly all impact categories; in the P&P kitchen the recycling process 'chipping for OSB production' results in high share of impacts, especially in the abiotic depletion for elements category. However, considering the limited mass of the stainless steel and coatings (i.e., melamine), we found that these materials contribute significantly to the total impacts, especially for the toxicity categories. When normalising the results (see also Appendix B.6, Tables App.B29-32), we found these are most significant. Finally, most of the impact originates from material production and VRPs; transport played a limited role.

TABLE APP. B.18 Contribution of impacts for modules CE-A and CE-C for the lower kitchen cabinet and subcomponents

		Global warming potential	Ozone layer depletion potential	Photochemical oxidation potential	Acidification potential	Eutrophication potential	Abiotic depletion potential for elements	Abiotic depletion potential for fossil fuels	Fresh water aquatic eco-toxicity potential	Human toxicity potential	Marine aquatic ecotoxicity potential	Terrestrial ecotoxicity potential
BAU	**CE-A | Production, construction and pre-use**											
	Lower kitchen cabinet	**72%**	**94%**	**84%**	**88%**	**79%**	**99%**	**93%**	**71%**	**91%**	**78%**	**93%**
	Panels	64%	89%	76%	78%	71%	96%	83%	47%	35%	63%	67%
	Structural lath	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%
	Glue	1%	0%	1%	1%	1%	0%	2%	1%	0%	1%	0%
	Feet	2%	1%	1%	2%	1%	3%	5%	1%	0%	1%	1%
	Connectors	5%	3%	4%	6%	5%	0%	4%	23%	55%	12%	25%
	CE-C | Value retention post-use											
	Lower kitchen cabinet	**28%**	**6%**	**16%**	**12%**	**21%**	**1%**	**1%**	**29%**	**9%**	**22%**	**7%**
	Panels	17%	1%	1%	3%	11%	0%	0%	22%	6%	11%	2%
	Structural lath	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Glue	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Feet	0%	0%	0%	0%	1%	0%	6%	2%	0%	5%	1%
	Connectors	10%	5%	15%	8%	9%	1%	0%	5%	3%	6%	4%

>>>

TOC

TABLE APP. B.18 Contribution of impacts for modules CE-A and CE-C for the lower kitchen cabinet and subcomponents

		Global warming potential	Ozone layer depletion potential	Photochemical oxidation potential	Acidification potential	Eutrophication potential	Abiotic depletion potential for elements	Abiotic depletion potential for fossil fuels	Fresh water aquatic eco-toxicity potential	Human toxicity potential	Marine aquatic ecotoxicity potential	Terrestrial ecotoxicity potential
Reclaim!	**CE-A | Production, construction and pre-use**											
	Lower kitchen cabinet	**59%**	**88%**	**69%**	**79%**	**68%**	**98%**	**87%**	**63%**	**90%**	**68%**	**89%**
	Panels	46%	80%	57%	62%	55%	76%	70%	28%	19%	43%	46%
	Structural lath	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	1%
	Glue	3%	0%	2%	3%	2%	0%	4%	1%	0%	3%	1%
	Feet	2%	2%	2%	2%	2%	0%	6%	1%	0%	1%	1%
	Connectors	8%	6%	8%	11%	9%	22%	7%	33%	70%	20%	41%
	CE-C | Value retention post-use											
	Lower kitchen cabinet	**41%**	**12%**	**31%**	**21%**	**32%**	**2%**	**13%**	**37%**	**10%**	**32%**	**11%**
	Panels	22%	1%	1%	4%	13%	0%	1%	25%	6%	14%	3%
	Structural lath	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%
	Glue	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%
	Feet	1%	1%	0%	0%	1%	0%	1%	3%	0%	8%	1%
	Connectors	17%	10%	30%	16%	18%	2%	12%	8%	4%	10%	7%
P&P	**CE-A | Production, construction and pre-use**											
	Lower kitchen cabinet	**61%**	**76%**	**70%**	**73%**	**66%**	**23%**	**74%**	**53%**	**79%**	**54%**	**68%**
	Construction	6%	8%	8%	8%	7%	2%	7%	5%	7%	5%	7%
	Infill	23%	31%	27%	28%	25%	6%	30%	11%	8%	17%	19%
	Finishing	26%	35%	31%	32%	29%	7%	33%	12%	9%	18%	21%
	Connectors	6%	3%	5%	6%	5%	8%	5%	25%	55%	14%	21%
	CE-C | Value retention post-use											
	Lower kitchen cabinet	**38%**	**23%**	**30%**	**26%**	**33%**	**77%**	**25%**	**47%**	**21%**	**46%**	**32%**
	Construction	2%	2%	2%	2%	3%	9%	2%	4%	2%	4%	3%
	Infill	11%	7%	5%	7%	10%	29%	7%	16%	7%	15%	11%
	Finishing	14%	9%	6%	9%	11%	37%	9%	21%	9%	19%	14%
	Connectors	12%	5%	16%	8%	10%	1%	7%	6%	3%	8%	4%

Note: The colour shows a gradient between the highest (blue) and lowest (light blue) percentual contribution of impact; percentages have been rounded up to the nearest whole number.

TOC

APP. B.4.2

Impact allocation over the RSP

To illustrate how impacts are allocated to the kitchen over the RSP we plotted the (allocated) GWP over time in Figure App.B.2. The y-axis shows the years within the RSP when impact is allocated to the kitchen. For the BAU and Reclaim! variants, impacts are allocated to the kitchen when the entire kitchen cabinet is placed and replaced every 20 or 10 years, respectively. For the P&P kitchen the largest shares of impact are allocated at initial placement (t=0), and the replacement of the finishing, infill and connectors (t=40). The replacement of the finishing and part of the infill at t=20 and t=60 result in a modest increase in allocated impact, showing the benefit of facilitating partial replacements.

This graph shows tipping points for the GWP: prior to t=7, the Reclaim! variant has the lowest allocated GWP compared to the other variants. When t>7 years, the P&P variant continues to have the lowest (allocated) GWP. If a similar analysis is done for other impact categories, the y-values on which impacts are allocated to the kitchen would remain the same. However, how much impact is allocated per (re)placement might differ per impact category – changing the tipping points.

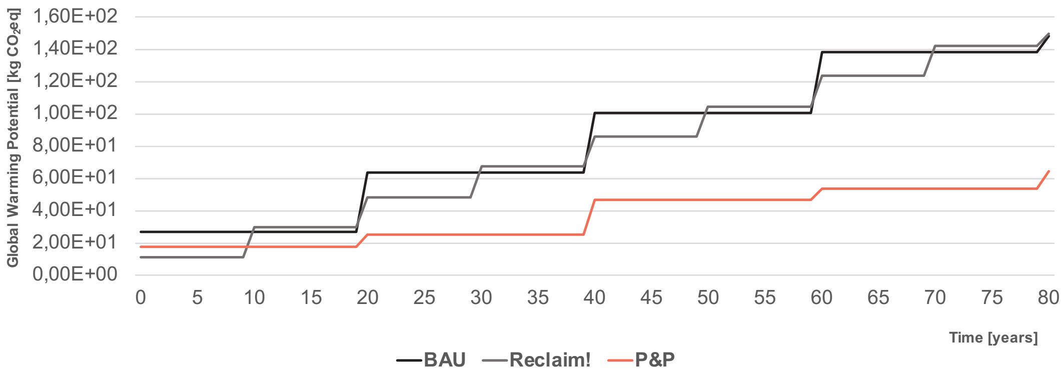


FIG. APP. B.2 Global Warming Potential allocated to kitchen variants over 80 years

APP. B.4.3 Impact between use cycles of materials applied in the kitchen in relation to the RSP

The abovementioned results merely show the impacts of the circular system allocated to the kitchen. Neither Table App.B.18 nor Figure App.B.2 provides insight into the distribution of impacts between the use cycle in the kitchen and the use cycles happening 'outside' of the assessed kitchen. Reporting the impacts allocated 'inside' and 'outside' of the use cycle of the assessed kitchen does not necessarily lead to more transparency. First, impacts which have already occurred in the use cycle of the kitchen are allocated to cycles occurring 'outside' of the assessed kitchen. Likewise, some of the impacts of cycles which are yet to occur have already been allocated to the use cycle of the kitchen. Second, depending on which materials are applied, impacts 'outside' of the assessed kitchen could compile impacts of multiple use cycles. For metals used in the kitchen, impacts outside the use cycle of the kitchen include impacts of 10 recycling cycles. Whilst for particle boards in the BAU variant, it only includes impacts of one use cycle (e.g., recovery of particle board for energy). To increase the transparency of multi-cycling LCAs, the impacts could be reported per use cycle – per material.

Figures App.B3-5 report the distribution of impacts between use cycles of materials applied in the kitchen variants plotted over the RSP. It shows the cohesion between the parameters N_{cycles}, C_{number}, R – and the resulting Af values per use cycle. Showing the impact distribution could increase transparency and comparability between CE-LCAs; it could support deeper analysis of the CE-LCIA results. However, reporting impacts per cycle could also (further) complexify CE-LCA. Interpretation of impacts reported per cycle might be feasible and insightful for building materials or simple building components. Yet, for more complex composites – as is the case in the kitchens – it results in extensive CE-LCIA datasets. We question if this supports decision-making: comparing environmental impact performance of sets of individual cycles between kitchen variants is more a comparison of circular systems than a comparison of circular building components (in a circular system).

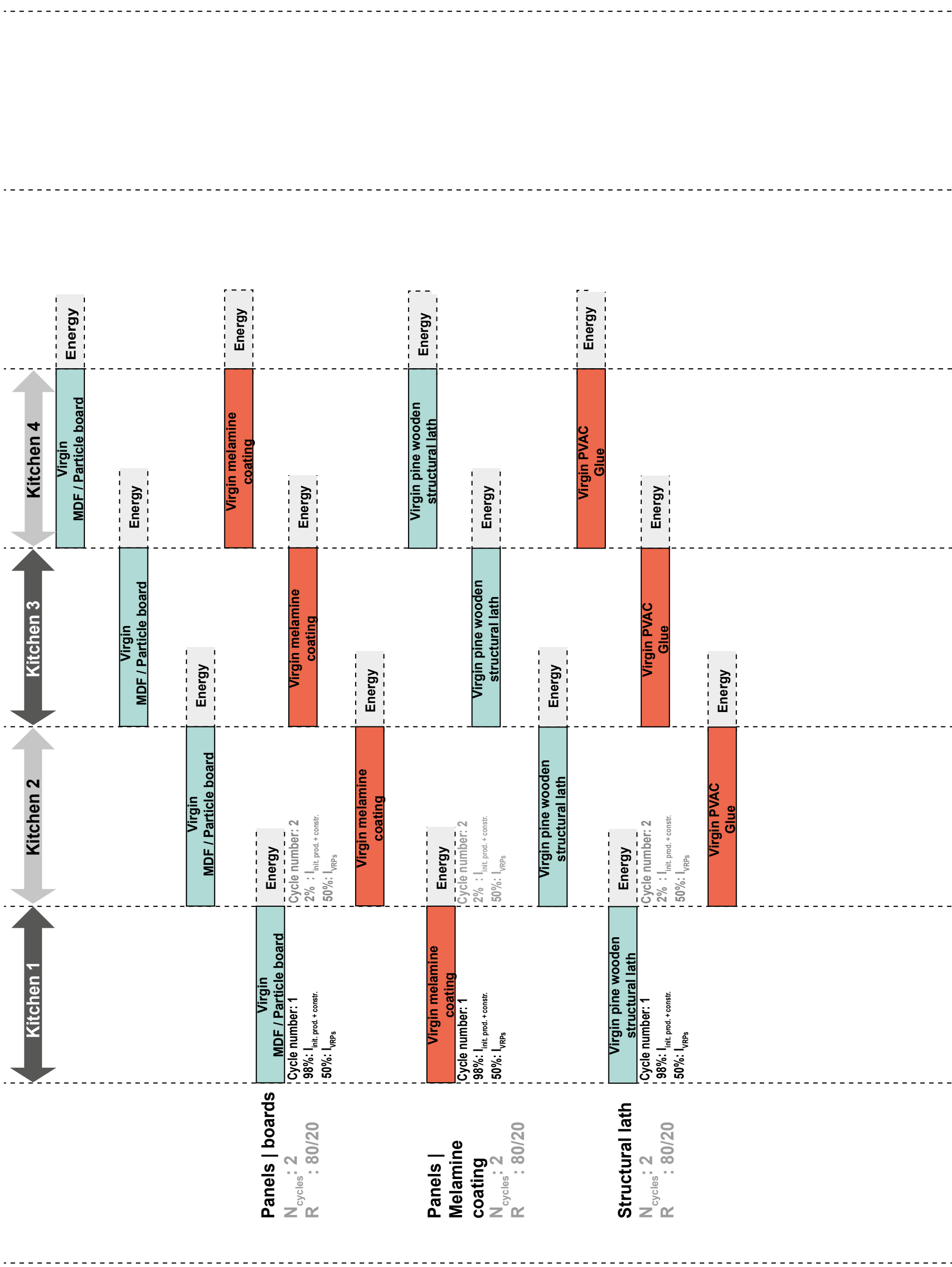
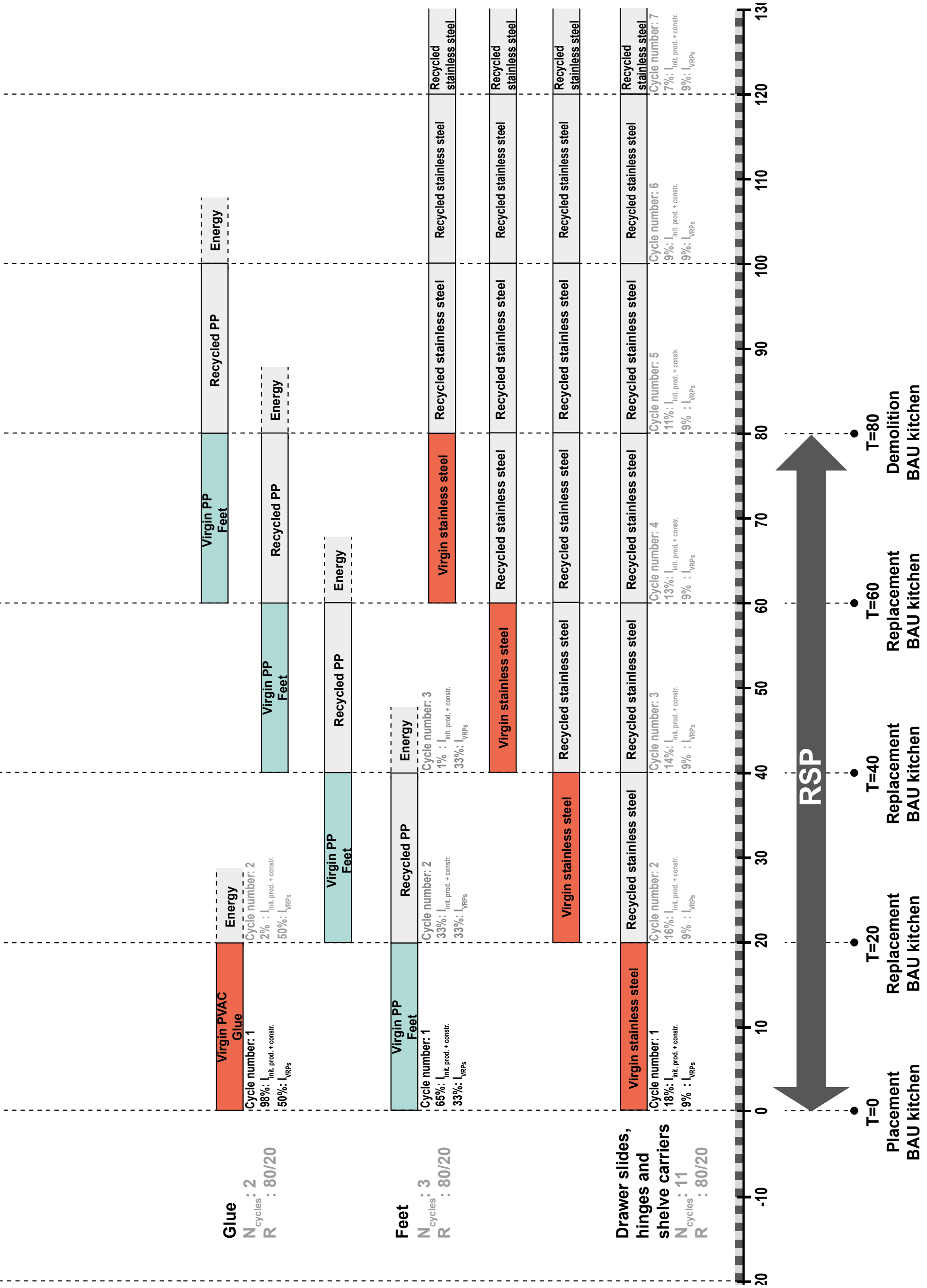


FIG. APP. B.3 Distribution of impacts between use cycles of materials applied in the BAU kitchen in relation to the RSP (the green and red colour highlight the use cycles when the material is applied in the assessed kitchen)



Glue
N cycles: 2
R: 80/20
Virgin PVAC Glue
Cycle number: 1
98%: I init. prod. + constr.
50%: I VRPs
Energy
Cycle number: 2
2% : I init. prod. + constr.
50%: I VRPs
Feet
N cycles: 3
R: 80/20
Virgin PP Feet
Cycle number: 1
65%: I init. prod. + constr.
33%: I VRPs
Recycled PP
Cycle number: 2
33%: I init. prod. + constr.
33%: I VRPs
Energy
Cycle number: 3
1% : I init. prod. + constr.
33%: I VRPs
Drawer slides, hinges and shelve carriers
N cycles: 11
R: 80/20
Virgin stainless steel
Recycled stainless steel
Recycled stainless steel
Cycle number: 1
18%: I init. prod. + constr.
9% : I VRPs
Cycle number: 2
16%: I init. prod. + constr.
9% : I VRPs
Cycle number: 3
14%: I init. prod. + constr.
9% : I VRPs
Cycle number: 4
13%: I init. prod. + constr.
9% : I VRPs
Cycle number: 5
11%: I init. prod. + constr.
9% : I VRPs
Cycle number: 6
9%: I init. prod. + constr.
9%: I VRPs
Cycle number: 7
7%: I init. prod. + constr.
9%: I VRPs
RSP
T=0 Placement BAU kitchen
T=20 Replacement BAU kitchen
T=40 Replacement BAU kitchen
T=60 Replacement BAU kitchen
T=80 Demolition BAU kitchen
20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130

TOC

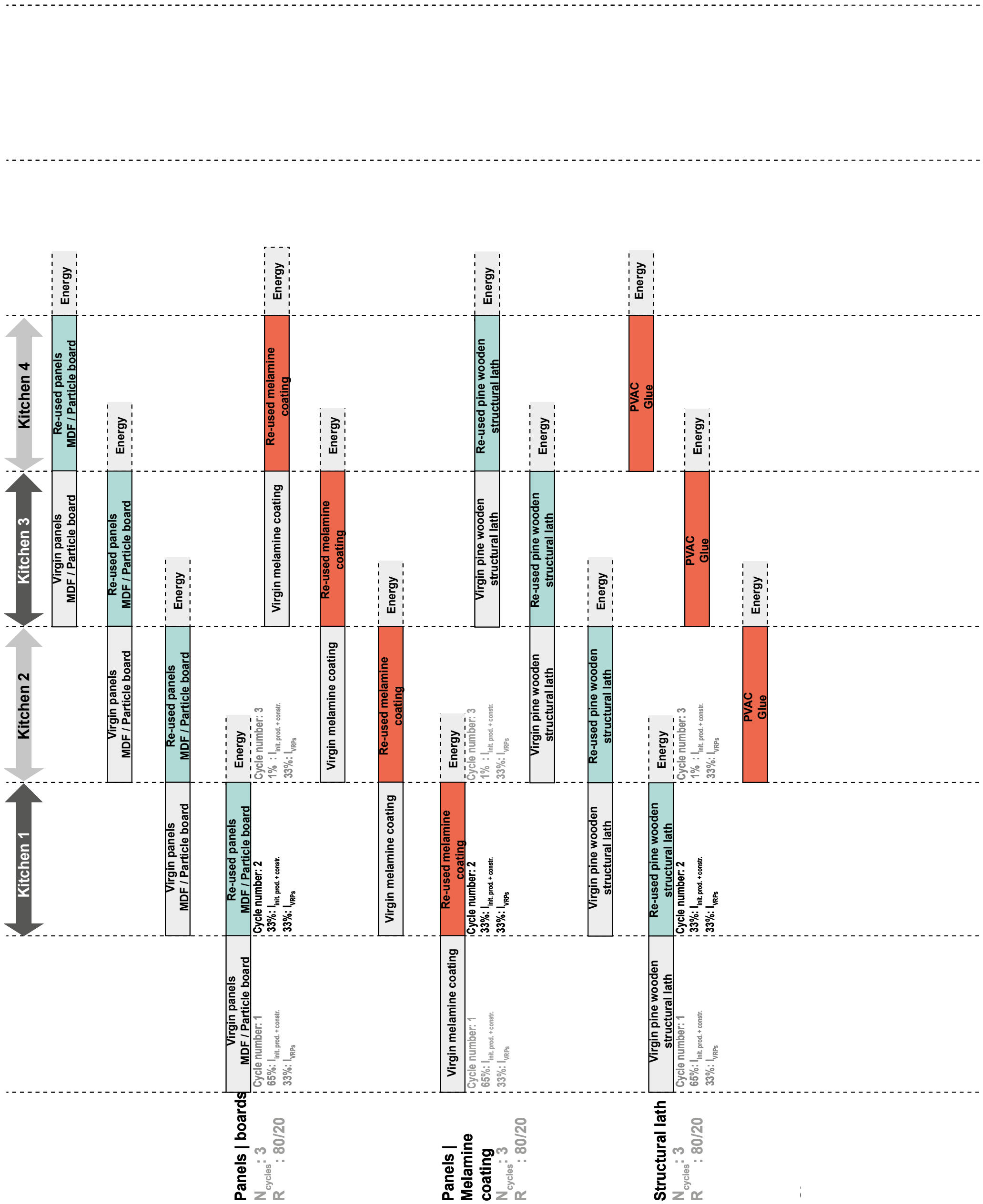
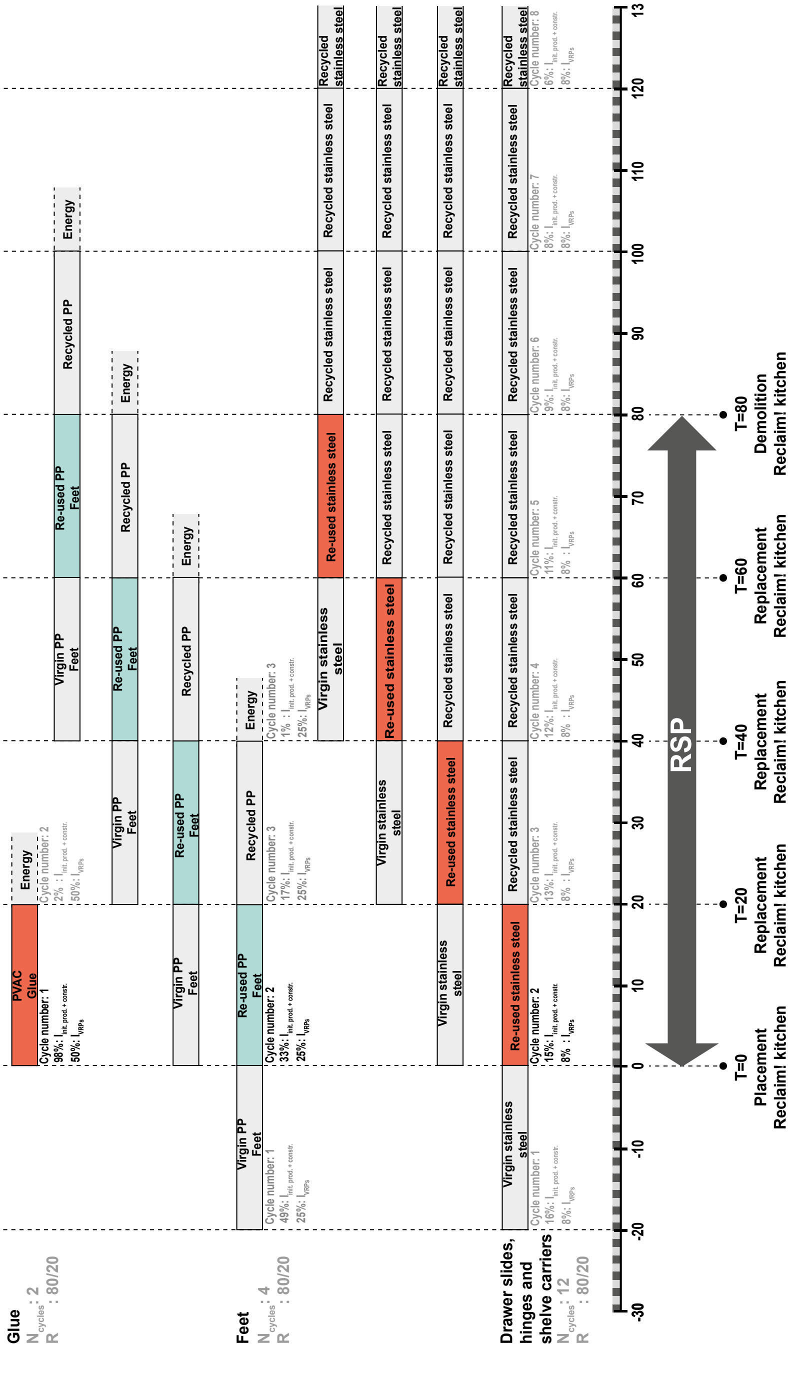


FIG. APP. B.4 Distribution of impacts between use cycles of materials applied in the Reclaim! kitchen in relation to the RSP (the green and red colour highlight the use cycles when the material is applied in the assessed kitchen)



Glue
N cycles : 2
R : 80/20
Feet
N cycles : 4
R : 80/20
Drawer slides, hinges and shelve carriers
N cycles : 12
R : 80/20
PVAC Glue
Energy
Virgin PP Feet
Re-used PP Feet
Recycled PP
Virgin stainless steel
Re-used stainless steel
Recycled stainless steel
RSP
T=0 Placement Reclaim! kitchen
T=20 Replacement Reclaim! kitchen
T=40 Replacement Reclaim! kitchen
T=60 Replacement Reclaim! kitchen
T=80 Demolition Reclaim! kitchen

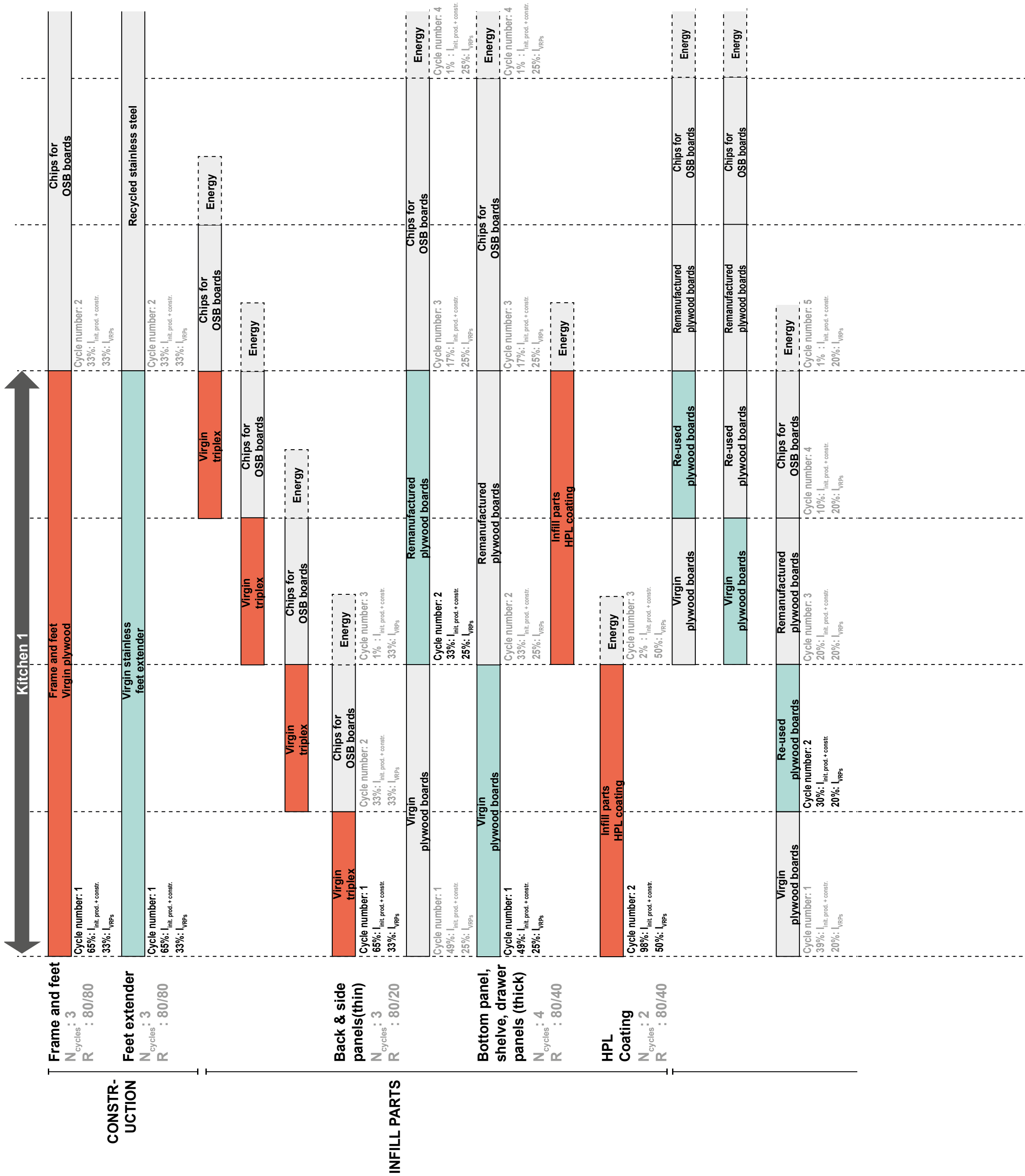
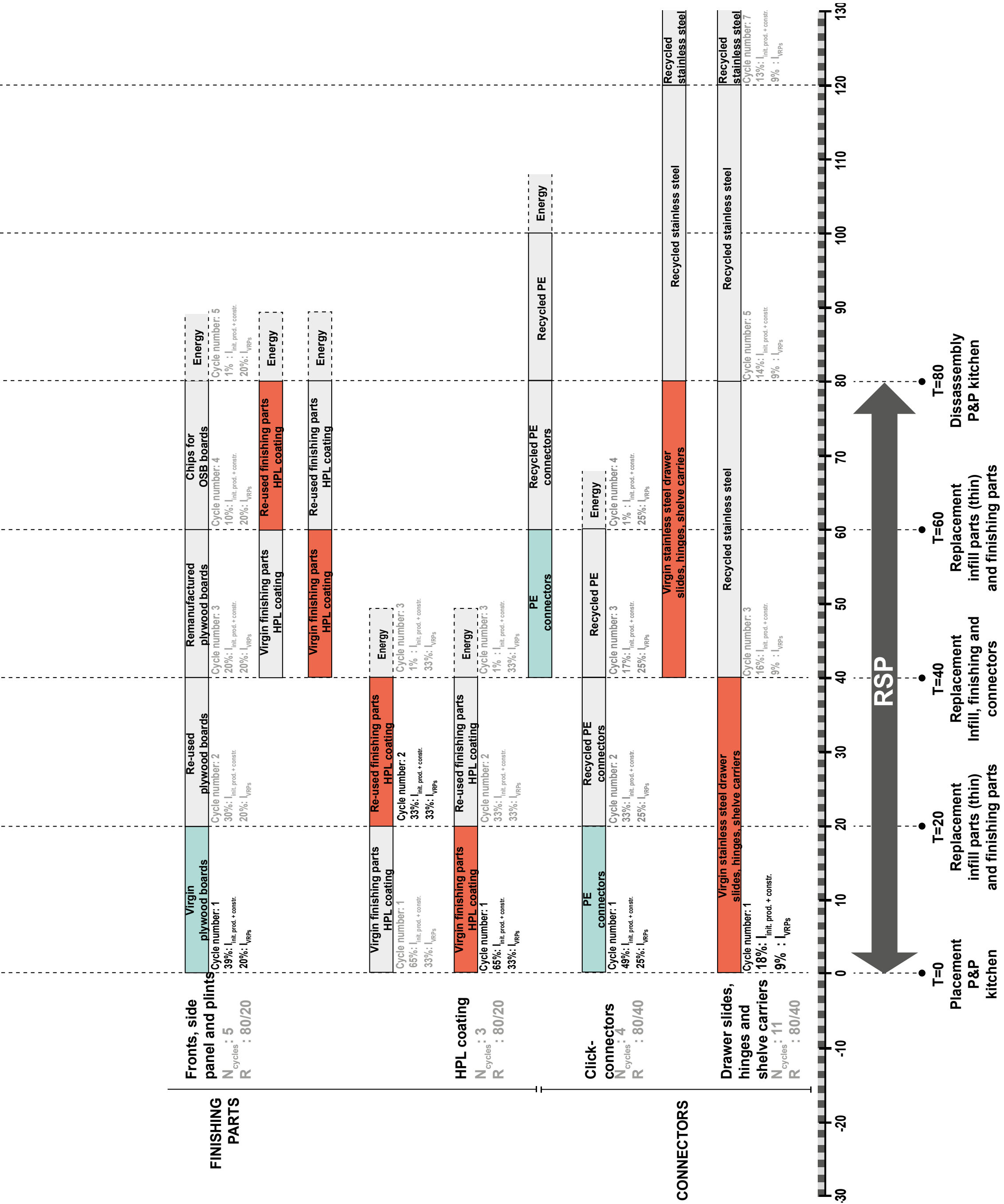


FIG. APP. B.5 Distribution of impacts between use cycles of materials applied in the P&P kitchen in relation to the RSP (the green and red colour highlight the use cycles when the material is applied in the assessed kitchen)


FINISHING PARTS
Fronts, side panel and plints
N_{cycles} : 5
R : 80/20
HPL coating
N_{cycles} : 3
R : 80/20
CONNECTORS
Click-connectors
N_{cycles} : 4
R : 80/40
Drawer slides, hinges and shelve carriers
N_{cycles} : 11
R : 80/40
Virgin plywood boards
Re-used plywood boards
Remanufactured plywood boards
Chips for OSB boards
Energy
Virgin finishing parts HPL coating
Re-used finishing parts HPL coating
PE connectors
Recycled PE connectors
Recycled PE
Virgin stainless steel drawer slides, hinges, shelve carriers
Recycled stainless steel
RSP
T=0 Placement P&P kitchen
T=20 Replacement infill parts (thin) and finishing parts
T=40 Replacement Infill, finishing and connectors
T=60 Replacement infill parts (thin) and finishing parts
T=80 Dissassembly P&P kitchen

TOC

APP. B.5 Sensitivity analysis scenarios

This appendix includes a detailed description of the sensitivity scenarios for the BAU, Reclaim! and P&P kitchen variants. Tables App.B.19-20 shows the 'what if question' tested per scenario; it gives the assumed N_{cycles} and $L_{technical}$ and $L_{functional}$ for (parts of) the kitchen variants, as well as the processes and parameters varied per scenario.

TOC

TABLE APP. B.19 Scenario's sensitivity analysis kitchen variants BAU and Reclaim!

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Lifespan technical kitchen [years]	Lifespan technical kitchen [years]	Number of future, local, reuse cycles entire kitchen	What processes / parameters are varied
BAU	Baseline			20	20	0	
	C+1	N_{cycles}	What if the entire BAU kitchen would be reused once locally?	20	20	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire BAU kitchen would be reused twice locally?	20	20	2	Decrease allocation fractions for all materials*
	L7	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would already be replaced after 7 years?	7	7	0	Increase replacement rate for all materials*
	L40	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would only be replaced after 40 years?	40	40	0	Decrease replacement rate for all materials*
	L80	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would only be replaced after 80 years?	80	80	0	Decrease replacement rate for all materials*

>>>

TOC

TABLE APP. B.19 Scenario's sensitivity analysis kitchen variants BAU and Reclaim!

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Lifespan technical kitchen [years]	Lifespan technical kitchen [years]	Number of future, local, reuse cycles entire kitchen	What processes / parameters are varied
Reclaim!	Baseline			10	10	0	
	C+1	N_{cycles}	What if the entire Reclaim! kitchen would be reused once locally?	20	20	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire Reclaim! kitchen would be reused twice locally?	20	20	2	Decrease allocation fractions for all materials*
	L7	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would already be replaced after 7 years?	7	7	0	Increase replacement rate for all materials*
	L20	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would last as long as the BAU kitchen?	20	20	0	Decrease replacement rate for all materials*
	L40	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would only be replaced after 40 years?	40	40	0	Decrease replacement rate for all materials*
	L80	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would only be replaced after 80 years?	80	80	0	Decrease replacement rate for all materials*

For the values of each varied parameters per sensitivity scenario, we refer to the Appendix B.3.

TABLE APP. B.20 Scenario's sensitivity analysis kitchen variant P&P

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Lifespan technical kitchen parts [years]				Lifespan functional kitchen parts [years]				Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Construction	Infill	Finishing	Connectors	Construction	Infill	Finishing	Connectors			
P&P	Baseline			80	40	40	40	80	40	20	40	0	0	
	C-3	N_{cycles}	What if all of the outer (uncertain) future cycles of materials would not come to pass?	80	40	40	40	80	40	20	40	3	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C-2	N_{cycles}	What if the two most-outer (uncertain) future cycle of materials would not come to pass?	80	40	40	40	80	40	20	40	2	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C-1	N_{cycles}	What if the most-outer (uncertain) future cycle of materials would not come to pass?	80	40	40	40	80	40	20	40	1	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C+1	N_{cycles}	What if the entire P&P kitchen has one local reuse cycle additional to the baseline scenario?	80	40	40	40	80	40	20	40	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire P&P kitchen has two local reuse cycles additional to the baseline scenario?	80	40	40	40	80	40	20	40	0	2	Decrease allocation fractions for all materials*
	Lf=80-40-7-40, Lt=80-40-40-40	$L_{functional}$ (finishing Sparts)	What if the finishing parts of the kitchen would be already be (ex) changed after 7 years?	80	40	40	40	80	40	7	40	0	0	Increase replacement rate for all finishing materials*; decrease allocation fractions for all finishing materials (as the number of reuse cycles of the finishing parts increases)*
	Lf=80-40-40-40, Lt=80-40-40-40	$L_{functional}$ (finishing Sparts)	What if the finishing parts of the kitchen would only be (ex)changed after 40 years?	80	40	40	40	80	40	40	40	0	0	Decrease replacement rate for all finishing materials*; Increase allocation fractions for all finishing materials (as the number of reuse cycles of the finishing parts decreases)*

>>>

TOC

TABLE APP. B.20 Scenario's sensitivity analysis kitchen variant P&P

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Lifespan technical kitchen parts [years]				Lifespan functional kitchen parts [years]				Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Construction	Infill	Finishing	Connectors	Construction	Infill	Finishing	Connectors			
P&P	Lt=7-7-7-7, Lf=7-7-3,5-7	$L_{technical}$ - $L_{functional}$	What if the entire kitchen lasts only ±7 years and the finishing parts are refurbished after ±3,5 years?	7	7	7	7	7	7	3.5	7	0	0	Increase replacement rate for all parts of the kitchen*
	Lt=20-20-20-20, Lf=20-20-10-20	$L_{technical}$ - $L_{functional}$	What if the P&P kitchen lasts as long as the BAU kitchen (with one refurbishment of the finishing parts at 10 years)?	20	20	20	20	20	20	10	20	0	0	Increase replacement rate for all parts of the kitchen*
	Lt=40-20-20-20, Lf=40-20-10-20	$L_{technical}$ - $L_{functional}$	What if the P&P kitchen lasts half as long and the finishing parts are (ex)changed twice as fast as the P&P baseline scenario?	40	20	20	20	40	20	10	20	0	0	Increase replacement rate for all parts of the kitchen*
	Lt=80-80-80-80, Lf=80-80-40-80	$L_{technical}$ - $L_{functional}$	What if the entire kitchen lasts 80 years and the finishing parts are refurbished after 40 years?	80	80	80	80	80	80	40	80	0	0	Decrease replacement rates for infill, finishing and connector parts of the kitchen*

*For the values of each varied parameters per sensitivity scenario, we refer to the Appendix B.3.

APP. B.6 Results CE-LCIA sensitivity analysis

This appendix includes the results of the CE-LCIA for the sensitivity analysis of the BAU, Reclaim! and P&P kitchen variants.

Tables App.B.21-24 present the results per impact category for all sensitivity scenarios for all design variants. Tables App.B.25-28 show the percentual reduction per scenario compared to the BAU baseline scenario for each impact category. Tables App.B.29-32 show the normalized values.

As an additional analysis, we illustrate how impacts are allocated to the kitchen over the RSP, for the sensitivity analysis on N_{cycles} in Figures App.B.6-8 and for the sensitivity analysis on lifespan in Figures App.B.9-12. Although this graph shows tipping points for the GWP, these tipping points can differ for other impact categories. Finally, for further clarification on each of the sensitivity scenarios, we refer to Appendix B.5.

TABLE APP. B.21 LCIA for BAU kitchen variant for all scenarios

Impact category	Unit	BAU					
		Baseline	C+1	C+2	L7	L40	L80
Global warming potential	kg CO2 eq	1,48E+02	1,03E+02	8,25E+01	4,44E+02	7,41E+01	3,70E+01
Ozone layer depletion potential	kg CFC-11 eq	1,32E-05	9,01E-06	7,00E-06	3,96E-05	6,60E-06	3,30E-06
Photochemical oxidation potential	kg C2H4 eq	5,10E-02	3,62E-02	2,94E-02	1,53E-01	2,55E-02	1,27E-02
Acidification potential	kg SO2 eq	5,99E-01	4,18E-01	3,32E-01	1,80E+00	2,99E-01	1,50E-01
Eutrophication potential	kg PO4--- eq	2,22E-01	1,54E-01	1,23E-01	6,65E-01	1,11E-01	5,54E-02
Abiotic depletion potential for elements	kg Sb eq	1,55E-03	1,07E-03	8,35E-04	4,65E-03	7,76E-04	3,88E-04
Abiotic depletion potential for fossil fuels	MJ	1,81E+03	1,25E+03	9,76E+02	5,43E+03	9,05E+02	4,52E+02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	8,30E+01	6,04E+01	4,95E+01	2,49E+02	4,15E+01	2,08E+01
Human toxicity potential	kg 1,4-DB eq	1,82E+02	1,45E+02	1,26E+02	5,46E+02	9,10E+01	4,55E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	1,70E+05	1,21E+05	9,71E+04	5,10E+05	8,51E+04	4,25E+04
Terrestrial ecotoxicity potential	kg 1,4-DB eq	4,93E-01	3,59E-01	2,95E-01	1,48E+00	2,47E-01	1,23E-01

TOC

TABLE APP. B.22 LCIA for Reclaim! kitchen variant for all scenarios

Impact category	Unit	Reclaim!						
		Baseline	C+1	C+2	L7	L20	L40	L80
Global warming potential	kg CO2 eq	1,50E+02	1,39E+02	1,22E+02	2,24E+02	7,48E+01	3,74E+01	1,87E+01
Ozone layer depletion potential	kg CFC-11 eq	1,12E-05	1,10E-05	9,99E-06	1,68E-05	5,59E-06	2,79E-06	1,40E-06
Photochemical oxidation potential	kg C2H4 eq	4,71E-02	4,65E-02	4,17E-02	7,07E-02	2,36E-02	1,18E-02	5,89E-03
Acidification potential	kg SO2 eq	5,34E-01	5,20E-01	4,67E-01	8,02E-01	2,67E-01	1,34E-01	6,68E-02
Eutrophication potential	kg PO4--- eq	1,98E-01	1,92E-01	1,71E-01	2,97E-01	9,92E-02	4,96E-02	2,48E-02
Abiotic depletion potential for elements	kg Sb eq	1,24E-03	1,22E-03	1,11E-03	1,86E-03	6,20E-04	3,10E-04	1,55E-04
Abiotic depletion potential for fossil fuels	MJ	1,56E+03	1,52E+03	1,37E+03	2,35E+03	7,82E+02	3,91E+02	1,96E+02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	9,37E+01	8,48E+01	7,51E+01	1,40E+02	4,68E+01	2,34E+01	1,17E+01
Human toxicity potential	kg 1,4-DB eq	2,37E+02	2,22E+02	2,03E+02	3,55E+02	1,18E+02	5,92E+01	2,96E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	1,71E+05	1,59E+05	1,41E+05	2,57E+05	8,56E+04	4,28E+04	2,14E+04
Terrestrial ecotoxicity potential	kg 1,4-DB eq	4,94E-01	4,75E-01	4,33E-01	7,42E-01	2,47E-01	1,24E-01	6,18E-02

TABLE APP. B.23 LCIA for P&P kitchen variant for scenarios varying the number of use cycles

Impact category	Unit	P&P					
		Baseline	C-3	C-2	C-1	C+1	C+2
Global warming potential	kg CO2 eq	6,40E+01	9,51E+01	7,13E+01	6,22E+01	5,22E+01	4,50E+01
Ozone layer depletion potential	kg CFC-11 eq	6,92E-06	1,18E-05	8,57E-06	7,23E-06	5,65E-06	4,80E-06
Photochemical oxidation potential	kg C2H4 eq	2,54E-02	4,19E-02	3,13E-02	2,62E-02	2,10E-02	1,83E-02
Acidification potential	kg SO2 eq	2,99E-01	4,84E-01	3,57E-01	3,01E-01	2,46E-01	2,12E-01
Eutrophication potential	kg PO4--- eq	1,05E-01	1,64E-01	1,22E-01	1,03E-01	8,69E-02	7,49E-02
Abiotic depletion potential for elements	kg Sb eq	9,77E-04	3,83E-04	2,98E-04	2,66E-04	8,25E-04	7,09E-04
Abiotic depletion potential for fossil fuels	MJ	7,88E+02	1,27E+03	9,27E+02	7,92E+02	6,43E+02	5,49E+02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	3,73E+01	3,84E+01	3,12E+01	2,86E+01	3,11E+01	2,72E+01
Human toxicity potential	kg 1,4-DB eq	9,11E+01	9,79E+01	8,64E+01	8,17E+01	7,85E+01	7,10E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	7,62E+04	8,55E+04	6,60E+04	5,83E+04	6,32E+04	5,47E+04
Terrestrial ecotoxicity potential	kg 1,4-DB eq	2,81E-01	3,53E-01	2,73E-01	2,36E-01	2,36E-01	2,05E-01

TABLE APP. B.24 LCIA for P&P kitchen variant for scenarios varying the functional and technical lifespan

Impact category	Unit	P&P					
		Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3, 5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Global warming potential	kg CO2 eq	7,85E+01	5,00E+01	4,01E+02	1,34E+02	1,28E+02	3,41E+01
Ozone layer depletion potential	kg CFC-11 eq	8,62E-06	5,22E-06	4,34E-05	1,45E-05	1,38E-05	3,73E-06
Photochemical oxidation potential	kg C2H4 eq	3,07E-02	2,00E-02	1,60E-01	5,34E-02	5,06E-02	1,37E-02
Acidification potential	kg SO2 eq	3,67E-01	2,32E-01	1,89E+00	6,30E-01	5,97E-01	1,61E-01
Eutrophication potential	kg PO4--- eq	1,30E-01	8,20E-02	6,67E-01	2,22E-01	2,10E-01	5,67E-02
Abiotic depletion potential for elements	kg Sb eq	1,34E-03	7,52E-04	6,41E-03	2,14E-03	1,95E-03	5,37E-04
Abiotic depletion potential for fossil fuels	MJ	9,69E+02	6,05E+02	4,94E+03	1,65E+03	1,57E+03	4,23E+02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	4,56E+01	3,08E+01	2,39E+02	7,96E+01	7,46E+01	2,01E+01
Human toxicity potential	kg 1,4-DB eq	1,02E+02	8,23E+01	5,88E+02	1,96E+02	1,82E+02	4,93E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	9,48E+04	6,09E+04	4,86E+05	1,62E+05	1,52E+05	4,10E+04
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,45E-01	2,27E-01	1,80E+00	6,00E-01	5,62E-01	1,52E-01

TABLE APP. B.25 Percentual reduction per BAU variant scenario compared to the BAU baseline scenario

Impact category	Unit	BAU					
		Baseline	C+1	C+2	L7	L40	L80
Global warming potential	%-saved	0%	30%	44%	-200%	50%	75%
Ozone layer depletion potential	%-saved	0%	32%	47%	-200%	50%	75%
Photochemi-cal oxidation potential	%-saved	0%	29%	42%	-200%	50%	75%
Acidification potential	%-saved	0%	30%	45%	-200%	50%	75%
Eutrophication potential	%-saved	0%	30%	45%	-200%	50%	75%
Abiotic depletion potential for elements	%-saved	0%	31%	46%	-200%	50%	75%
Abiotic depletion potential for fossil fuels	%-saved	0%	31%	46%	-200%	50%	75%
Fresh water aquatic ecotox-icity potential	%-saved	0%	27%	40%	-200%	50%	75%
Human toxicity potential	%-saved	0%	21%	31%	-200%	50%	75%
Marine aquatic ecotoxicity potential	%-saved	0%	29%	43%	-200%	50%	75%
Terrestrial ecotoxicity potential	%-saved	0%	27%	40%	-200%	50%	75%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) over all design variants and scenarios, per impact category.

TABLE APP. B.26 Percentual reduction per Reclaim! variant scenario compared to the BAU baseline scenario

Impact category	Unit	Reclaim!						
		Baseline	C+1	C+2	L7	L20	L40	L80
Global warming potential	%-saved	-1%	6%	18%	-51%	50%	75%	87%
Ozone layer depletion potential	%-saved	15%	16%	24%	-27%	58%	79%	89%
Photochemical oxidation potential	%-saved	7%	9%	18%	-39%	54%	77%	88%
Acidification potential	%-saved	11%	13%	22%	-34%	55%	78%	89%
Eutrophication potential	%-saved	11%	14%	23%	-34%	55%	78%	89%
Abiotic depletion potential for elements	%-saved	20%	21%	28%	-20%	60%	80%	90%
Abiotic depletion potential for fossil fuels	%-saved	14%	16%	24%	-30%	57%	78%	89%
Fresh water aquatic ecotoxicity potential	%-saved	-13%	-2%	9%	-69%	44%	72%	86%
Human toxicity potential	%-saved	-30%	-22%	-12%	-95%	35%	67%	84%
Marine aquatic ecotoxicity potential	%-saved	-1%	7%	17%	-51%	50%	75%	87%
Terrestrial ecotoxicity potential	%-saved	0%	4%	12%	-50%	50%	75%	87%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) over all design variants and scenarios, per impact category.

TABLE APP. B.27 Percentual reduction per P&P variant scenario compared to the BAU baseline scenario

Impact category	Unit	P&P					
		Baseline	C-3	C-2	C-1	C+1	C+2
Global warming potential	%-saved	57%	36%	52%	58%	65%	70%
Ozone layer depletion potential	%-saved	48%	10%	35%	45%	57%	64%
Photochemi-cal oxidation potential	%-saved	50%	18%	39%	49%	59%	64%
Acidification potential	%-saved	50%	19%	40%	50%	59%	65%
Eutrophication potential	%-saved	53%	26%	45%	54%	61%	66%
Abiotic depletion potential for elements	%-saved	37%	75%	81%	83%	47%	54%
Abiotic depletion potential for fossil fuels	%-saved	56%	30%	49%	56%	64%	70%
Fresh water aquatic ecotox-icity potential	%-saved	55%	54%	62%	66%	62%	67%
Human toxicity potential	%-saved	50%	46%	53%	55%	57%	61%
Marine aquatic ecotoxicity potential	%-saved	55%	50%	61%	66%	63%	68%
Terrestrial ecotoxicity potential	%-saved	43%	28%	45%	52%	52%	58%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) over all design variants and scenarios, per impact category.

TABLE APP. B.28 (Continued) percentual reduction per P&P variant scenario compared to the BAU baseline scenario

Impact category	Unit	P&P					
		Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3, 5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Global warming potential	%-saved	47%	66%	-171%	10%	14%	77%
Ozone layer depletion potential	%-saved	35%	60%	-229%	-10%	-4%	72%
Photochemical oxidation potential	%-saved	40%	61%	-214%	-5%	1%	73%
Acidification potential	%-saved	39%	61%	-216%	-5%	0%	73%
Eutrophication potential	%-saved	41%	63%	-201%	0%	5%	74%
Abiotic depletion potential for elements	%-saved	14%	52%	-313%	-38%	-26%	65%
Abiotic depletion potential for fossil fuels	%-saved	46%	67%	-173%	9%	13%	77%
Fresh water aquatic ecotoxicity potential	%-saved	45%	63%	-188%	4%	10%	76%
Human toxicity potential	%-saved	44%	55%	-223%	-8%	0%	73%
Marine aquatic ecotoxicity potential	%-saved	44%	64%	-186%	5%	11%	76%
Terrestrial ecotoxicity potential	%-saved	30%	54%	-265%	-22%	-14%	69%

Note: The colour shows a gradient between the highest percentual savings (blue) and lowest percentual savings (light blue) over all design variants and scenarios, per impact category.

TABLE APP. B.29 Normalised impacts for each sensitivity scenario of the BAU kitchen variant per impact category

Impact category	BAU					
	Baseline	C+1	C+2	L7	L40	L80
Global warming potential	3,54E-12	2,47E-12	1,97E-12	1,06E-11	1,77E-12	8,86E-13
Ozone layer depletion potential	5,81E-14	3,97E-14	3,08E-14	1,74E-13	2,91E-14	1,45E-14
Photochemical oxidation potential	1,39E-12	9,83E-13	7,98E-13	4,16E-12	6,93E-13	3,46E-13
Acidification potential	2,50E-12	1,75E-12	1,39E-12	7,51E-12	1,25E-12	6,26E-13
Eutrophication potential	1,40E-12	9,78E-13	7,78E-13	4,21E-12	7,02E-13	3,51E-13
Abiotic depletion potential for elements	7,42E-12	5,11E-12	3,99E-12	2,23E-11	3,71E-12	1,86E-12
Abiotic depletion potential for fossil fuels	4,76E-12	3,28E-12	2,57E-12	1,43E-11	2,38E-12	1,19E-12
Fresh water aquatic ecotoxicity potential	3,52E-11	2,56E-11	2,10E-11	1,06E-10	1,76E-11	8,79E-12
Human toxicity potential	7,05E-11	5,60E-11	4,90E-11	2,12E-10	3,53E-11	1,76E-11
Marine aquatic ecotoxicity potential	8,77E-10	6,23E-10	5,01E-10	2,63E-09	4,39E-10	2,19E-10
Terrestrial ecotoxicity potential	4,52E-13	3,30E-13	2,71E-13	1,36E-12	2,26E-13	1,13E-13

Note: The colour shows a gradient between the highest (light blue) and lowest (blue) value per scenario per design variant.

TABLE APP. B.30 Normalised impacts for each sensitivity scenario of the Reclaim! kitchen variant per impact category

Impact category	Reclaim!						
	Baseline	C+1	C+2	L7	L20	L40	L80
Global warming potential	3,58E-12	3,32E-12	2,92E-12	5,37E-12	1,79E-12	8,95E-13	4,47E-13
Ozone layer depletion potential	4,92E-14	4,87E-14	4,40E-14	7,38E-14	2,46E-14	1,23E-14	6,15E-15
Photochemical oxidation potential	1,28E-12	1,26E-12	1,13E-12	1,92E-12	6,41E-13	3,20E-13	1,60E-13
Acidification potential	2,24E-12	2,17E-12	1,95E-12	3,35E-12	1,12E-12	5,59E-13	2,80E-13
Eutrophication potential	1,26E-12	1,21E-12	1,09E-12	1,88E-12	6,28E-13	3,14E-13	1,57E-13
Abiotic depletion potential for elements	5,93E-12	5,84E-12	5,32E-12	8,90E-12	2,97E-12	1,48E-12	7,42E-13
Abiotic depletion potential for fossil fuels	4,12E-12	4,01E-12	3,60E-12	6,18E-12	2,06E-12	1,03E-12	5,15E-13
Fresh water aquatic ecotoxicity potential	3,97E-11	3,59E-11	3,18E-11	5,95E-11	1,98E-11	9,92E-12	4,96E-12
Human toxicity potential	9,18E-11	8,61E-11	7,89E-11	1,38E-10	4,59E-11	2,29E-11	1,15E-11
Marine aquatic ecotoxicity potential	8,82E-10	8,17E-10	7,27E-10	1,32E-09	4,41E-10	2,21E-10	1,10E-10
Terrestrial ecotoxicity potential	4,54E-13	4,36E-13	3,97E-13	6,80E-13	2,27E-13	1,13E-13	5,67E-14

Note: The colour shows a gradient between the highest (light blue) and lowest (blue) value per scenario per design variant.

TABLE APP. B.31 Normalised impacts for the scenarios varying the number of use cycles of the P&P kitchen variant per impact category

Impact category	P&P					
	Baseline	C-3	C-2	C-1	C+1	C+2
Global warming potential	1,53E-12	2,28E-12	1,71E-12	1,49E-12	1,25E-12	1,08E-12
Ozone layer depletion potential	3,05E-14	5,22E-14	3,78E-14	3,18E-14	2,49E-14	2,11E-14
Photochemical oxidation potential	6,89E-13	1,14E-12	8,50E-13	7,13E-13	5,71E-13	4,98E-13
Acidification potential	1,25E-12	2,02E-12	1,49E-12	1,26E-12	1,03E-12	8,85E-13
Eutrophication potential	6,66E-13	1,04E-12	7,72E-13	6,50E-13	5,50E-13	4,74E-13
Abiotic depletion potential for elements	4,67E-12	1,83E-12	1,43E-12	1,27E-12	3,95E-12	3,39E-12
Abiotic depletion potential for fossil fuels	2,07E-12	3,34E-12	2,44E-12	2,08E-12	1,69E-12	1,44E-12
Fresh water aquatic ecotoxicity potential	1,58E-11	1,63E-11	1,32E-11	1,21E-11	1,32E-11	1,15E-11
Human toxicity potential	3,53E-11	3,79E-11	3,35E-11	3,17E-11	3,04E-11	2,75E-11
Marine aquatic ecotoxicity potential	3,93E-10	4,41E-10	3,40E-10	3,00E-10	3,26E-10	2,82E-10
Terrestrial ecotoxicity potential	2,58E-13	3,24E-13	2,51E-13	2,17E-13	2,16E-13	1,89E-13

Note: The colour shows a gradient between the highest (light blue) and lowest (blue) value per scenario per design variant.

TABLE APP. B.32 Normalised impacts for the scenarios varying technical and functional lifespans of the P&P kitchen variant per impact category

Impact category	P&P					
	Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3, 5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Global warming potential	1,88E-12	1,20E-12	9,59E-12	3,20E-12	3,05E-12	8,17E-13
Ozone layer depletion potential	3,80E-14	2,30E-14	1,91E-13	6,37E-14	6,06E-14	1,64E-14
Photochemical oxidation potential	8,35E-13	5,44E-13	4,35E-12	1,45E-12	1,38E-12	3,72E-13
Acidification potential	1,54E-12	9,72E-13	7,90E-12	2,63E-12	2,50E-12	6,75E-13
Eutrophication potential	8,23E-13	5,19E-13	4,22E-12	1,41E-12	1,33E-12	3,59E-13
Abiotic depletion potential for elements	6,41E-12	3,60E-12	3,07E-11	1,02E-11	9,35E-12	2,57E-12
Abiotic depletion potential for fossil fuels	2,55E-12	1,59E-12	1,30E-11	4,34E-12	4,13E-12	1,11E-12
Fresh water aquatic ecotoxicity potential	1,93E-11	1,30E-11	1,01E-10	3,37E-11	3,16E-11	8,51E-12
Human toxicity potential	3,95E-11	3,19E-11	2,28E-10	7,59E-11	7,06E-11	1,91E-11
Marine aquatic ecotoxicity potential	4,89E-10	3,14E-10	2,51E-09	8,36E-10	7,85E-10	2,11E-10
Terrestrial ecotoxicity potential	3,17E-13	2,09E-13	1,65E-12	5,50E-13	5,16E-13	1,40E-13

Note: The colour shows a gradient between the highest (light blue) and lowest (blue) value per scenario per design variant.

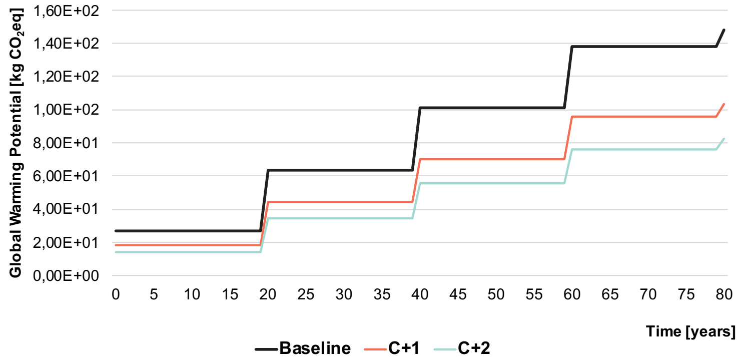


FIG. APP. B.6 Sensitivity analysis on the number of cycles for the BAU kitchen (GWP over 80 years)

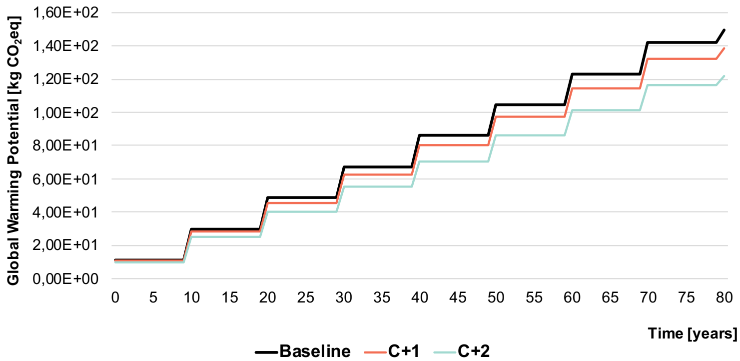


FIG. APP. B.7 Sensitivity analysis on the number of cycles for the Reclaim! kitchen (GWP over 80 years)

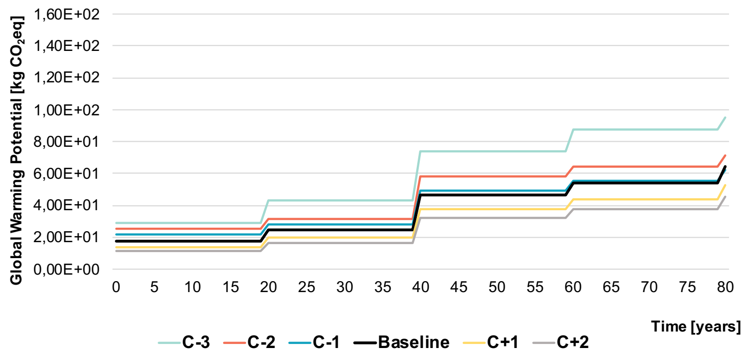


FIG. APP. B.8 Sensitivity analysis on the number of cycles for the P&P kitchen (GWP over 80 years)

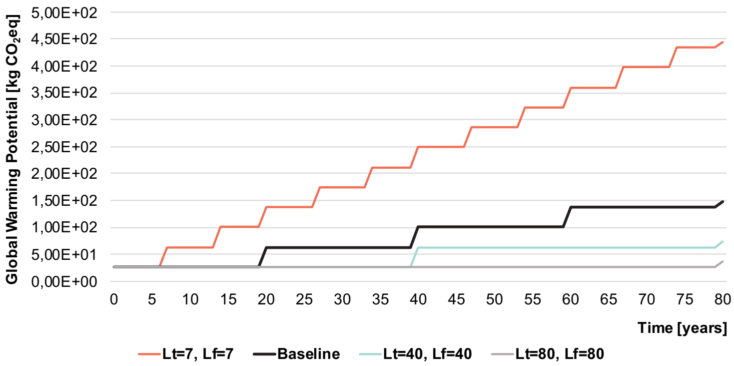


FIG. APP. B.9 Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BAU kitchen (GWP over 80 years)

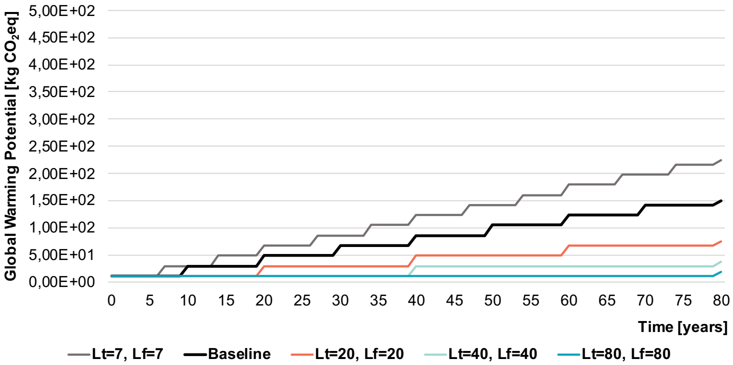


FIG. APP. B.10 Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the Reclaim! kitchen (GWP over 80 years)

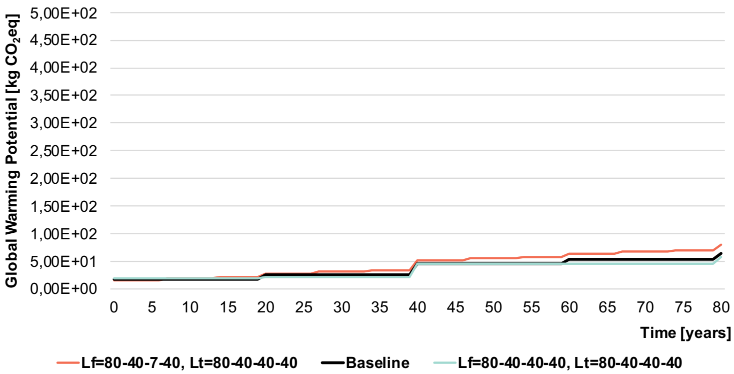


FIG. APP. B.11 Sensitivity analysis on the $L_{functional}$ for the finishing of the P&P kitchen (GWP over 80 years)

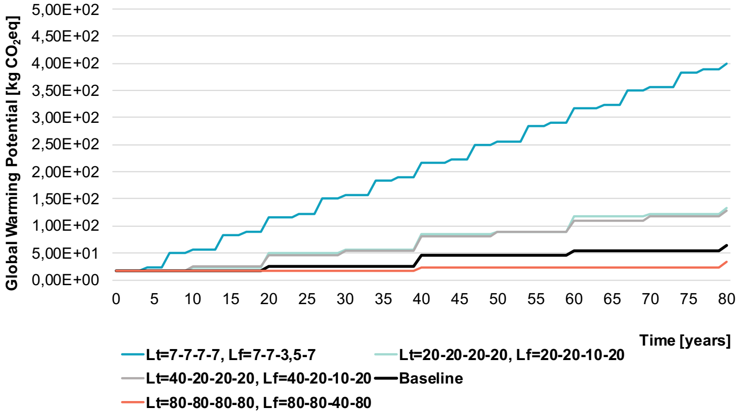


FIG. APP. B.12 Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P&P kitchen (GWP over 80 years)

TOC

APP. C Appendix Chapter 6

APP. C.1 CE-LCIA and MFA equations and parameters

In this appendix we clarify the used equations in the CE-LCIA and MFA and define all parameters.

APP. C.1.1 Nomenclature Appendix C

TABLE APP. C.1 Nomenclature used in Appendix C

CE-LCA	Circular Economy Life Cycle Assessment
RSP	Reference Study Period
$I_{life\ cycle\ stage}$	Impact of a life cycle stage in the material's lifecycle which is allocated to the assessed building component during the RSP
$R_{life\ cycle\ stage}$	Rate in which a life cycle stage occurs in the RSP and following chain of cycles of the material
$P_{life\ cycle\ stage}$	Probability of a life cycle stage occurring
$Af_{life\ cycle\ stage}$	Allocation Fraction of a lifecycle stage: fraction of impact of a life cycle stage which is allocated to the material in the use cycle of the assessed building component
$AI_{life\ cycle\ stage}$	Absolute Impacts (i.e., before allocation) from completing a life cycle stage once
CE LD	Circular Economy Linearly Degressive
N_{cycles}	Number of use cycles within a material's lifecycle
F	Factor determining how much more initial production and construction impacts are allocated to the first cycle versus the last cycle, and vice versa for disposal impacts
C_{number}	Cycle number in which the material is when applied in the assessed building component
AI_x	Absolute Impact of material, transport, process or energy used to complete a lifecycle stage
Qty	Quantity

>>>

TOC

TABLE APP. C.1 Nomenclature used in Appendix C

CE-LCA	Circular Economy Life Cycle Assessment
$\frac{AI_x}{unit}$	Absolute Impact of material, transport, process or energy per unit
$M_{mat., x}$	Mass of the material per placement in [kg].
$M\ import$	Total mass of all material applied in the assessed building component during the RSP
$M\ import_{mat., x}$	Mass of material x applied in the assessed building component during the RSP
$R_{mat., x}$	Rate in which material x is placed in the building component during the RSP
$M\ flow\ x_{mat., x}$	Mass of import or export flows of material x with 'quality x'
$r\ flow\ x_{mat., x}$	Ratio describing the percentage of material x that has quality x
$r\ virgin_{mat., x}$	Ratio describing the percentage of material x that is virgin material
$r\ non\text{-}virgin_{mat., x}$	Ratio describing the percentage of material x that is non-virgin material
$M\ consumption_{mat., x}$	Mass of material x which is consumed during its use cycle in the assessed building component during the RSP
$M\ reuse_{mat., x}$	Mass of material x which is reused after its use cycle in the assessed building component during the RSP
$M\ reman._{mat., x}$	Mass of material x which is remanufactured after its use cycle in the assessed building component during the RSP
$M\ Recyc_{mat., x}$	Mass of material x which is recycled after its use cycle in the assessed building component during the RSP

APP. C.1.2 CE-LCIA equations

To assess the life cycle impacts of the circular building components, we followed the CE-LCA model presented in Chapter 5. In this model, the environmental impacts of the building component are calculated in a series of sums. The environmental impact of the building component is calculated by adding the impact of all parts. Likewise, the impact of a part is a sum of the impact of all its materials. Materials are not only distinguished based on type (e.g., stainless steel, aluminum or spruce) but also if they have different lifespans and use cycles in the material's total lifecycle. The impact of the material is a sum of the impact of all the materials lifecycle stages which are allocated to the assessed building component over the RSP.

To calculate the impact of each life cycle stage in the material's lifecycle which is allocated to the assessed building component during the RSP, we use equation C.1:

$$I_{lifecycle\ stage} = R_{life\ cycle\ stage} \cdot P_{life\ cycle\ stage} \cdot Af_{life\ cycle\ stage} \cdot AI_{life\ cycle\ stage} \quad (C.1)$$

TOC

in which $R_{life\ cycle\ stage}$ is the rate – the number of times – in which a life cycle stage occurs in the RSP and following chain of cycles of the material. For example, a virgin stainless-steel connector is replaced 2 times during the RSP; after use as a connector, the stainless steel has 10 recycling cycles. In this example, the rate of the recycling lifecycle stage equals 20.

$P_{life\ cycle\ stage}$ represents the probability of a life cycle stage to occur. For example, repair of parts might only occur in a certain percentage of the building components. Due to the selected goal and scope of the kitchen and façade assessments, the value of P was set at 1: all lifecycle stages were assumed to occur.

The allocation fraction $(Af_{life\ cycle\ stage})$ is the fraction of impact of a life cycle stage which is allocated to the material in the use cycle of the assessed building component. The Af can be determined using different allocation approaches including an equal distribution approach or the Circular Economy Linearly Degressive (CE LD) approach of Malabi Eberhardt, van Stijn, Nygaard Rasmussen, Birkved and Birgisdottir (2020) (see also van Stijn, Malabi Eberhardt, Wouterszoon Jansen and Meijer (2021)). In both approaches the share of impact of a material's lifecycle stage which is allocated to the use cycle when the material is applied in the assessed building component is influenced by the total number of use cycles (N_{cycles}) within this material's lifecycle. In the previous example, the stainless steel had a total number of 11 use cycles. The more use cycles, the less impact is allocated to individual cycles. In the assessments of the façades and kitchens, we applied the CE LD approach. In this approach the impact share is further influenced by factor F. F determines how much more initial production and construction impacts are allocated to the first cycle versus the last cycle, and vice versa for disposal impacts. In our assessment this factor is a fixed value (50). Additionally, in CE LD the value for Af is influenced by the cycle number (C_{number}) in which the material is when applied in the assessed building component. In the example of the virgin stainless-steel connector, the material is in its first use cycle, If the stainless-steel connector would be of recycled material, it might be in a second-, third use cycle, or more. Using CE-LD, a material in its first use cycle gets more initial production and construction impacts than in its second cycle (vice versa for disposal impacts).

$AI_{life\ cycle\ stage}$ represents the *absolute* environmental impacts (i.e., before allocation) from completing a life cycle stage once. This is a sum of *absolute* impacts of the material, transport, process and energy in this life cycle stage as described in equation C.2:

TOC

$$AI_{lifecycle\ stage} = AI_{materials} + AI_{transport} + AI_{process} + AI_{energy} \quad (C.2)$$

In which the absolute impact of material, transport, process and energy can be calculated using equation C.3:

$$AI_x = Qty \cdot \frac{AI_x}{unit} \quad (C.3)$$

in which the absolute impact of a materials, transport, processes or energy (AI_x) can be calculated by multiplying the quantity (Qty) with the absolute impact per unit $(\frac{AI_x}{unit})$. For example, to calculate the production impacts of the stainless-steel connector, the mass $(M_{mat.,\ x})$ of the required stainless steel would be multiplied with the production impacts of stainless steel per kg.

APP. C.1.3

MFA equations

The total mass of all materials applied in the assessed building component during the RSP is the material import $(M\ \ import)$, which is calculated by adding the material import for each separate material applied in the building component during the RSP. To determine the material import for each individual material, we use equation C.4:

$$M\ \ import_{mat.,\ x} = R_{mat.,x} \cdot M_{mat.,x} \quad (C.4)$$

in which $(R_{mat.,x})$ is the rate – the number of times – in which that material is placed in the building component during the RSP. $M_{mat.,x}$ is the mass of the material per placement in [kg].

Following the law of matter conservation, the $M\ \ import$ equals the export mass for that material. $M\ \ flow\ x_{mat.,\ x}$ describes the mass of import or export flows of a material with a certain 'quality'. For example, an import flow can be virgin, non-virgin,

TOC

renewable, or non-renewable; an export flow can be reusable, remanufacturable, recyclable, biodegradable, recoverable or discarded. To calculate $M\ \ flow\ x_{mat.,\ x}$, equation C.5 is used:

$$M\ \ flow\ x_{mat.,\ x} = M\ \ import_{mat.,x} \cdot r\ \ flow\ x_{\ mat.,\ x} \tag{C.5}$$

where the $M\ \ import$ of a material is multiplied by a ratio describing the percentage of the material flow that has the to-be-analyzed quality $\left(r\ \ flow\ x_{mat.,\ x}\right)$. For example, the ratio might describe how much of the stainless steel applied in a connector of the building component is virgin $\left(r\ \ virgin\right)$ or non-virgin $\left(r\ \ non-virgin\right)$. Finally, the material consumption is then calculated using equation C.6.

$$M\ \ consumption_{mat.,\ x} = M\ \ import_{mat.,x} - M\ \ reuse_{mat.,x}\ - M\ \ reman._{\ mat.,x} - M\ \ Recyc._{\ mat.,x} \tag{C.6}$$

where the reused export flows of a material, the remanufactured export flows $(M\ \ reman._{mat.,x}\ )$ and the recycled export flows $(M\ \ recyc._{mat.,x}\ )$ are subtracted from the $M\ \ import$ of a material.

References

Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability*, 12(22), 9579. https://doi.org/10.3390/su12229579

van Stijn, A., Malabi Eberhardt, L. C., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling*, 174(105683), 1–34. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.105683

APP. C.2 Detailed Life Cycle Inventory and Life Cycle Impact Assessment parameters

For the complete Circular Economy Life Cycle Inventory and overview of applied values for each Circular Economy Life Cycle Impact Assessment parameter – of all assessed kitchen and façade variants, for all scenarios – we refer to the excel files which have been made available online.

TABLE APP. C.2 Circular Economy Life Cycle Inventory and Circular Economy Life Cycle Impact Assessment parameters for the kitchen variants for all scenarios

Accessible via: https://ars.els-cdn.com/content/image/1-s2.0-S0959652622009994-mmc1.xlsx

TABLE APP. C.3 Circular Economy Life Cycle Inventory and Circular Economy Life Cycle Impact Assessment parameters for the façade variants for all scenarios

Accessible via: https://ars.els-cdn.com/content/image/1-s2.0-S0959652622009994-mmc2.xlsx

APP. C.3 Clarification sensitivity scenarios CE-LCA and MFA

We tested the sensitivity of two key circular economy parameters: (1) the number of cycles and (2) the lifespan of (parts of) the building component. The sensitivity analysis was based on 'what-if' scenarios. An overview of the sensitivity scenarios for the kitchen variants has been included in Tables App.C.4-6 and for the façade in Tables App.C.7-10. For a detailed description of the kitchen and façade design variants, we refer to Appendix C.5.

The number of cycles for each material influences the percentual division of export flows in the MFA and how much environmental impact is allocated to the assessed building component in the CE-LCA; if assumptions are too optimistic, flows might be dispersed to non-existing reused flows and impacts might be spread over non-existent cycles. Hence, we investigated the effects of adding and subtracting cycles. When adding cycles, we assumed local, direct reuse: no extra transportation or processes were added to the model. For variants with uncertain reuse, remanufacturing and recycling cycles in their baseline scenario, we also tested the effects if these cycles would not be realised. When subtracting cycles, we subtracted from more uncertain to more certain cycles. In the design variants of the façade and kitchen, we found the uncertainty is largest for cycles far in the future and open cycles (i.e., when the producing partners are not in control or involved in the VRPs). When subtracting cycles, we upheld the final cycle. This is usually either recycling, recovery or disposal). We then subtracted from the outer cycles, inwards. For example, for the shelves in the kitchen P&P variant, we always maintained final recovery (incineration); in scenario ‘minus 1 cycle’, we removed recycling (i.e., chipping of the wood for OSB production); in scenario ‘minus 2 cycles’, we also removed the remanufacturing cycle (i.e., recoating of shelves); in scenario ‘minus 3 cycles’, we also removed the direct reuse cycle. This C-3 scenario can be considered a linear scenario.

The second sensitivity analysis focussed on lifespan – and so, the rate of (re) placements. How often production, use, VRPs and disposal cycles take place is influenced by assumptions on the functional, technical and economic lifespans of the materials, parts and building component. The functional lifespan is influenced by changing regulations and user needs, including function or appearance of the component (Geraedts, Vande Putte, Vercouteren, & Binnekamp, 2009; Méquignon & Ait Haddou, 2014). The technical lifespan can be defined as “the maximum period during which it can physically [perform]” (Cooper, 1994, p. 5). The economic lifespan is the period in which the benefits outweigh the costs (Geraedts et al., 2009). We tested the effect of varying different types of lifespans for the building component as a whole and for specific subcomponents, parts and materials. First, for all kitchen and façade variants, we varied the technical and functional lifespan of the building component, parts and materials in parallel. This is closest to a ‘traditional replacement rate’ or ‘service life’ sensitivity analysis. For example, for the BIO kitchen, the technical and functional lifespan was set at 10 years in the baseline scenario. What would happen if the whole kitchen is replaced every 7 years (i.e., average tenancy period); what if it has a similar lifespan as the BAU kitchen (i.e., 20 years); what if it lasts double or even four times as long (i.e., 40 or 80 years, respectively)? Second, for the LIFE+ and P&P kitchen variants, the finishing parts can be updated separately in order to increase the lifespan of the whole kitchen. Likewise, in the P&P façade, the insulation modules and façade finishing can be adjusted easily. But, allowing for such adjustments might result in a higher replacement rate of these parts. Therefore, we tested the effect of varying the functional lifespan of these parts, whilst maintaining their technical lifespan. For example, if the functional lifespan of the fronts in the P&P kitchen decreases, more fronts are produced; fronts are reused more often.

TABLE APP. C.4 Detailed description scenarios sensitivity analysis BAU, BIO and Reclaim! kitchen variants

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
BAU	Baseline			20	0	0	
	C+1	N_{cycles}	What if the entire BAU kitchen would be reused once locally?	20	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire BAU kitchen would be reused twice locally?	20	0	2	Decrease allocation fractions for all materials*
	L7	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would already be replaced after ±7 years?	7	0	0	Increase replacement rate for all materials*
	L40	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would only be replaced after 40 years?	40	0	0	Decrease replacement rate for all materials*
	L80	$L_{technical}$ - $L_{functional}$	What if the BAU kitchen would only be replaced after 80 years?	80	0	0	Decrease replacement rate for all materials*

>>>

TOC

TABLE APP. C.4 Detailed description scenarios sensitivity analysis BAU, BIO and Reclaim! kitchen variants

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
BIO	Baseline			10	0	0	
	C+1	N_{cycles}	What if the entire BIO kitchen would be reused once locally?	10	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire BIO kitchen would be reused twice locally?	10	0	2	Decrease allocation fractions for all materials*
	L7	$L_{technical}$ - $L_{functional}$	What if the BIO kitchen would already be replaced after ±7 years?	7	0	0	Increase replacement rate for all materials*
	L20	$L_{technical}$ - $L_{functional}$	What if the BIO kitchen would last as long as the BAU kitchen?	20	0	0	Decrease replacement rate for all materials*
	L40	$L_{technical}$ - $L_{functional}$	What if the BIO kitchen would only be replaced after 40 years?	40	0	0	Decrease replacement rate for all materials*
	L80	$L_{technical}$ - $L_{functional}$	What if the BIO kitchen would only be replaced after 80 years?	80	0	0	Decrease replacement rate for all materials*

>>>

TOC

TABLE APP. C.4 Detailed description scenarios sensitivity analysis BAU, BIO and Reclaim! kitchen variants

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
Reclaim!	Baseline			10	0	0	
	C+1	N_{cycles}	What if the entire Reclaim! kitchen would be reused once locally?	10	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire Reclaim! kitchen would be reused twice locally?	10	0	2	Decrease allocation fractions for all materials*
	L7	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would already be replaced after ±7 years?	7	0	0	Increase replacement rate for all materials*
	L20	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would last as long as the BAU kitchen?	20	0	0	Decrease replacement rate for all materials*
	L40	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would only be replaced after 40 years?	40	0	0	Decrease replacement rate for all materials*
	L80	$L_{technical}$ - $L_{functional}$	What if the Reclaim! kitchen would only be replaced after 80 years?	80	0	0	Decrease replacement rate for all materials*

** For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.*

TABLE APP. C.5 Detailed description scenarios sensitivity analysis LIFE+ kitchen variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]				Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Construction panel, feet, structural lath	Infill panels, back-panel, connectors	Fronts	connectors			
LIFE+	Baseline			40	20	10	20	0	0	
	C+1	N_{cycles}	What if the entire LIFE+ kitchen would be reused once locally?	40	20	10	20	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire LIFE+ kitchen would be reused twice locally?	40	20	10	20	0	2	Decrease allocation fractions for all materials*
	Lf=40-20-7-20	$L_{functional}$ (finishing parts)	What if the fronts of the LIFE+ kitchen would already be (ex)changed after 7 years?	40	20	7	20	0	0	Increase replacement rate for front materials*
	Lf=40-20-20-20	$L_{functional}$ (finishing parts)	What if the fronts of the LIFE+ kitchen would only be (ex)changed after 20 years?	40	20	20	20	0	0	Decrease replacement rate for front materials*
	L=7-7-7-7	$L_{technical}$ - $L_{functional}$	What if the LIFE+ kitchen would already be replaced after ±7 years?	7	7	7	7	0	0	Increase replacement rate for all materials*
	L=20-10-7-10	$L_{technical}$ - $L_{functional}$	What if the LIFE+ kitchen last half as long and the fronts ±7 years?	20	10	7	10	0	0	Increase replacement rate for all materials*
	L=80-40-20-40	$L_{technical}$ - $L_{functional}$	What if the LIFE+ kitchen lasts double as long?	80	40	20	40	0	0	Decrease replacement rate for all materials*
	L=80-80-80-80	$L_{technical}$ - $L_{functional}$	What if the LIFE+ kitchen would only be replaced after 80 years?	80	80	80	80	0	0	Decrease replacement rate for all materials*

** For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.*

TABLE APP. C.6 Detailed description scenarios sensitivity analysis P&P kitchen variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]				Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Construction	Infill	Finishing	Connectors			
P&P	Baseline			80	40	20	40	0	0	
	C-3	N_{cycles}	What if all of the outer (uncertain) future cycles of materials would not come to pass?	80	40	20	40	3	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C-2	N_{cycles}	What if the two most-outer (uncertain) future cycle of materials would not come to pass?	80	40	20	40	2	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C-1	N_{cycles}	What if the most-outer (uncertain) future cycle of materials would not come to pass?	80	40	20	40	1	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed outer cycles*
	C+1	N_{cycles}	What if the entire P&P kitchen has one local reuse cycle additional to the baseline scenario?	80	40	20	40	0	1	Decrease allocation fractions for all materials*

>>>

TOC

TABLE APP. C.6 Detailed description scenarios sensitivity analysis P&P kitchen variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years] Construction	Infill	Finishing	Connectors	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
P&P	C+2	N_{cycles}	What if the entire P&P kitchen has two local reuse cycles additional to the baseline scenario?	80	40	20	40	0	2	Decrease allocation fractions for all materials*
	Lf=80-40-7-40, Lt=80-40-40-40	$L_{functional}$ (finishing parts)	What if the finishing parts of the kitchen would be already (ex)changed after ±7 years whilst their technical lifespan remains the same?	80	40	7	40	0	+3 (finishing parts)	Increase replacement rate for all finishing materials*; decrease allocation fractions for all finishing materials (as the number of reuse cycles of the finishing parts increases)*
	Lf=80-40-40-40, Lt=80-40-40-40	$L_{functional}$ (finishing parts)	What if the finishing parts of the kitchen would only be (ex)changed after 40 years whilst their technical lifespan remains the same?	80	40	40	40	-2 (finishing parts)		Decrease replacement rate for all finishing materials*; Increase allocation fractions for all finishing materials (as the number of reuse cycles of the finishing parts decreases)*
	Lt=7-7-7-7, Lf=7-7-3,5-7	$L_{technical}$ - $L_{functional}$	What if the entire kitchen lasts only ±7 years and the finishing parts are refurbished after ±3,5 years?	7	7	3.5	7	0	0	Increase replacement rate for all parts of the kitchen*

>>>

TOC

TABLE APP. C.6 Detailed description scenarios sensitivity analysis P&P kitchen variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]				Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Construction	Infill	Finishing	Connectors			
P&P	Lt=20-20-20-20, Lf=20-20-10-20	$L_{technical}$ - $L_{functional}$	What if the P&P kitchen lasts as long as the BAU kitchen (with one refurbishment of the finishing parts at 10 years)?	20	20	10	20	0	0	Increase replacement rate for all parts of the kitchen*
	Lt=40-20-20-20, Lf=40-20-10-20	$L_{technical}$ - $L_{functional}$	What if the P&P kitchen lasts half as long and the finishing parts are (ex)changed twice as fast as the P&P baseline scenario?	40	20	10	20	0	0	Increase replacement rate for all parts of the kitchen*
	Lt=80-80-80-80, Lf=80-80-40-80	$L_{technical}$ - $L_{functional}$	What if the entire kitchen lasts 80 years and the finishing parts are refurbished after 40 years?	80	80	40	80	0	0	Decrease replacement rates for infill, finishing and connector parts of the kitchen*

* For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.

TOC

TABLE APP. C.7 Detailed description scenarios sensitivity analysis BAU façade variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
BAU	Baseline			30	0	0	
	C+1	N_{cycles}	What if the entire BAU façade would be reused once locally?	30	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire BAU façade would be reused twice locally?	30	0	2	Decrease allocation fractions for all materials*
	L15	$L_{technical}$ - $L_{functional}$	What if the BAU façade would already be replaced after 15 years?	15	0	0	Increase replacement rate for all materials*
	L45	$L_{technical}$ - $L_{functional}$	What if the BAU façade would only be replaced after 45 years?	45	0	0	Decrease replacement rate for all materials*
	L90	$L_{technical}$ - $L_{functional}$	What if the BAU façade would only be replaced after 90 years?	90	0	0	Decrease replacement rate for all materials*

** For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.*

TABLE APP. C.8 Detailed description scenarios sensitivity analysis BIO and Reclaim! façade variants

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years] All other materials	Replacement [years] Clay plaster	Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
BIO	Baseline			30	15	0	0	
	C+1	N_{cycles}	What if the entire BIO façade would be reused once locally?	30	15	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire BIO façade would be reused twice locally?	30	15	0	2	Decrease allocation fractions for all materials*
	L15	$L_{technical}$ - $L_{functional}$	What if the BIO façade would already be replaced after 15 years?	15	15	0	0	Increase replacement rate for all other materials*
	L45	$L_{technical}$ - $L_{functional}$	What if the BIO façade would only be replaced after 45 years?	45	15	0	0	Decrease replacement rate for all other materials*
	L90	$L_{technical}$ - $L_{functional}$	What if the BIO façade would only be replaced after 90 years?	90	15	0	0	Decrease replacement rate for all other materials*

>>>

TOC

TABLE APP. C.8 Detailed description scenarios sensitivity analysis BIO and Reclaim! façade variants

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]		Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				All other materials	Clay plaster			
Reclaim!	Baseline			30		0	0	
	C+1	N_{cycles}	What if the entire Reclaim! façade would be reused once locally?	30		0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire Reclaim! façade would be reused twice locally?	30		0	2	Decrease allocation fractions for all materials*
	L15	$L_{technical}$ - $L_{functional}$	What if the Reclaim! façade would already be replaced after 15 years?	15		0	0	Increase replacement rate for all materials*
	L45	$L_{technical}$ - $L_{functional}$	What if the Reclaim! façade would only be replaced after 45 years?	45		0	0	Decrease replacement rate for all materials*
	L90	$L_{technical}$ - $L_{functional}$	What if the Reclaim! façade would only be replaced after 90 years?	90		0	0	Decrease replacement rate for all materials*

** For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.*

TABLE APP. C.9 Detailed description scenarios sensitivity analysis P2P façade variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]			Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				PU insulator, Aluminium frames and connectors, EPS boards	Ceramic tiles	stainless steel bolts / screws			
P2P	Baseline			30	30	30	0	0	
	C-2	N_{cycles}	What if the two most-outer (uncertain) future cycle of materials would not come to pass?	30	30	30	2	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed cycles*
	C-1	N_{cycles}	What if the most-outer (uncertain) future cycle of materials would not come to pass?	30	30	30	1	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed cycles*
	C+1	N_{cycles}	What if the entire P2P façade would be reused once locally?	30	30	30	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire P2P façade would be reused twice locally?	30	30	30	0	2	Decrease allocation fractions for all materials*
	L15	$L_{technical}$ - $L_{functional}$	What if the P2P façade would be used and last half as long?	15	15	15	0	0	Increase replacement rate for all materials*
	L45	$L_{technical}$ - $L_{functional}$	What if the P2P façade would be used and last 1, 5 times as long?	45	45	45	0	0	Decrease replacement rate for all materials*
	L90	$L_{technical}$ - $L_{functional}$	What if the P2P façade would be used and last 3 times as long?	90	90	90	0	0	Decrease replacement rate for all materials*

** For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.*

TABLE APP. C.10 Detailed description scenarios sensitivity analysis P&P façade variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]			Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Docking-station	Insulation modules	Façade finishing			
P&P	Baseline			90	30	30	0	0	
	C-2	N_{cycles}	What if the two most-outer (uncertain) future cycle of materials would not come to pass?	90	30	30	2	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed cycles*
	C-1	N_{cycles}	What if the most-outer (uncertain) future cycle of materials would not come to pass?	90	30	30	1	0	Increase allocation fractions for materials of which future cycles are removed*; remove processes of removed cycles*
	C+1	N_{cycles}	What if the entire P&P façade would be reused once locally?	90	30	30	0	1	Decrease allocation fractions for all materials*
	C+2	N_{cycles}	What if the entire P&P façade would be reused twice locally?	90	30	30	0	2	Decrease allocation fractions for all materials*
	L15	$L_{technical}$ - $L_{functional}$	What if the P&P façade modules and finishing would be used and last half as long?	90	15	15	0	0	Increase replacement rate for all materials*
	L45	$L_{technical}$ - $L_{functional}$	What if the P&P façade modules and finishing would be used and last 1, 5 times as long?	90	45	45	0	0	Decrease replacement rate for all materials*
	L90	$L_{technical}$ - $L_{functional}$	What if theP&P façade modules and finishing would be used and last 3 times as long?	90	90	90	0	0	Decrease replacement rate for all materials*

>>>

TABLE APP. C.10 Detailed description scenarios sensitivity analysis P&P façade variant

Design variant	Scenario	Type of sensitivity scenario	What if question for scenario	Replacement [years]			Number of future cycles removed	Number of additional direct, local reuse cycles entire kitchen	What processes / parameters are varied
				Docking-station	Insulation modules	Façade finishing			
P&P	Lf=15	$L_{functional}$	What if the P&P modules and finishing would be used half as long?	45	15	15	0	+3 (modules) +6 (finishing)	Increase replacement rate for all modules and finishing materials*; decrease allocation fractions for all modules and finishing materials (as the number of reuse cycles increases)*
	Lf=45	$L_{functional}$	What if the P&P modules and finishing would be used 1,5 times as long?	90	45	45	-1 (modules) -2 (finishing)	0	Decrease replacement rate for all modules and finishing materials*; Increase allocation fractions for all modules and finishing materials (as the number of reuse cycles decreases)*
	Lf=90	$L_{functional}$	What if the P&P modules and finishing would be used 3 times as long?	90	90	90	-2 (modules) -3 (finishing)	0	Decrease replacement rate for all modules and finishing materials*; Increase allocation fractions for all modules and finishing materials (as the number of reuse cycles decreases)*

For the value of each varied parameter, we refer to the detailed overview of all CE-LCIA parameter in Appendix C.2.

References

Cooper, T. (1994). Beyond recycling: The longer life option. *The New Economics Foundation*, (November), 1–22. Retrieved from http://irep.ntu.ac.uk/id/eprint/24666/1/201125_7266 Cooper Publisher.pdf

Geraedts, R. P., Vande Putte, H. J. M., Vercouteren, J., & Binnekamp, R. (2009). Tijd. In J. W. F. Wamelink, R. P. Geraedts, F. A. M. Hobma, L. H. M. J. Lousberg, & P. De Jong (Eds.), *Inleiding Bouwmanagement* (pp. 273–303). VSSD.

Méquignon, M., & Ait Haddou, H. (2014). The construction industry and lifespan. In *Lifetime Environmental Impact of Buildings. SpringerBriefs in Applied Sciences and Technology* (pp. 3–23). https://doi.org/10.1007/978-3-319-06641-7_1

APP. C.4 Results from the expert sessions

The results of the expert sessions are summarized in Table App.C.11. Participants suggested the guidelines were clear, providing useful information to designers of circular building components, and vital to support the transition to a circular built environment. Participants explicitly mentioned the guidelines align with their existing assumptions on environmental performance in circular building components. However, participants also questioned aspects of individual guidelines. These comments were related to validity, uncertainty, usability, relevancy and implementability; they have been used to refine the guidelines. The participants raised their concern on the inclusion of multiple future cycles in the LCA: this increases the uncertainty of assumptions and, subsequently, the accuracy of the results underlying the environmental design guidelines. It was argued that the validity of the guidelines is largely dependent if industry can determine, document and realise future cycles. Furthermore, participants suggested that determining future cycles is beyond their practice and the scope in building projects.

The participants provided opportunities for improvement of the presented guidelines: these concerned opportunities for clarification, increasing the validity, transparency, ease of use and implementability. Participants posed that transparency in the applied CE-LCA and MFA methods, results and limitations of the study is crucial for validity of the guidelines. Also, experts suggested rigorous sensitivity analysis of circular design parameters to improve the certainty of the guidelines – which has been included within the scope of the study. The participants advised to improve the usability of the guidelines by making them less abstract, and include more concrete examples. They also stressed that guidelines should not be merely induced from the LCA, but directly, quantitatively derived. Their suggestions have resulted in the deeper analysis (and development of the scorecards).

The majority of the improvements suggested during the expert sessions have been – iteratively – implemented (see the fourth column in Table App.C.11). Remaining recommendations for further development were included in Section 6.7.

TABLE APP. C.11 Results expert sessions

	Cat.	Remarks	Implementation remarks
Guidelines are valid	Validity	The guidelines align with existing assumptions and/or circular design strategies	
		The guidelines are based on relevant CE design variants	
		The design guidelines are clear	
		The guidelines are based on, and distinguish between components with different lifespans	
	Urgency	The guidelines are vital to transition to a CE in the built environment	
	Relevancy	The guidelines stimulate more circular thinking	
		The design guidelines are useful for practitioners	
		The guidelines show the complexity of true circularity in the built environment	
Guidelines are not valid	Validity	The guidelines can vary depending on the applied LCA, MFA, decision-making methods	Influence of applied assessment method was emphasized in discussion and conclusion; suggested as future direction of research
		The design variants are not fully comparable as they have different functionalities, clouding the LCA and MFA results	Need for assessing the funtional value performance included in discussion and conclusion
		Some of the guidelines are not valid in all cases, contradict previous knowledge or expectations	Tipping-points based on changing design assumptions was emphasized in guidelines; need for more assessments included in discussion and conclusion
		Some variants and guidelines propose opposite or unlikely combinations of design principles (e.g., modular and material efficiency, long lifespan and reused materials)	Guidelines were reformulated to emphasize priorities. Unlikely combinations of circular design options were pointed out in the interpretation of the results
	Uncertainty	The results of the guidelines are highly dependant on uncertain future cycles	Importance of testing sensitivity of uncertain future cycles was emphasized in method section
		The circularity of the guidelines depends if future cycles can be determined, documented and realised by industry in the long term	Importance of ability to determine, guarantee and realize cycles was included in the guidelines
	Usability	The guidelines remain too abstract and general	More concrete examples could improve usability; direction for future research included in discussion and conclusion
		The guidelines are complex	Guidelines were reformulated; a list is provided in the Appendix
		Guidelines are not sufficient to make truly circular designs, circular assessment (and developing EPD's) of developed designs is necessary	Discussion on value of design aids for synthesis, evaluation and LCA- and MFA-based guidelines included in introduction
	Relevancy	The guidelines do not provide novel information (are reduced to high level of abstraction where they merely confirm previous guidelines)	Guidelines built upon existing knowledge. Contribution more precisely indicated in discussion and conclusion

>>>

TABLE APP. C.11 Results expert sessions

	Cat.	Remarks	Implementation remarks
Guidelines are not valid	Implementability	Industry focusses on current cycles; it does not consider or organise multiple cycles as suggested in the guidelines	Questionable feasibility of guidelines noted in discussion and conclusion
		During design, industry focusses on 'best value' for low initial costs in decision making; including environmental design guidelines will be challenging	Questionable feasibility of guidelines noted in discussion and conclusion
		Current regulations prevent following guidelines (e.g., legislation on non-virgin materials)	Questionable feasibility of guidelines noted in discussion and conclusion
		Difficult to use materials from innovative suppliers: they might not be able to prove they conform to the guidelines (i.e., too expensive)	Questionable feasibility of guidelines noted in discussion and conclusion
		The guidelines ask for many simultaneous changes by industry: priorities need to be identified	Need to prioritize in decision-making included in discussion and conclusion
		In practice it is very complex to 'determine' many of the circular design parameters (e.g., leading lifespan) mentioned in the guidelines	Questionable feasibility of guidelines noted in discussion and conclusion
Improvements	Clarification	Clarify what the guidelines provide 'advice on'	Mentioned the types of components for which guidelines apply (i.e., short vs. medium lifespan)
		Provide a clear explanation with each guideline	A list with short explanations is provided in the Appendix
		Clarify, simplify and distinguish the terminology in the design guidelines (e.g., lean, open-loop, reloop, bio-based and biodegradable, leading lifespan)	Terminology simplified and explained in description of design variants
	Increasing validity guidelines	Quantify the design guidelines (e.g., scorecard of each design principles)	Quantitative analysis of CE-LCA and MFA results used to develop scorecards
		Curtail the scope of variations between the design variants to improve the clarity of results (and usefulness of the guidelines)	Need for more assessments testing (individual) assumptions included as direction for future research in discussion and conclusion
		Consider chances of cycles according to design variant (e.g., when glue is applied there is 0% chance of reuse)	A probability parameter was included in the assessment method.
		Perform additional sensitivity analysis (e.g., future cycles, transport, materials)	Sensitivity analysis was conducted, focussing on assumptions on cycles and lifespans; need for more assessments testing assumptions included in discussion and conclusion
		Test the guidelines with stakeholders to improve validity and/or implementability	Direction for future research noted in discussion and conclusion
	Transparency	Present the LCA and MFA data in parallel with the design guidelines	The data of the CE-LCA and MFA was presented separately from the design guidelines
		Describe the applied assessment methods and the method to derive the design guidelines from the LCA and MFA	Procedure for developing guidelines described in method section
		Visualise the LCA and MFA results more transparent (e.g., visualise impacts per time, impacts per cycle)	Additional visualisations plotting impacts allocated over RSP provided in the article

>>>

TOC

TABLE APP. C.11 Results expert sessions

	Cat.	Remarks	Implementation remarks
Improvements	Ease of use	Provide non-abstract guidelines (e.g., practical advice, concrete rules of thumb, dos and don'ts, visualise the building component)	Direction for future research noted in discussion and conclusion
		Provide concrete examples for guidelines	Direction for future research noted in discussion and conclusion
		Provide insight in relative contributions of building components to the building over time to determine priorities	Analysis on contributions included in Appendix
		Adapt the guidelines into a synthesis tool	Direction for future research noted in discussion and conclusion
		Include guidelines based on single design parameters (e.g., choices of materials)	Direction for future research noted in discussion and conclusion
		Provide instructions to designers on how and when to use the design guidelines (and/or additional assessment methods) during the design process	Discussion on use of design aids for synthesis, evaluation and LCA- and MFA-based guidelines included in introduction
		Relate the guidelines to other sustainability guidelines (e.g., operational energy efficiency)	Noted, not included in scope of paper
		Reduce the amount of guidelines to core principles; provide extra background document for further information	Core findings included in abstract and highlights
	Implementability	Include guidelines into legislation to incentivise their uptake	Noted, not included in scope of paper

APP. C.5 Detailed description, flowcharts and (re) placement charts of the kitchen and renovation façade variants

APP. C.5.1 Business-as-usual and circular kitchen variants

The business-as-usual (BAU) kitchen represents the current practice: the cabinets are made with melamine-coated chipboard. Static joints are glued and connectors are used for movable joints (i.e., hinges and drawer sliders). The entire kitchen is replaced, on average, every 20 years. The manufacturer sells the BAU kitchen to housing associations; as the initial cost price is low, kitchens are seldom repaired, refurbished, or reused. At the End-of-Life (EoL), a contractor demolishes the kitchen and separates waste flows. The chipboard is (usually) incinerated for energy recovery at a municipal incineration plant.

The 'Biological (BIO) kitchen' follows the biological cycle of the circular economy: the cabinets are made, entirely, with panels from renewable and biodegradable materials. Examples of such materials are boards from (untreated) wood, agaric waste, or mycelium. We applied laminated timber boards bound with a biological resin. Panels are joint with connectors made from bio-based, biodegradable plastics. The manufacturer sells the BIO kitchen to housing associations. As bio-materials are untreated, we assume a shorter lifespan of 10 years; at EoL, the kitchens are composted at an industrial compost plant.

In the 'Reclaim! kitchen', virgin materials are substituted with non-virgin alternatives. Examples are materials with recycled content (e.g., recycled cellulose boards, recycled plastics) or materials which are directly reused. For this variant, we assumed a similar technical, industrial and business model as the BAU kitchen, only applying directly reused material. As the material is directly reused, we assume the Reclaim! kitchens have a lifespan of 10 years.

The LIFE+ kitchen optimizes the BAU kitchen through modest adaptations in the technical, industrial and business model. A combination of circular design options is applied. The technical lifespan of parts is optimized based on functional lifespan: the construction of the kitchen cabinet could be used longer than the current 20 years. Hence, it is designed for long-life by substituting the chipboard with plywood.

On the other hand, the finishing parts (e.g., fronts) are designed for a shorter functional lifespan by applying low-impact, biological materials. The industrial model and business model is not altered compared to the BAU. The reduced sales of the construction parts – due to the longer lifespan – are offset by offering update services for the finishing.

The Plug-and-Play (P&P) kitchen applies a combination of circular design options focusing on slowing and closing resource loops. The P&P kitchen is a modular design; parts are separated based on their functional and technical lifespan. The P&P kitchen consists of a docking station to which kitchen modules can be attached allowing for future changes in lay-out. The construction of the modules is a long-life frame. Infill (e.g., drawers, shelves) with a medium lifespan and the finishing (e.g., fronts) with a short use-cycle are attached to the construction with click-on connections. This design allows for adjustments in the function and appearance of the cabinet. The kitchen is constructed with (durable) plywood, prolonging the technical lifespan so multiple use-cycles of parts are possible. The kitchen manufacturer sells the docking station and kitchen modules directly to the housing associations with a take-back guarantee and maintenance subscription. Extra kitchen modules and finishing-updates are offered to users. Financial arrangements – such as lease and sale-with-deposit – motivate returning the product at End of Use (EoU). This business model offers a clear incentive for the manufacturer to realize a kitchen which is easy to repair, reuse, refurbish and recycle. Products are returned to a local 'return-street', where they are sorted to be traded, resold, lightly refurbished or sent back to the kitchen manufacturer. Products that are sent back to the national 'return-factory' are sorted to be refurbished (i.e., infill and finishing parts are re-coated and reused), cascaded or recycled (e.g., the plywood is used for particle-board production). See Figures App.C.1-5 for the flowcharts of all kitchen design variants and Figure App.C.6 for a chart showing the lifespan of kitchen parts and their replacement rate in the RSP.

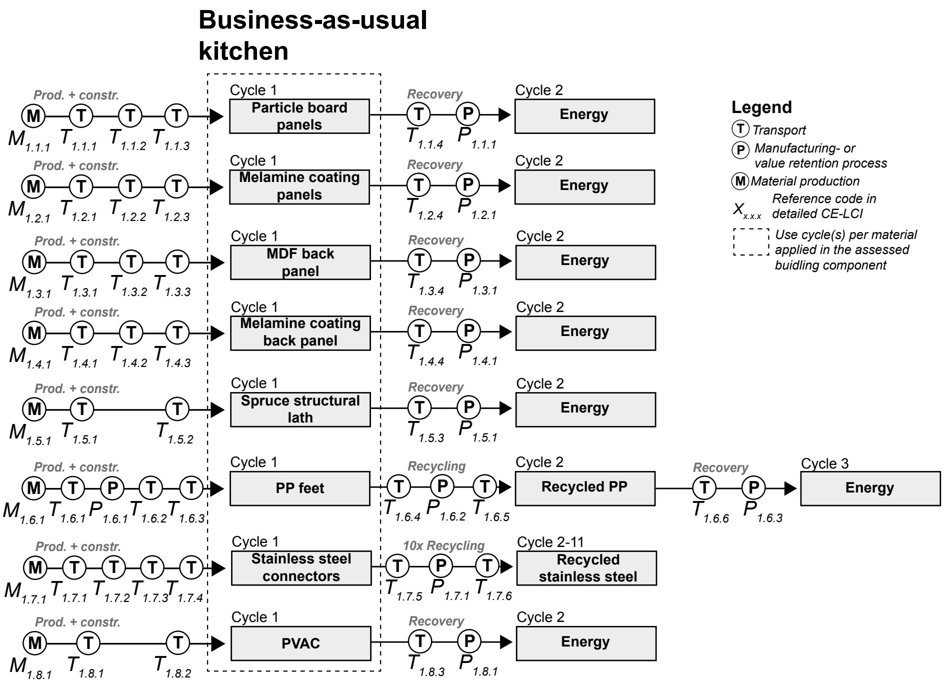


FIG. APP. C.1 Flowchart of the BAU kitchen design variant

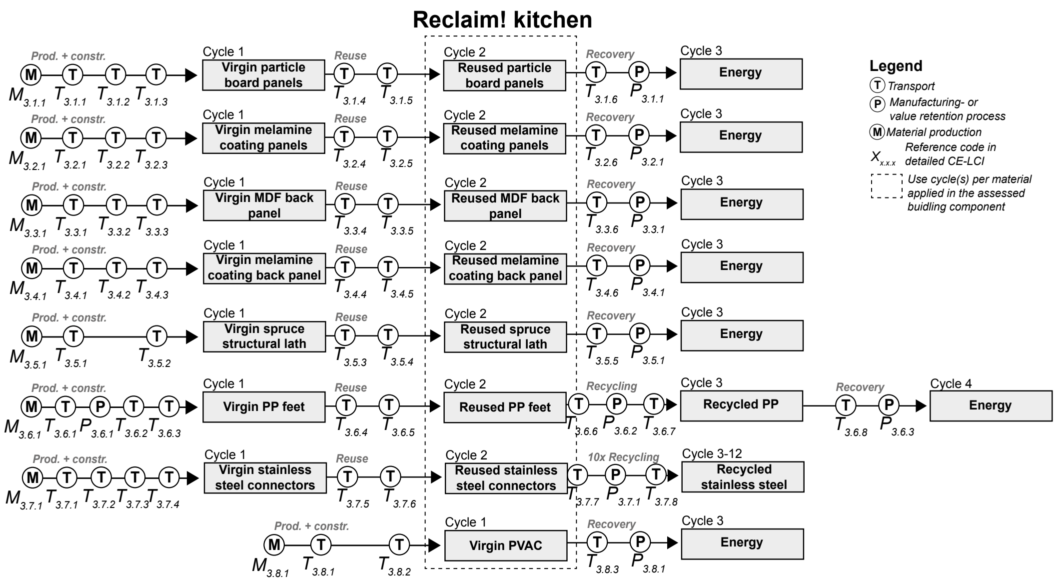


FIG. APP. C.2 Flowchart of the Reclaim! kitchen design variant

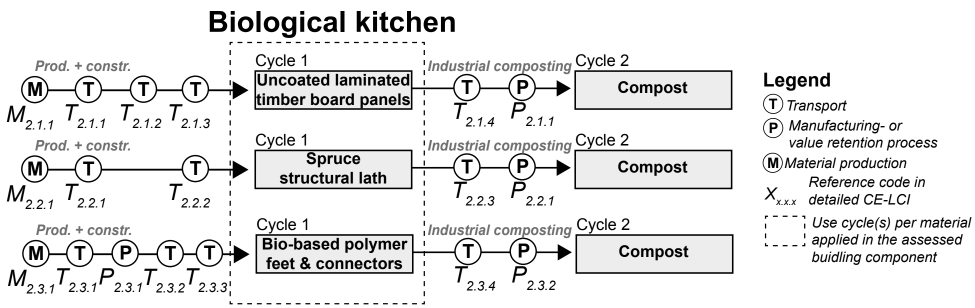


FIG. APP. C.3 Flowchart of the BIO kitchen design variant

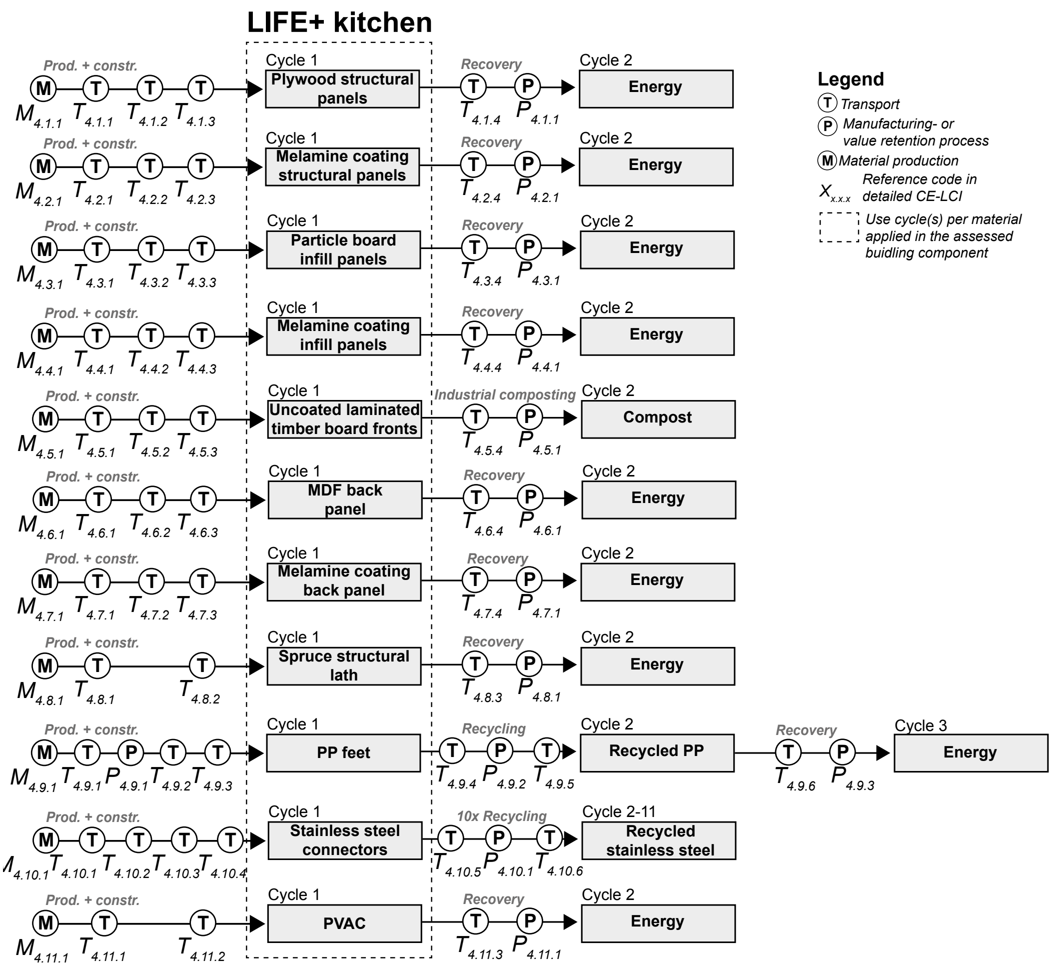


FIG. APP. C.4 Flowchart of the LIFE+ kitchen design variant

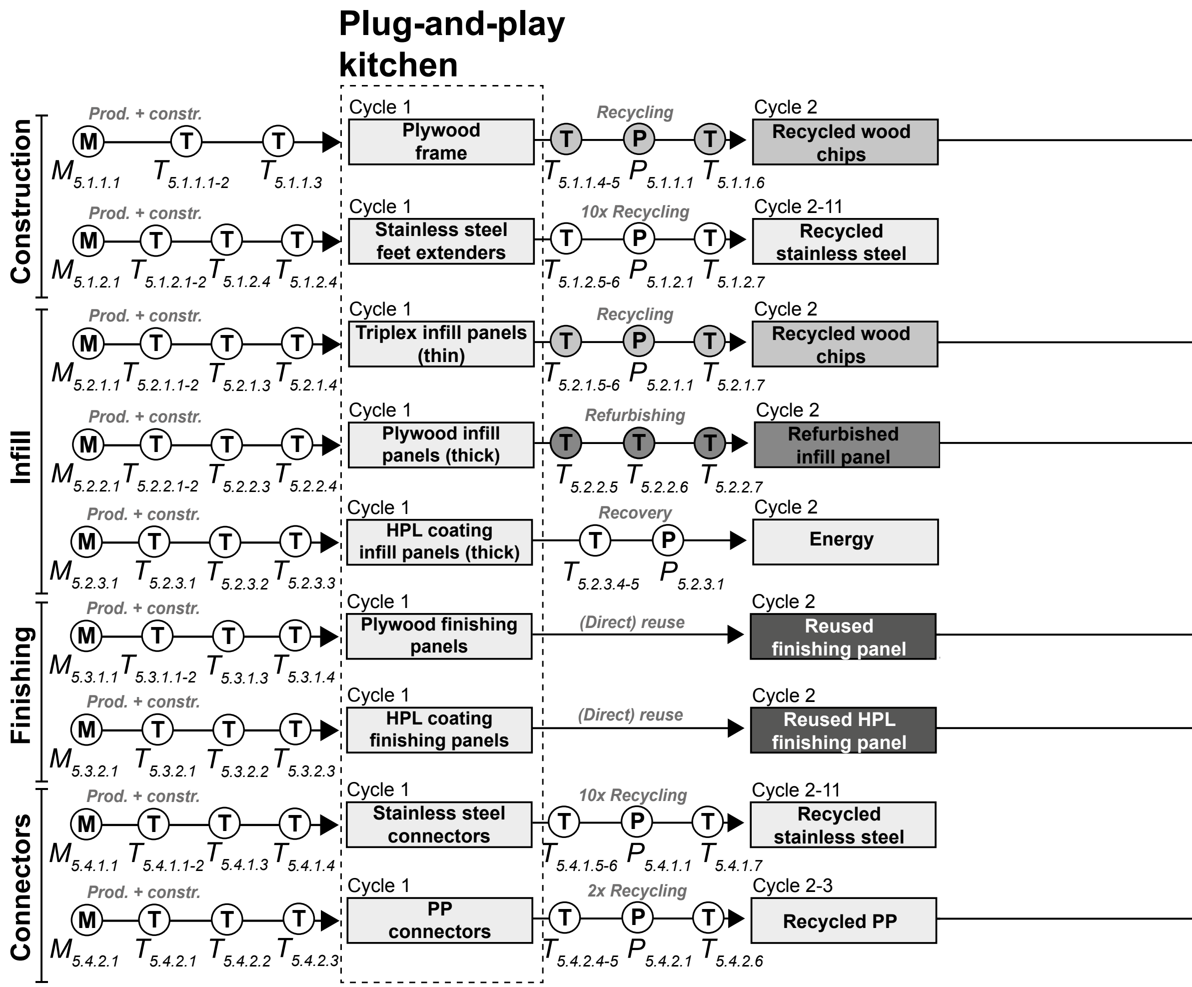
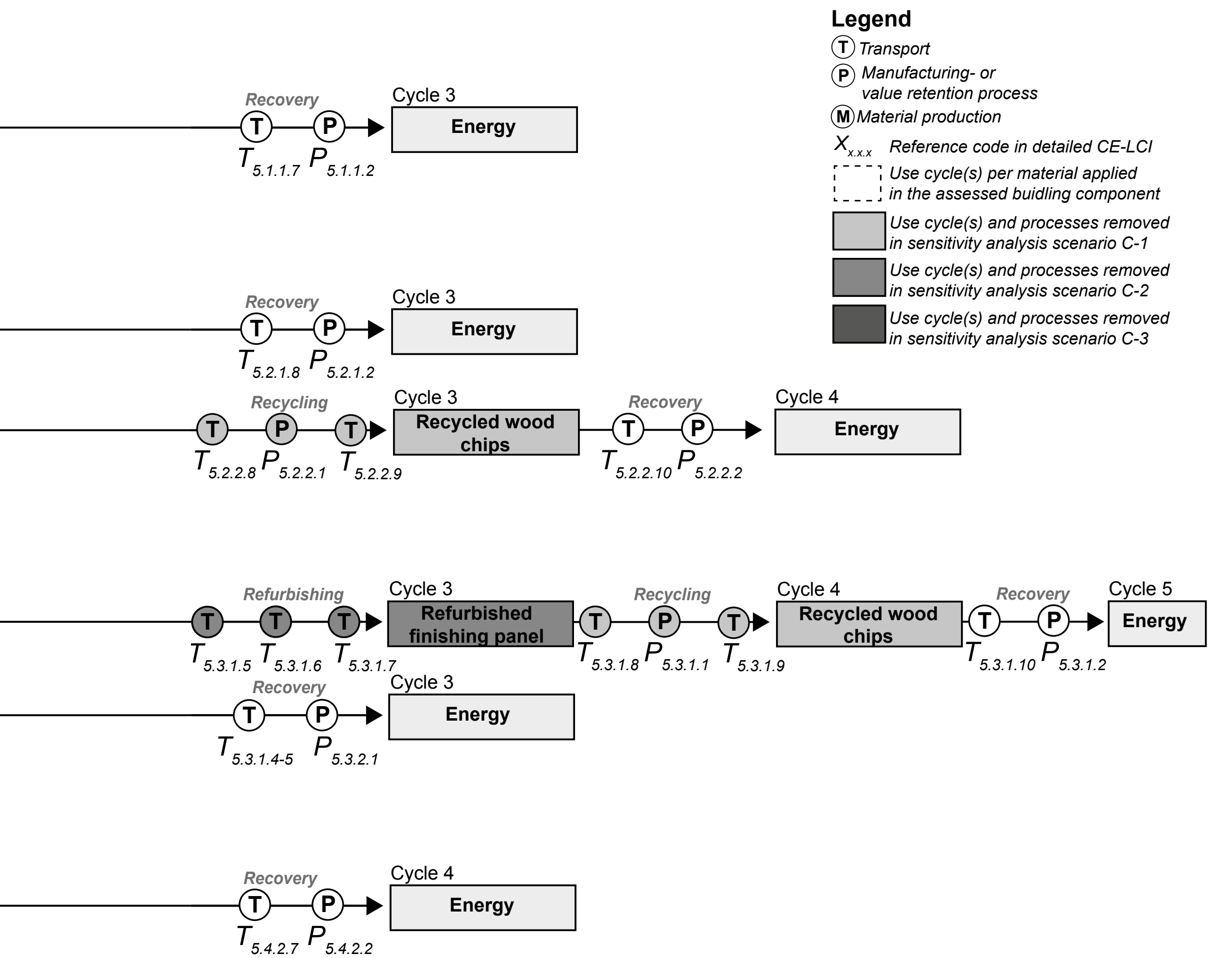


FIG. APP. C.5 Flowchart of the Plug-and-play kitchen design variant



Legend
T Transport
P Manufacturing- or value retention process
M Material production
X x.x.x Reference code in detailed CE-LCI
Use cycle(s) per material applied in the assessed buidling component
Use cycle(s) and processes removed in sensitivity analysis scenario C-1
Use cycle(s) and processes removed in sensitivity analysis scenario C-2
Use cycle(s) and processes removed in sensitivity analysis scenario C-3
Recovery
Cycle 3
Energy
T 5.1.1.7
P 5.1.1.2
Recovery
Cycle 3
Energy
T 5.2.1.8
P 5.2.1.2
Recycling
Cycle 3
Recycled wood chips
T 5.2.2.8
P 5.2.2.1
T 5.2.2.9
Recovery
Cycle 4
Energy
T 5.2.2.10
P 5.2.2.2
Refurbishing
Cycle 3
Refurbished finishing panel
T 5.3.1.5
T 5.3.1.6
T 5.3.1.7
Recycling
Cycle 4
Recycled wood chips
T 5.3.1.8
P 5.3.1.1
T 5.3.1.9
Recovery
Cycle 5
Energy
T 5.3.1.10
P 5.3.1.2
Recovery
Cycle 3
Energy
T 5.3.1.4-5
P 5.3.2.1
Recovery
Cycle 4
Energy
T 5.4.2.7
P 5.4.2.2

TOC

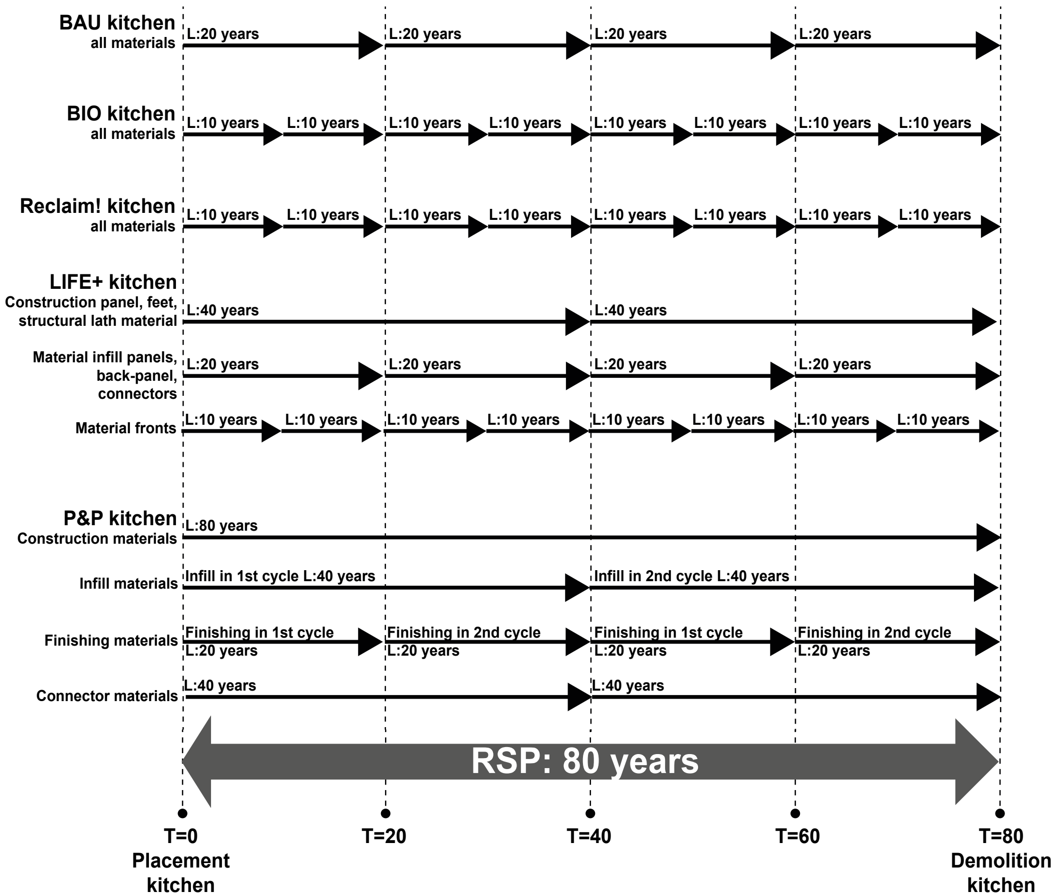


FIG. APP. C.6 Lifespan of kitchen parts per design variant and their (re)placements during the RSP

APP. C.5.2 Business-as-usual and circular renovation façade variants

The circular renovation façade is an exterior insulation solution. An insulation layer and new façade finishing are applied on top of the existing façade. This intervention is typically applied in (Nearly) Zero Energy housing renovations; it improves the energy efficiency of the building during use phase and, simultaneously, provides an aesthetic upgrade. Such renovation façades are typically placed for an exploitation period of around 30 years. For each of the variants, in-situ application or off-site prefabrication is imaginable.

The 'Business-As Usual (BAU) façade' represents an exterior insulation solution commonly applied in practice. The BAU solution is a 'lean' solution, which is integrated and light-weight. It consists of EPS foam which is glued to the façade with a PU-adhesive; a glue and grout mortar and glass-fibre mesh is applied on top of the EPS, followed by thin-layered mineral brick-strips. The BAU façade is sold to the housing association. We assumed a relatively short lifespan of the glue (±30 years); the integrated system is tailor-sized to the specific project. It has limited potential for repair, future adjustments in lay-out and finishing, or reuse on other façades. Therefore, we assumed that EoU will equal EoL, setting the lifespan of the façade at 30 years. At EoL, the materials of the façade are separated – as much as possible – into separate waste flows and incinerated or land-filled.

The 'Bio-façade' (BIO) applies bio-based and biodegradable materials; it consists of a timber frame, attached to the existing façade with anchors. The timber frame is filled with hemp insulation. A hemp-insulation board is applied on the exterior side of the timber frame and finished with clay plaster. All connectors are made from bio-based, and biodegradable plastics. For the bio-materials we assume a relatively short technical lifespan. The clay-plaster is re-applied every 15 years; we assume that EoU of the façade will equal EoL at 30 years. At EoL, the materials are industrially composted.

The 'Reclaim! façade' applies non-virgin materials, either directly reused or recycled materials. It consists of a reused wooden timber frame attached to the existing façade with stainless steel anchors. The timeframe is filled with recycled mineral wool insulation. Hard-pressed, wood-wool boards – manufactured with secondary wood – are applied on the exterior side of the timber frame. The finishing consists of reused wood cladding attached to reused wooden furring strips. The joints (i.e., screws and anchors) are made of recycled stainless steel; they allow the timber frame to be disassembled at EoL. EoL is assumed to be at 30 years at which the façade is disassembled and materials are either directly reused (e.g., the timber frame), recycled (e.g., mineral wool insulation), or incinerated (e.g., the wooden furring strips).

The 'Product2Product (P2P) façade' is based on direct reuse of building products: it consists of building products with a long technical lifespan (> 90 years), applying standardized sizes and connectors which allow for easy dis-, and re-assembly. The P2P is constructed with EPS foam boards clamped behind an aluminium framework; on the framework, ceramic façade panels are clicked-on. We assume a business model in which the façade is sold to the building owner. At EoU (30 years), the façade can be dissembled, resold (e.g., on a building material platform), and re-assembled on another façade.

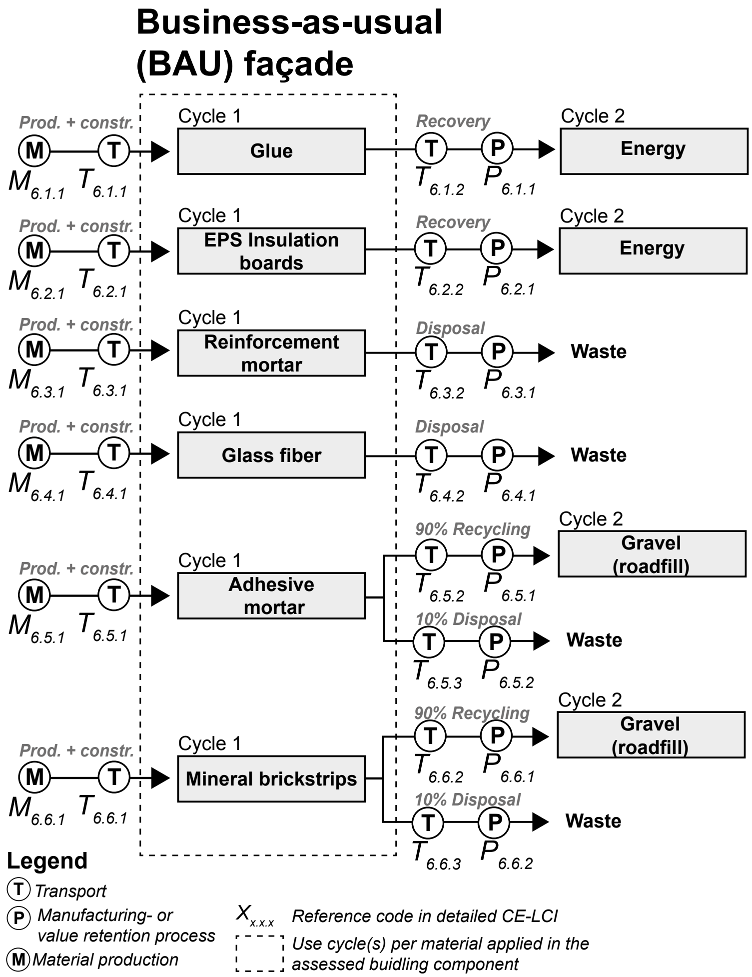


FIG. APP. C.7 Flowchart of the Business-as-Usual (BAU) façade design variant

The 'Plug-and-play (P&P) façade' applies a combination of circular design options to slow and close the loops. The P&P façade is modular, separating parts based on their functional and technical lifespan. The façade has a long-life docking station consisting of wall anchors to which insulation modules are attached. The insulation modules consist of an adjustable timber frame which facilitates future changes in lay-out and reuse on another façade. The timber frame is filled with recycled cellulose insulation. A recycled, wood-wool board covers the exterior side of the timber frame. For the finishing of the façade, a wide variety of standard-sized panels can be easily (de-, and re-) attached using aluminium board anchors;

TOC

here, we assumed high-quality ceramic brick-strip panels. The P&P façade is either leased, sold with (prepaid) buy-back guarantee, or take-back guarantee. If sold, accompanying maintenance subscription and update services are offered. This business model provides an incentive for the provider (i.e., manufacturer and contractor) to realize a façade which is easy to repair, update, reuse or recycle. At EoU (30 years), we assume the insulation modules can be adjusted and/or reused on the same or another façade twice, whilst the façade panels have four reuse cycles. At EoL, the docking station, insulation module and finishing panels are disassembled and their materials are either recycled, down-cycled or incinerated.

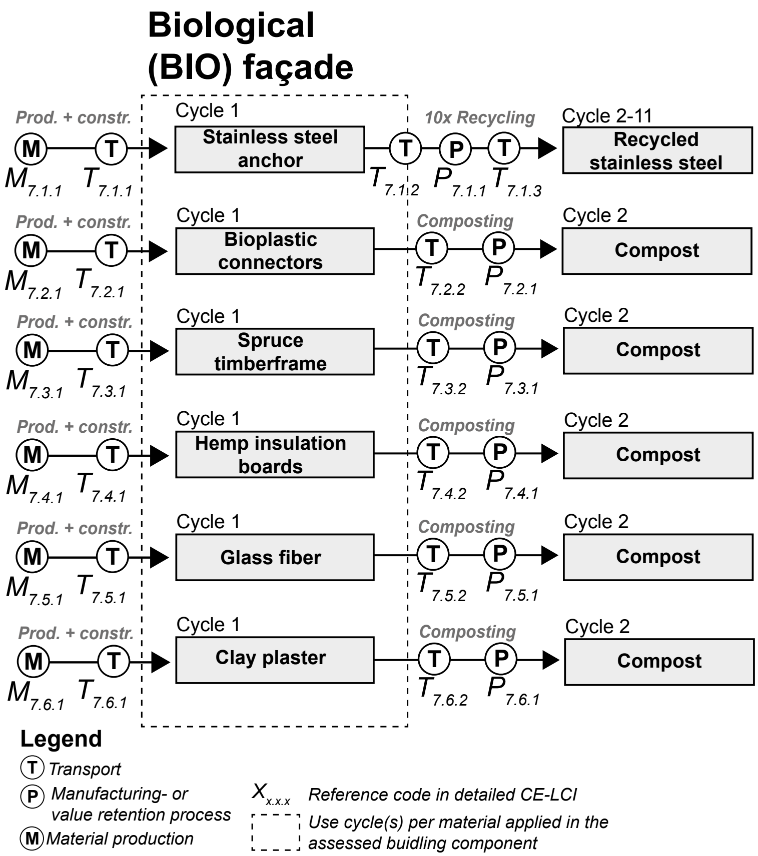


FIG. APP. C.8 Flowchart of the Biological (BIO) façade design variant

TOC

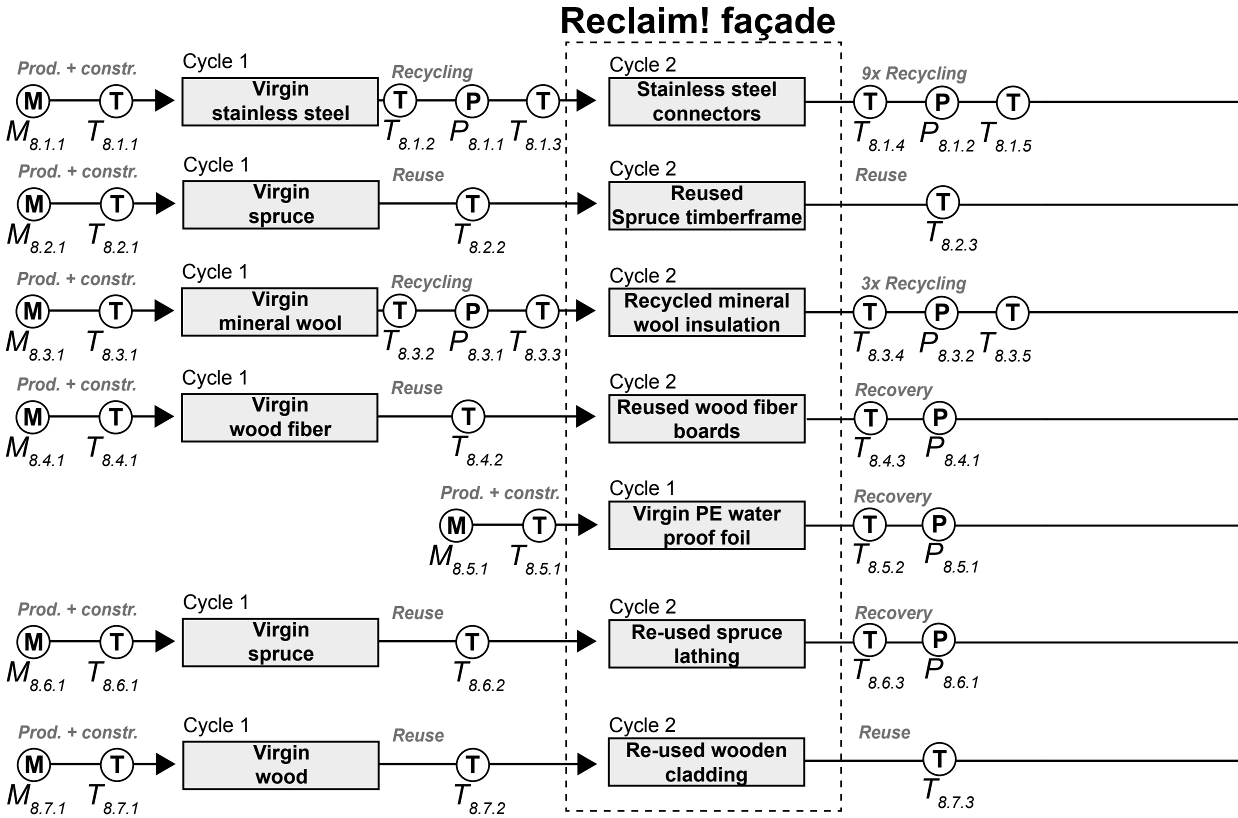
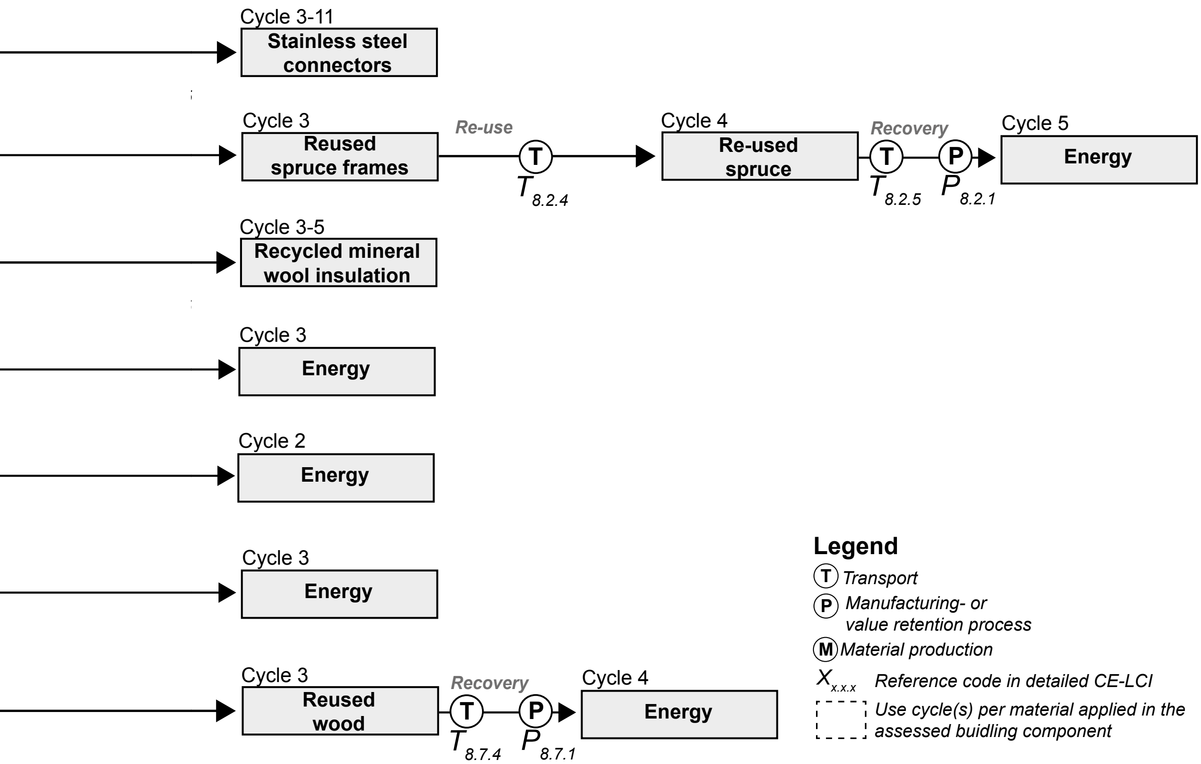


FIG. APP. C.9 Flowchart of the Reclaim! façade design variant

For each variant, in-situ construction or off-site prefabrication are imaginable. For example, the BAU façade could be prefabricated in an off-site factory, transported as façade panels to the site and installed on the existing façade with a construction crane. Alternatively, the materials could be transported to the site and manually glued on the existing façade. Both methods result in different designs and manufacturing, transport and installation processes. As these different scenarios are possible for all façade variants, we aligned our assumptions between variants. We assumed the materials have a standard transport to the site (i.e., based on kg*km) and excluded prefabrication and installation processes. See Figures App.C.7-11 for the flowcharts of all façade variants and Figure App.C.12 for a chart showing the lifespan of façade parts and their replacement rate in the RSP.


Cycle 3-11
Stainless steel connectors
Cycle 3
Reused spruce frames
Re-use
T
T 8.2.4
Cycle 4
Re-used spruce
Recovery
T
P
T 8.2.5
P 8.2.1
Cycle 5
Energy
Cycle 3-5
Recycled mineral wool insulation
Cycle 3
Energy
Cycle 2
Energy
Cycle 3
Energy
Cycle 3
Reused wood
Recovery
T
P
T 8.7.4
P 8.7.1
Cycle 4
Energy
Legend
T Transport
P Manufacturing- or value retention process
M Material production
X x.x.x Reference code in detailed CE-LCI
Use cycle(s) per material applied in the assessed buidling component

TOC

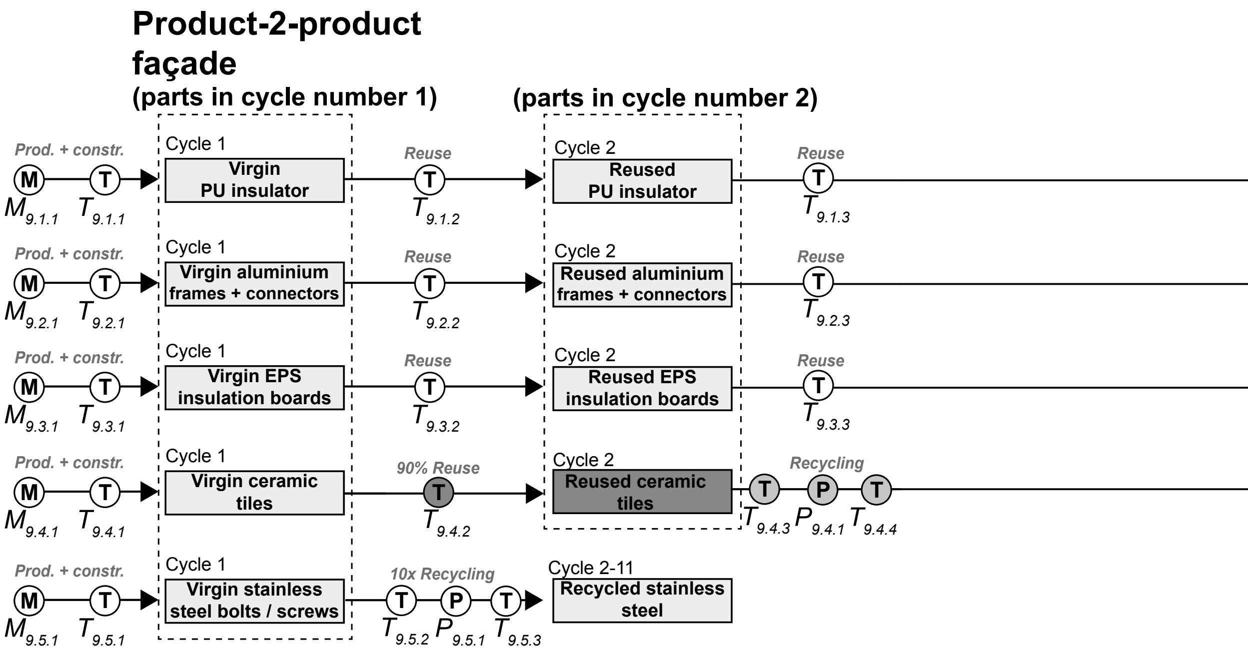
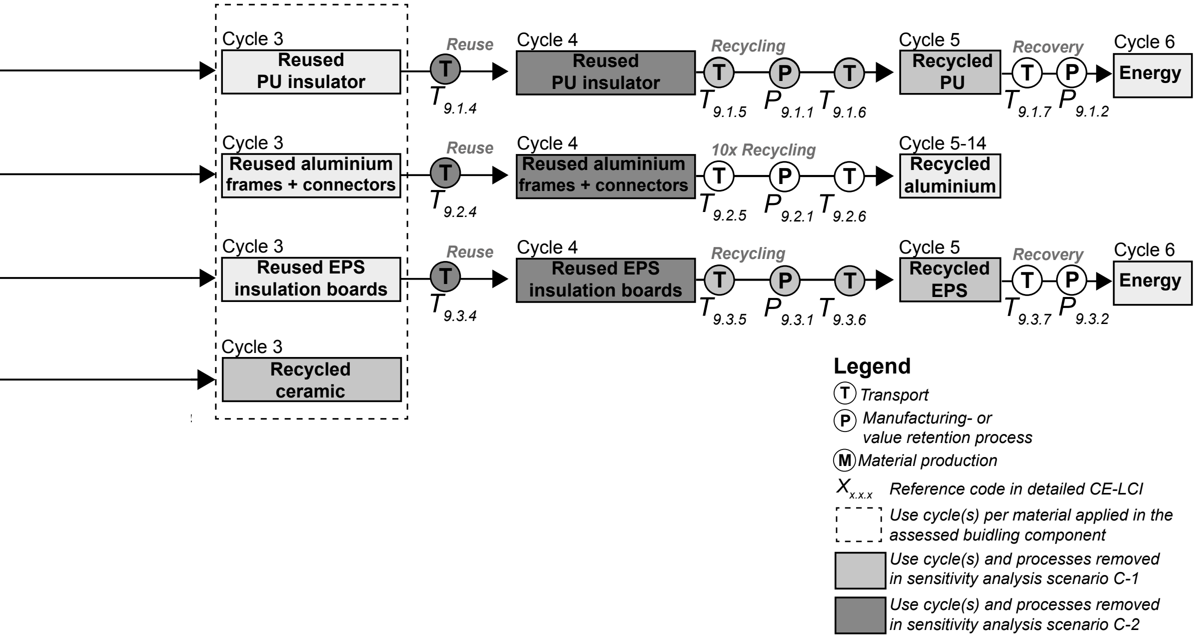


FIG. APP. C.10 Flowchart of the Product-to-Product (P2P) façade design variant

(parts in cycle number 3)



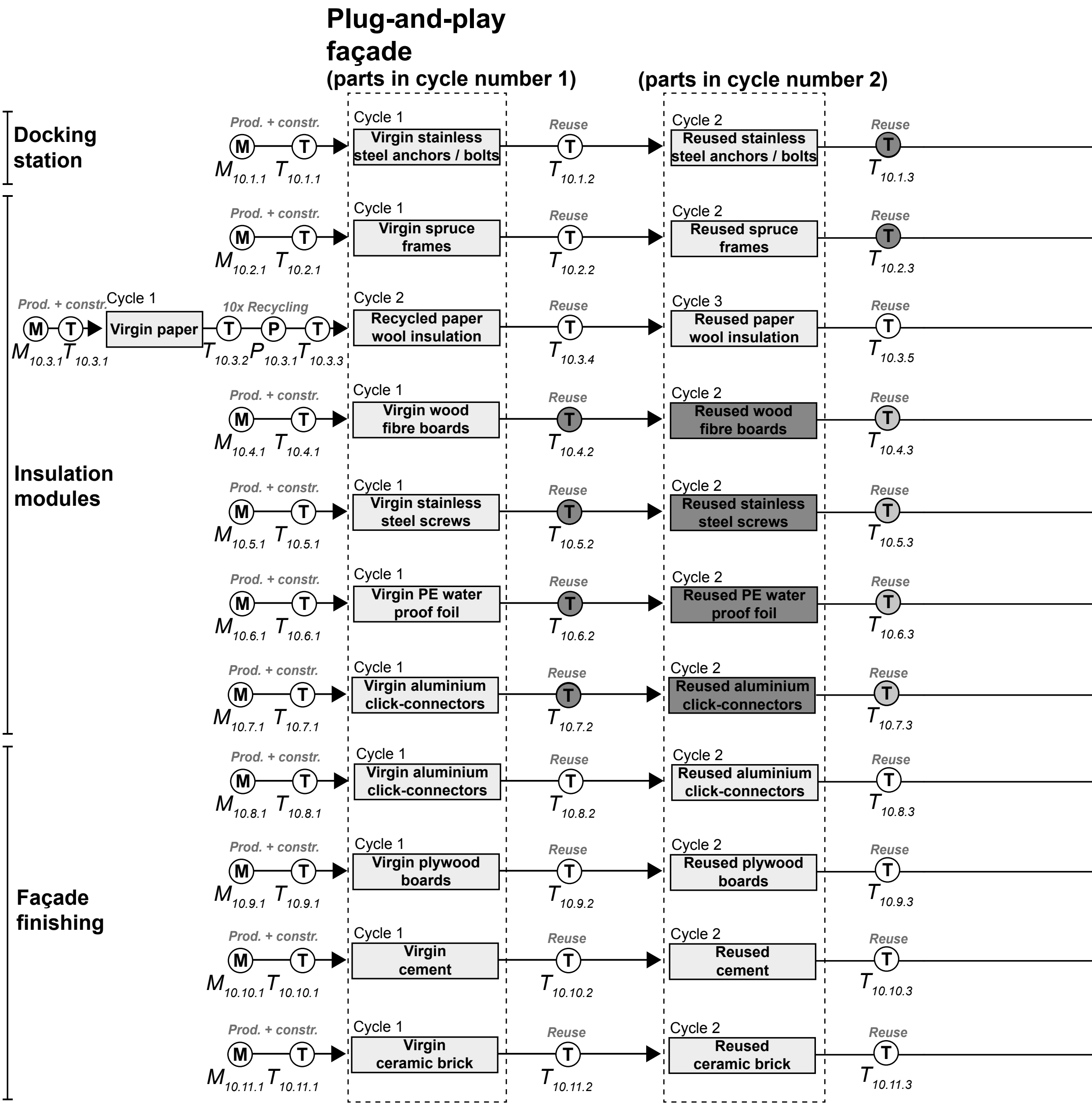
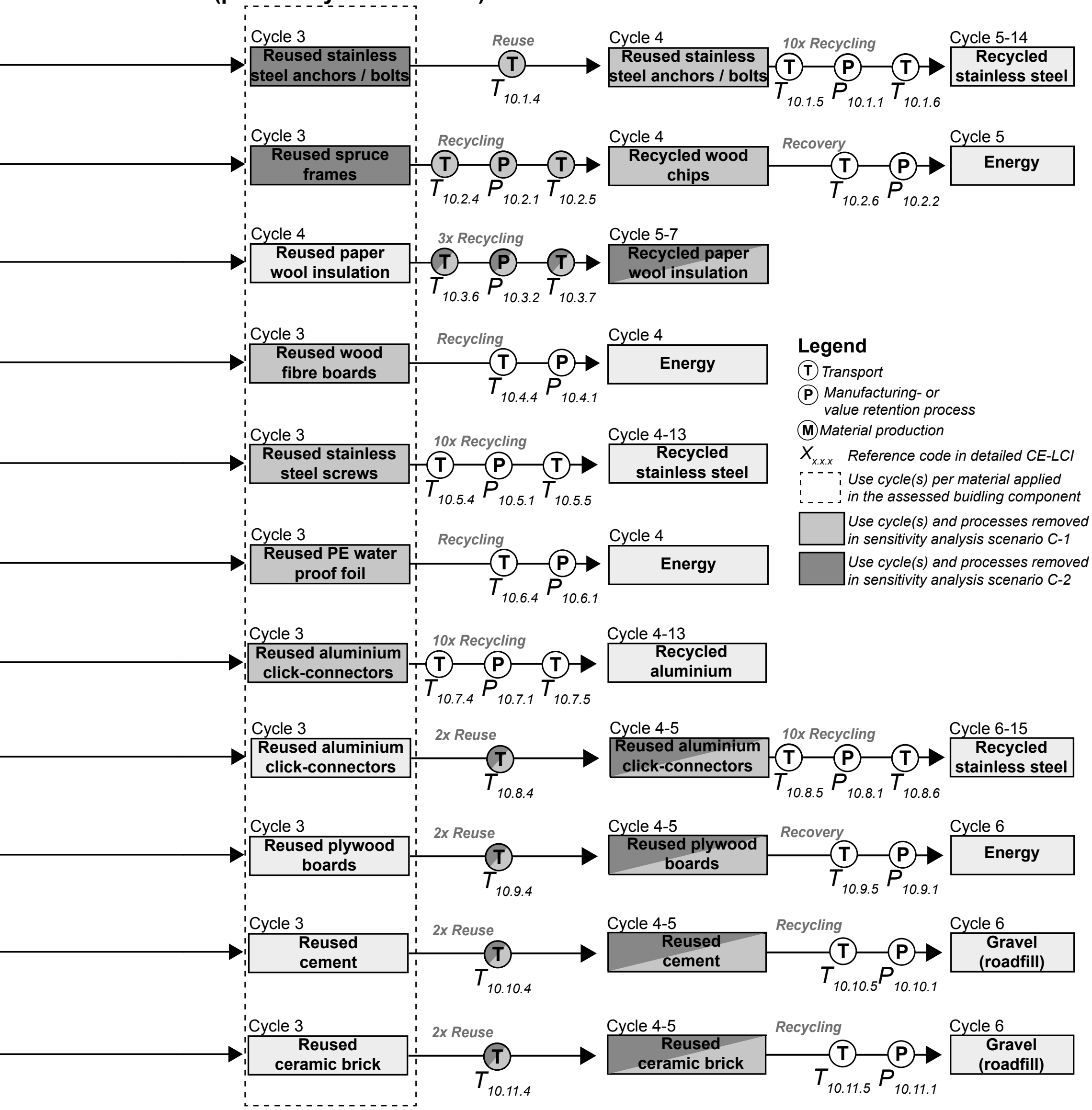


FIG. APP. C.11 Flowchart of the Plug-and-play (P&P) façade design variant

(parts in cycle number 3)



TOC

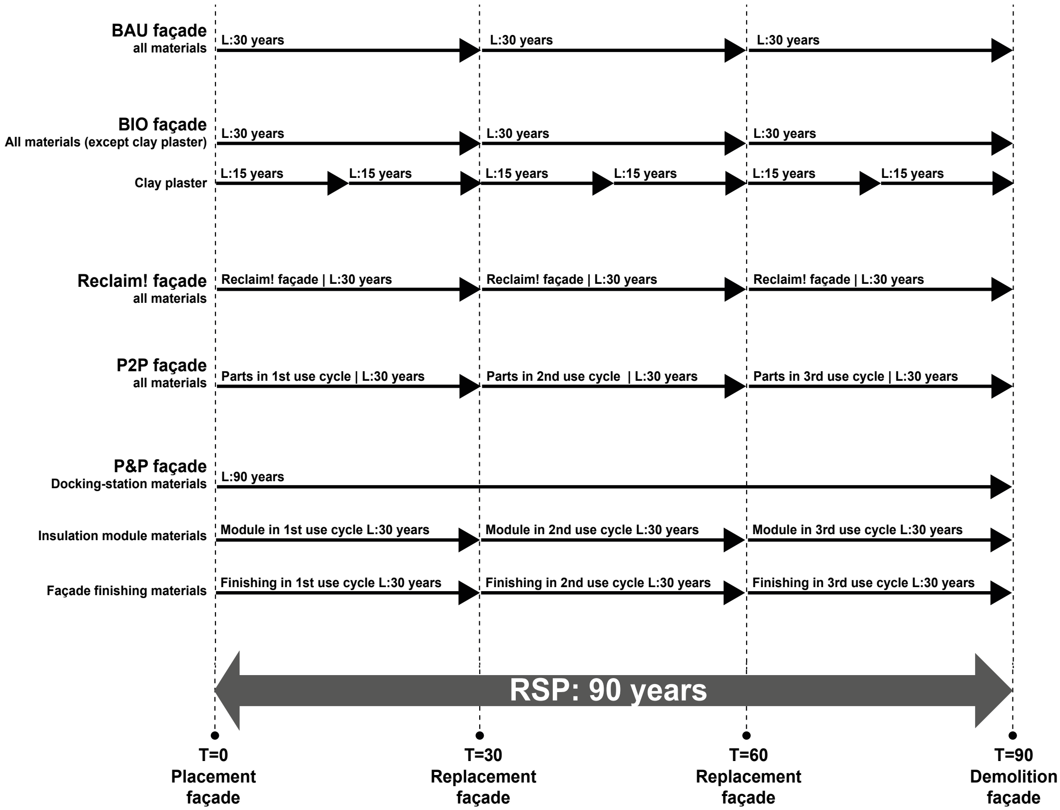


FIG. APP. C.12 Lifespan of façade parts per design variant and their (re)placements during the RSP

TOC

APP. C.6

Sensitivity analysis results on number of cycles for the kitchen variants: allocated GWP over time and MFA

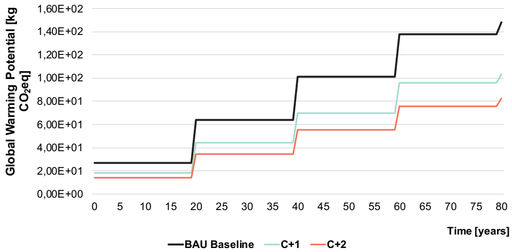


FIG. APP. C.13 LCA Sensitivity analysis on the number of cycles for the BAU kitchen (GWP over 80 years)

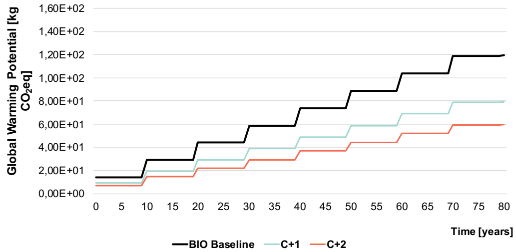


FIG. APP. C.14 LCA Sensitivity analysis on the number of cycles for the BIO kitchen (GWP over 80 years)

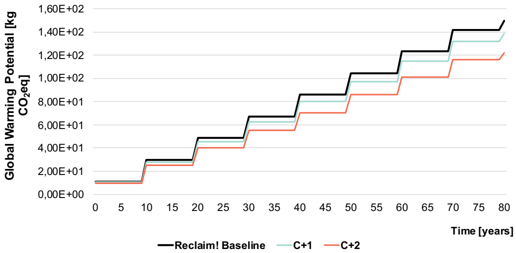


FIG. APP. C.15 LCA Sensitivity analysis on the number of cycles for the Reclaim! kitchen (GWP over 80 years)

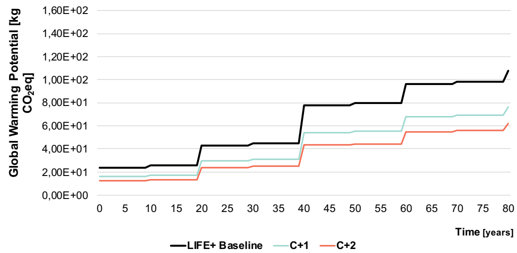


FIG. APP. C.16 LCA Sensitivity analysis on the number of cycles for the LIFE+ kitchen (GWP over 80 years)

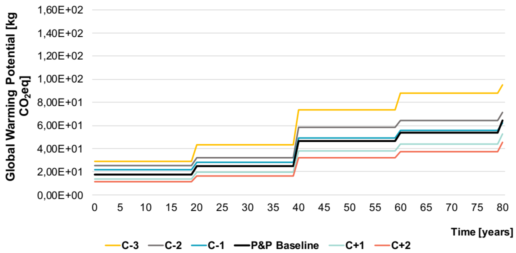


FIG. APP. C.17 LCA Sensitivity analysis on the number of cycles for the P&P kitchen (GWP over 80 years)

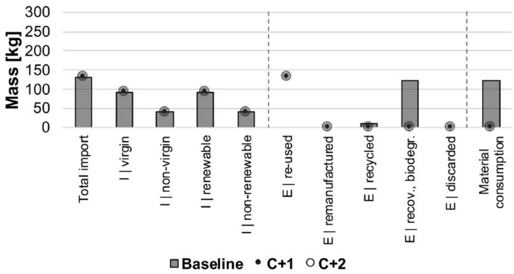


FIG. APP. C.18 MFA Sensitivity analysis on the number of cycles for the BAU kitchen (material flows over 80 years)

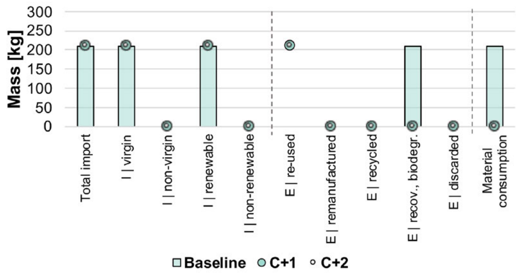


FIG. APP. C.19 MFA Sensitivity analysis on the number of cycles for the BIO kitchen (material flows over 80 years)

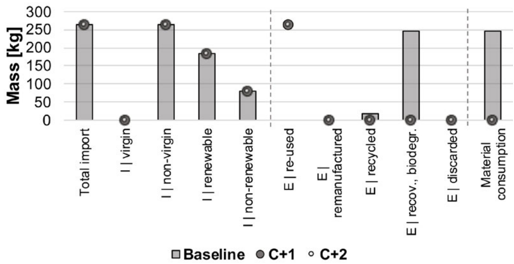


FIG. APP. C.20 MFA Sensitivity analysis on the number of cycles for the Reclaim! kitchen (material flows over 80 years)

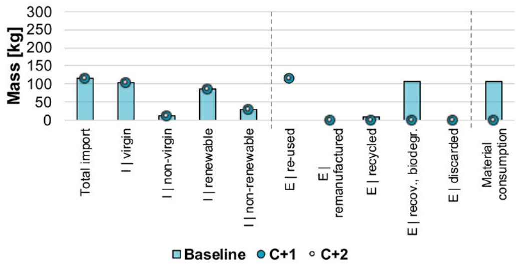


FIG. APP. C.21 MFA Sensitivity analysis on the number of cycles for the LIFE+ kitchen (material flows over 80 years)

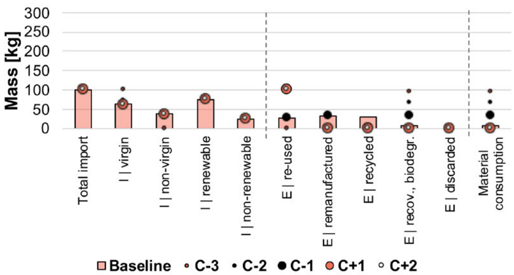


FIG. APP. C.22 MFA Sensitivity analysis on the number of cycles for the P&P kitchen (material flows over 80 years)

APP. C.7 Sensitivity analysis results on number of cycles for the façade variants: allocated GWP over time and MFA

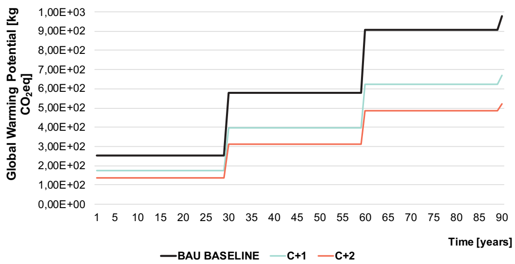


FIG. APP. C.23 LCA Sensitivity analysis on the number of cycles for the BAU façade (GWP over 90 years)

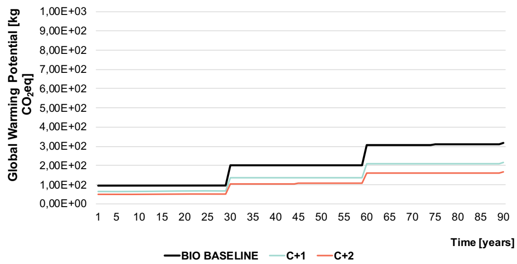


FIG. APP. C.24 LCA Sensitivity analysis on the number of cycles for the BIO façade (GWP over 90 years)

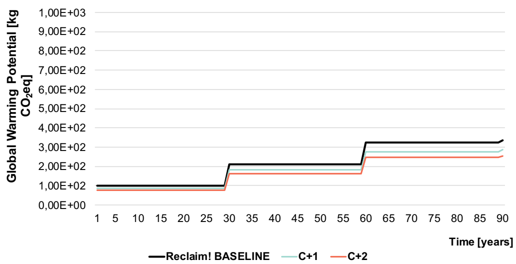


FIG. APP. C.25 LCA Sensitivity analysis on the number of cycles for the Reclaim! Façade (GWP over 90 years)

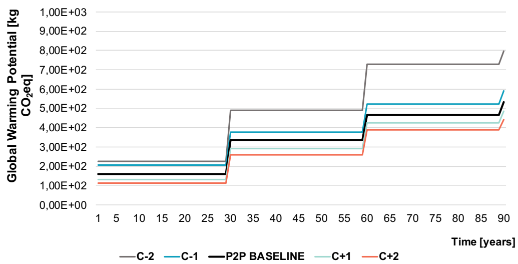


FIG. APP. C.26 LCA Sensitivity analysis on the number of cycles for the P2P façade (GWP over 90 years)

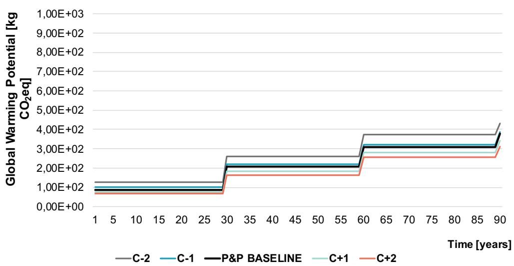


FIG. APP. C.27 LCA Sensitivity analysis on the number of cycles for the P&P façade (GWP over 90 years)

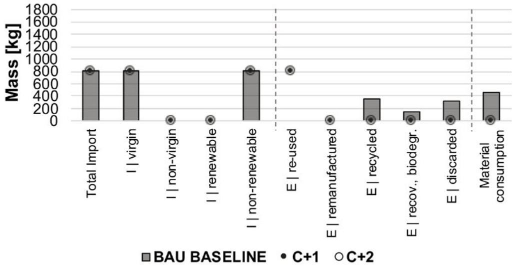


FIG. APP. C.28 MFA Sensitivity analysis on the number of cycles for the BAU façade (material flows over 90 years)

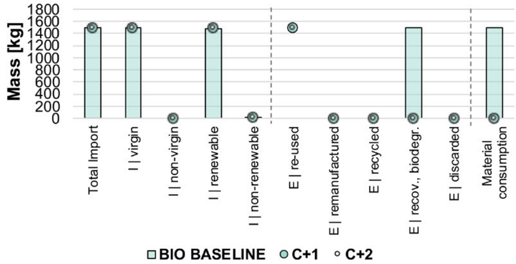


FIG. APP. C.29 MFA Sensitivity analysis on the number of cycles for the BIO façade (material flows over 90 years)

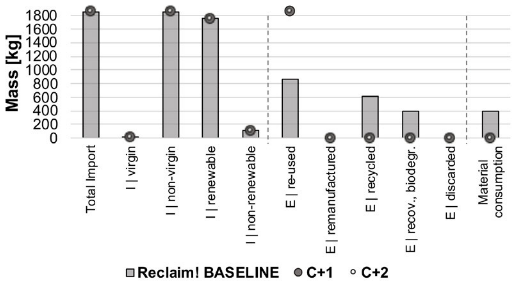


FIG. APP. C.30 MFA Sensitivity analysis on the number of cycles for the Reclaim! façade (material flows over 90 years)

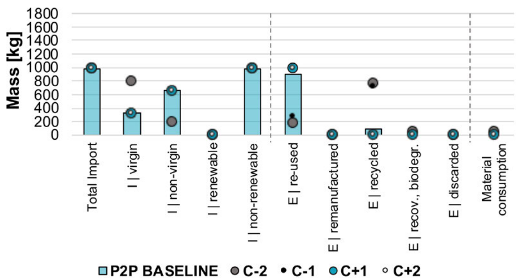


FIG. APP. C.31 MFA Sensitivity analysis on the number of cycles for the P2P façade (material flows over 90 years)

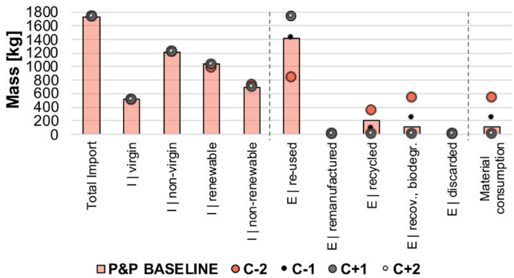


FIG. APP. C.32 MFA Sensitivity analysis on the number of cycles for the P&P façade (material flows over 90 years)

APP. C.8

Sensitivity analysis results on lifespans for the kitchen variants: allocated GWP over time and MFA

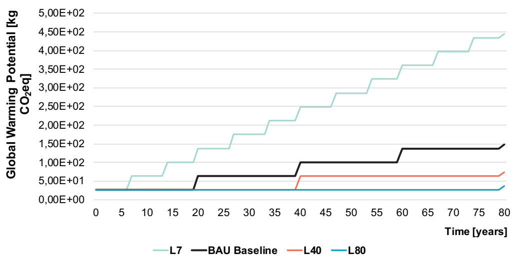


FIG. APP. C.33 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BAU kitchen (GWP allocated over 80 years)

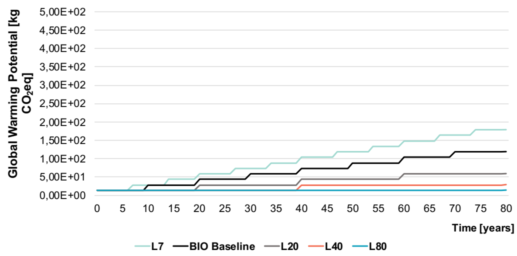


FIG. APP. C.34 LCA Sensitivity analysis on the $L_{technical}$ and Lfunctional for the BIO kitchen (GWP allocated over 80 years)

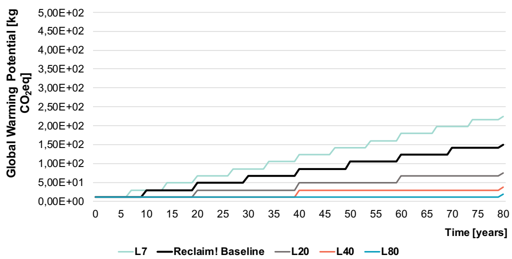


FIG. APP. C.35 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the Reclaim! kitchen (GWP allocated over 80 years)

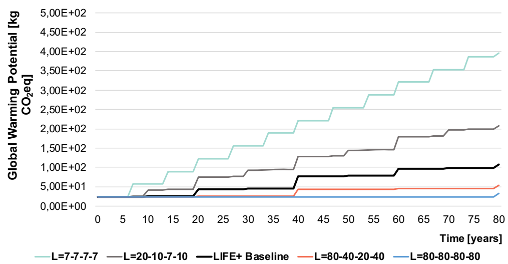


FIG. APP. C.36 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the LIFE+ kitchen (GWP allocated over 80 years)

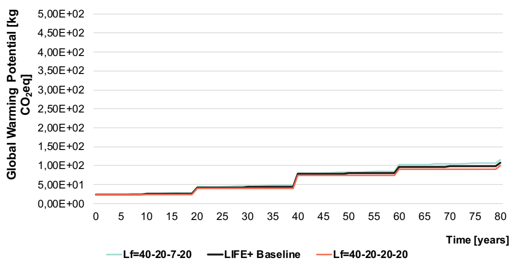


FIG. APP. C.37 LCA Sensitivity analysis on the $L_{functional}$ for the LIFE+ kitchen (GWP allocated over 80 years)

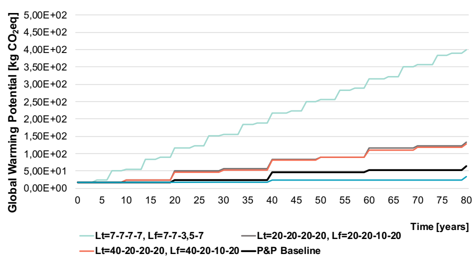


FIG. APP. C.38 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P&P kitchen (GWP allocated over 80 years)

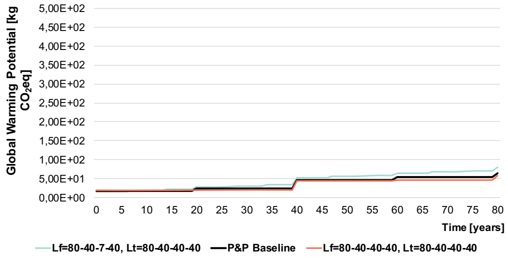


FIG. APP. C.39 LCA Sensitivity analysis on the $L_{functional}$ for the P&P kitchen (GWP allocated over 80 years)

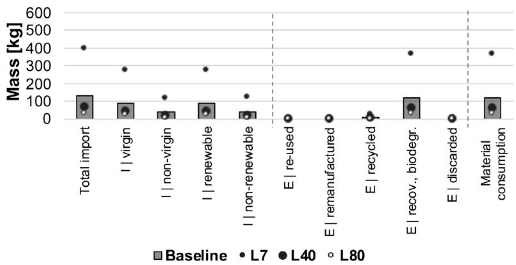


FIG. APP. C.40 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BAU kitchen (material flows over 80 years)

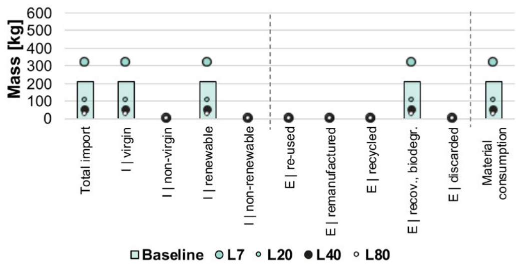


FIG. APP. C.41 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BIO kitchen (material flows over 80 years)

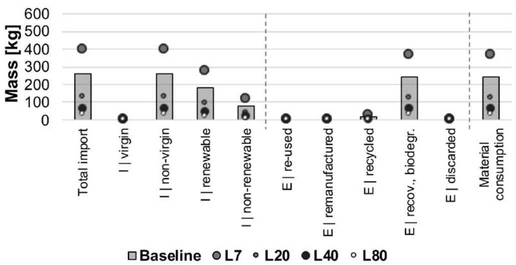


FIG. APP. C.42 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the Reclaim! kitchen (material flows over 80 years)

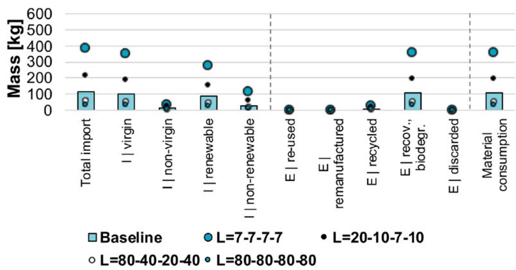


FIG. APP. C.43 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the LIFE+ kitchen (material flows over 80 years)

TOC

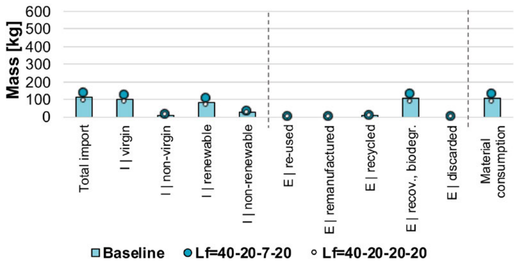


FIG. APP. C.44 MFA Sensitivity analysis on the $L_{functional}$ for the LIFE+ kitchen (material flows over 80 years)

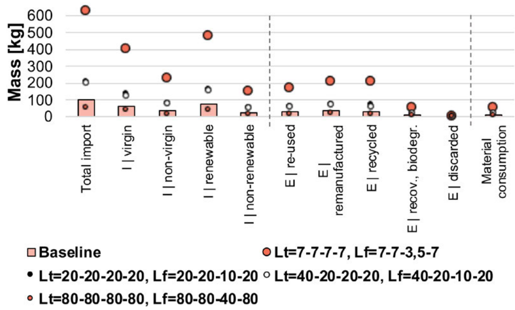


FIG. APP. C.45 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P&P kitchen (GWP allocated over 80 years)

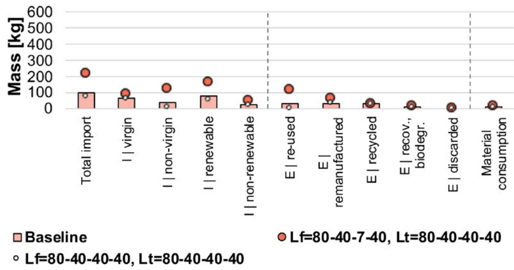


FIG. APP. C.46 MFA Sensitivity analysis on the $L_{functional}$ for the P&P kitchen (material flows over 80 years)

Sensitivity analysis results on lifespans for the façade variants: allocated GWP over time and MFA

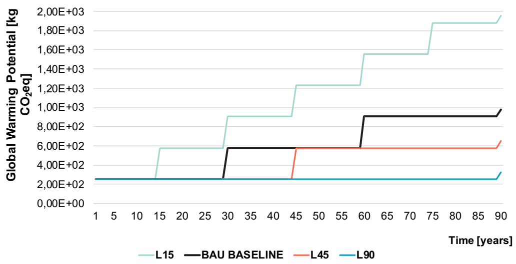


FIG. APP. C.47 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BAU façade (GWP allocated over 90 years)

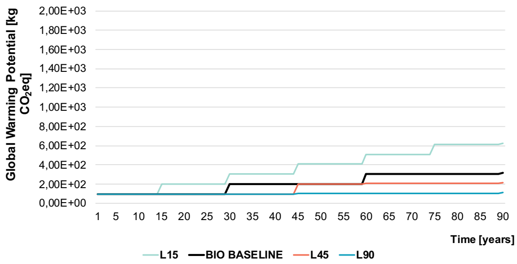


FIG. APP. C.48 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BIO façade (GWP allocated over 90 years)

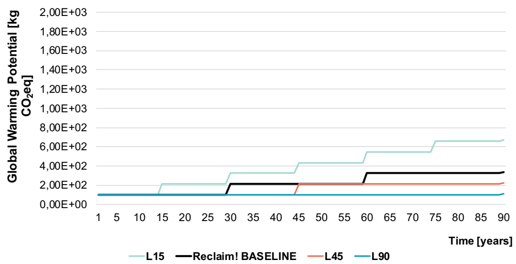


FIG. APP. C.49 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the Reclaim! façade (GWP allocated over 90 years)

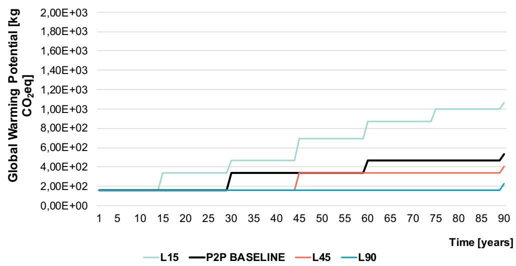


FIG. APP. C.50 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P2P façade (GWP allocated over 90 years)

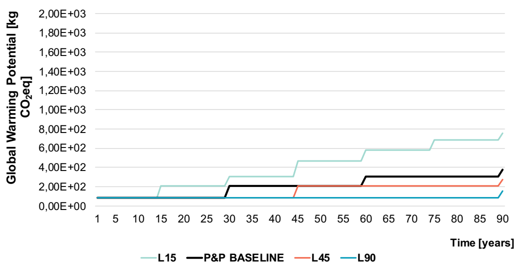


FIG. APP. C.51 LCA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P&P façade (GWP allocated over 90 years)

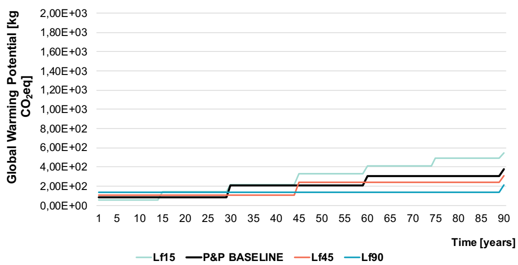
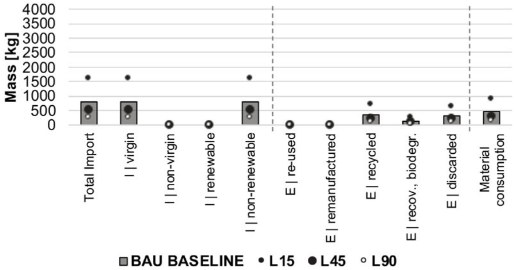


FIG. APP. C.52 LCA Sensitivity analysis on the $L_{functional}$ for the P&P façade (GWP allocated over 90 years)

TOC



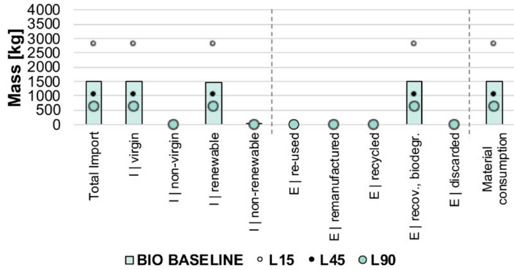
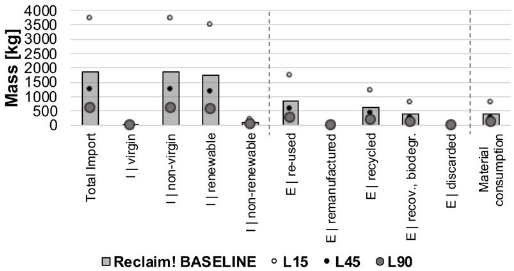


FIG. APP. C.53 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BAU façade (material flows over 90 years)

FIG. APP. C.54 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the BIO façade (material flows over 90 years)



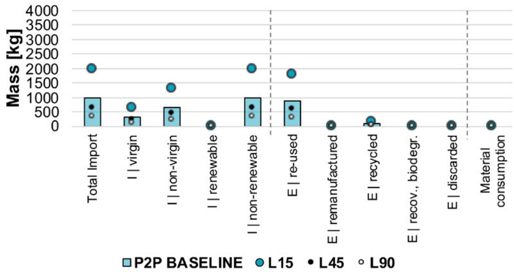
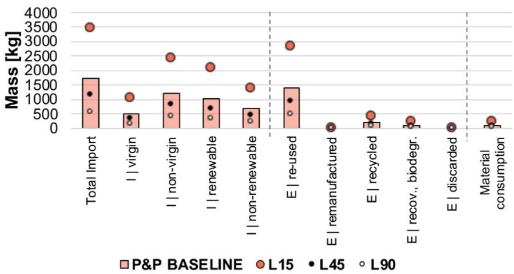


FIG. APP. C.55 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the Reclaim! façade (material flows over 90 years)

FIG. APP. C.56 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P2P façade (material flows over 90 years)



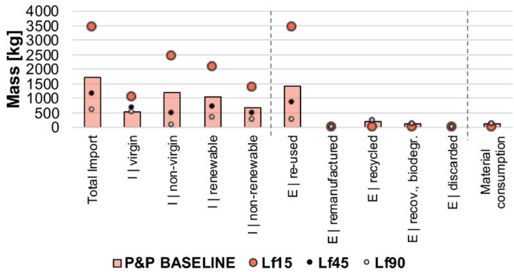


FIG. APP. C.57 MFA Sensitivity analysis on the $L_{technical}$ and $L_{functional}$ for the P&P façade (material flows over 90 years)

FIG. APP. C.58 MFA Sensitivity analysis on the $L_{functional}$ for the P&P façade (material flows over 90 years)

TOC

APP. C.10

Results all sensitivity analysis scenarios kitchen and façade variants

TABLE APP. C.12 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the BAU kitchen variant

Category	Unit	BAU					
		Baseline	C+1	C+2	L=7	L=40	L=80
Total import	kg	132	132	132	395	66	33
Import virgin	kg	92	92	92	276	46	23
Import non-virgin	kg	40	40	40	120	20	10
Import renewable	kg	92	92	92	275	46	23
Import non-renewable	kg	40	40	40	120	20	10
Export re-usable	kg	-	132	132	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-
Export recyclable	kg	9	-	-	27	4	2
Export recovered, degraded	kg	123	-	-	369	61	31
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	123	-	-	369	61	31
Abiotic depletion potential for for elements	kg Sb eq	1,81E+03	1,25E+03	9,76E+02	5,43E+03	9,05E+02	4,52E+02
Abiotic depletion potential for fossil fuels	MJ	1,55E-03	1,07E-03	8,35E-04	4,65E-03	7,76E-04	3,88E-04
Acidification potential	kg SO2 eq	5,99E-01	4,18E-01	3,32E-01	1,80E+00	2,99E-01	1,50E-01
Eutrophication potential	kg PO4--- eq	2,22E-01	1,54E-01	1,23E-01	6,65E-01	1,11E-01	5,54E-02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	8,30E+01	6,04E+01	4,95E+01	2,49E+02	4,15E+01	2,08E+01
Global warming potential	kg CO2 eq	1,48E+02	1,03E+02	8,25E+01	4,44E+02	7,41E+01	3,70E+01
Human toxicity potential	kg 1,4-DB eq	1,82E+02	1,45E+02	1,26E+02	5,46E+02	9,10E+01	4,55E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	1,70E+05	1,21E+05	9,71E+04	5,10E+05	8,51E+04	4,25E+04
Ozone layer depletion potential	kg CFC-11 eq	1,32E-05	9,01E-06	7,00E-06	3,96E-05	6,60E-06	3,30E-06
Photochemical oxidation potential	kg C2H4 eq	5,10E-02	3,62E-02	2,94E-02	1,53E-01	2,55E-02	1,27E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	4,93E-01	3,59E-01	2,95E-01	1,48E+00	2,47E-01	1,23E-01

TABLE APP. C.13 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the BIO kitchen variant

Category	Unit	BIO						
		Baseline	C+1	C+2	L=7	L=20	L=40	L=80
Total import	kg	210	210	210	316	105	53	26
Import virgin	kg	210	210	210	316	105	53	26
Import non-virgin	kg	-	-	-	-	-	-	-
Import renewable	kg	210	210	210	316	105	53	26
Import non-renewable	kg	-	-	-	-	-	-	-
Export re-usable	kg	-	210	210	-	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-	-
Export recyclable	kg	-	-	-	-	-	-	-
Export recovered, degraded	kg	210	-	-	316	105	53	26
Export discarded	kg	-	-	-	-	-	-	-
Material consumption	kg	210	-	-	316	105	53	26
Abiotic depletion potential for for elements	kg Sb eq	1,73E+03	1,15E+03	8,65E+02	2,59E+03	8,65E+02	4,32E+02	2,16E+02
Abiotic depletion potential for fossil fuels	MJ	1,71E-03	1,13E-03	8,55E-04	2,57E-03	8,55E-04	4,28E-04	2,14E-04
Acidification potential	kg SO2 eq	7,02E-01	4,65E-01	3,51E-01	1,05E+00	3,51E-01	1,75E-01	8,77E-02
Eutrophication potential	kg PO4--- eq	2,45E-01	1,63E-01	1,23E-01	3,68E-01	1,23E-01	6,14E-02	3,07E-02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	3,59E+01	2,38E+01	1,80E+01	5,39E+01	1,80E+01	8,98E+00	4,49E+00
Global warming potential	kg CO2 eq	1,20E+02	7,93E+01	5,98E+01	1,79E+02	5,98E+01	2,99E+01	1,49E+01
Human toxicity potential	kg 1,4-DB eq	5,41E+01	3,59E+01	2,71E+01	8,12E+01	2,71E+01	1,35E+01	6,76E+00
Marine aquatic ecotox-icity potential	kg 1,4-DB eq	1,05E+05	6,98E+04	5,26E+04	1,58E+05	5,26E+04	2,63E+04	1,32E+04
Ozone layer depletion potential	kg CFC-11 eq	1,83E-05	1,22E-05	9,16E-06	2,75E-05	9,16E-06	4,58E-06	2,29E-06
Photochemical oxidation potential	kg C2H4 eq	4,05E-02	2,69E-02	2,03E-02	6,08E-02	2,03E-02	1,01E-02	5,06E-03
Terrestrial ecotoxicity potential	kg 1,4-DB eq	6,64E-01	4,40E-01	3,32E-01	9,96E-01	3,32E-01	1,66E-01	8,30E-02

TABLE APP. C.14 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the Reclaim! kitchen variant

Category	Unit	Reclaim!						
		Baseline	C+1	C+2	L=7	L=20	L=40	L=80
Total import	kg	264	264	264	395	132	66	33
Import virgin	kg	-	-	-	-	-	-	-
Import non-virgin	kg	264	264	264	395	132	66	33
Import renewable	kg	184	184	184	275	92	46	23
Import non-renewable	kg	80	80	80	120	40	20	10
Export re-usable	kg	-	264	264	-	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-	-
Export recyclable	kg	18	-	-	27	9	4	2
Export recovered, degraded	kg	246	-	-	369	123	61	31
Export discarded	kg	-	-	-	-	-	-	-
Material consumption	kg	246	-	-	369	123	61	31
Abiotic depletion potential for for elements	kg Sb eq	1,56E+03	1,52E+03	1,37E+03	2,35E+03	7,82E+02	3,91E+02	1,96E+02
Abiotic depletion potential for fossil fuels	MJ	1,24E-03	1,22E-03	1,11E-03	1,86E-03	6,20E-04	3,10E-04	1,55E-04
Acidification potential	kg SO2 eq	5,34E-01	5,20E-01	4,67E-01	8,02E-01	2,67E-01	1,34E-01	6,68E-02
Eutrophication potential	kg PO4--- eq	1,98E-01	1,92E-01	1,71E-01	2,97E-01	9,92E-02	4,96E-02	2,48E-02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	9,37E+01	8,48E+01	7,51E+01	1,40E+02	4,68E+01	2,34E+01	1,17E+01
Global warming potential	kg CO2 eq	1,50E+02	1,39E+02	1,22E+02	2,24E+02	7,48E+01	3,74E+01	1,87E+01
Human toxicity potential	kg 1,4-DB eq	2,37E+02	2,22E+02	2,03E+02	3,55E+02	1,18E+02	5,92E+01	2,96E+01
Marine aquatic ecotox-icity potential	kg 1,4-DB eq	1,71E+05	1,59E+05	1,41E+05	2,57E+05	8,56E+04	4,28E+04	2,14E+04
Ozone layer depletion potential	kg CFC-11 eq	1,12E-05	1,10E-05	9,99E-06	1,68E-05	5,59E-06	2,79E-06	1,40E-06
Photochemical oxidation potential	kg C2H4 eq	4,71E-02	4,65E-02	4,17E-02	7,07E-02	2,36E-02	1,18E-02	5,89E-03
Terrestrial ecotoxicity potential	kg 1,4-DB eq	4,94E-01	4,75E-01	4,33E-01	7,42E-01	2,47E-01	1,24E-01	6,18E-02

TABLE APP. C.15 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the LIFE+ kitchen variant

Category	Unit	LIFE+								
		Baseline	C+1	C+2	Lf=40-20-7-20	Lf=40-20-20-20	L= 7-7-7-7	L=20-10-7-10	L=80-40-20-40	L=80-80-80-80
Total import	kg	115	115	115	134	95	384	210	57	32
Import virgin	kg	103	103	103	123	84	350	187	52	29
Import non-virgin	kg	11	11	11	11	11	34	23	6	3
Import renewable	kg	85	85	85	103	67	275	152	43	23
Import non-renew-able	kg	30	30	30	32	28	109	58	15	9
Export re-usable	kg	-	115	115	-	-	-	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-	-	-	-
Export recyclable	kg	8	-	-	8	8	27	16	4	2
Export recovered, degraded	kg	107	-	-	126	87	358	194	53	30
Export discarded	kg	-	-	-	-	-	-	-	-	-
Material consump-tion	kg	107	-	-	126	87	358	194	53	30
Abiotic depletion potential for for elements	kg Sb eq	1,27E+03	8,83E+02	7,01E+02	1,37E+03	1,17E+03	4,76E+03	2,43E+03	6,33E+02	3,97E+02
Abiotic depletion potential for fossil fuels	MJ	9,62E-04	6,77E-04	5,40E-04	1,11E-03	8,14E-04	2,73E-03	1,78E-03	4,81E-04	2,28E-04
Acidification potential	kg SO2 eq	4,66E-01	3,29E-01	2,65E-01	5,09E-01	4,24E-01	1,70E+00	8,90E-01	2,33E-01	1,42E-01
Eutrophication potential	kg PO4--- eq	1,77E-01	1,25E-01	1,00E-01	1,94E-01	1,60E-01	6,52E-01	3,38E-01	8,87E-02	5,43E-02
Fresh water aquatic ecotoxicity potential	kg 1, 4-DB eq	5,87E+01	4,42E+01	3,73E+01	6,13E+01	5,62E+01	2,08E+02	1,15E+02	2,94E+01	1,73E+01
Global warming potential	kg CO2 eq	1,08E+02	7,65E+01	6,21E+01	1,16E+02	1,00E+02	3,96E+02	2,08E+02	5,39E+01	3,30E+01
Human toxicity potential	kg 1, 4-DB eq	1,51E+02	1,24E+02	1,11E+02	1,55E+02	1,47E+02	4,89E+02	2,99E+02	7,56E+01	4,07E+01
Marine aquatic eco-toxicity potential	kg 1, 4-DB eq	1,17E+05	8,50E+04	6,99E+04	1,24E+05	1,10E+05	4,26E+05	2,27E+05	5,84E+04	3,55E+04
Ozone layer depletion potential	kg CFC-11 eq	1,02E-05	6,98E-06	5,46E-06	1,12E-05	9,15E-06	3,76E-05	1,93E-05	5,08E-06	3,13E-06
Photochemical oxidation potential	kg C2H4 eq	4,06E-02	2,92E-02	2,41E-02	4,34E-02	3,78E-02	1,52E-01	7,84E-02	2,03E-02	1,26E-02
Terrestrial ecotox-icity potential	kg 1, 4-DB eq	4,52E-01	3,32E-01	2,75E-01	5,06E-01	3,99E-01	1,50E+00	8,52E-01	2,26E-01	1,25E-01

TABLE APP. C.16 Results CE-LCIA and MFA of the sensitivity analysis scenarios varying number of use cycles for the P&P kitchen variant

Category	Unit	P&P					
		Baseline	C-3	C-2	C-1	C+1	C+2
Total import	kg	101	101	101	101	101	101
Import virgin	kg	63	101	73	63	63	63
Import non-virgin	kg	38	-	28	38	38	38
Import renewable	kg	76	76	76	76	76	76
Import non-renewable	kg	25	25	25	25	25	25
Export re-usable	kg	28	-	28	28	101	101
Export re-manufact.	kg	34	-	-	34	-	-
Export recyclable	kg	30	4	4	4	-	-
Export recovered, degraded	kg	8	97	69	35	-	-
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	8	97	69	35	-	-
Abiotic depletion potential for for elements	kg Sb eq	7,88E+02	1,27E+03	9,27E+02	7,92E+02	6,43E+02	5,49E+02
Abiotic depletion potential for fossil fuels	MJ	9,77E-04	3,83E-04	2,98E-04	2,66E-04	8,25E-04	7,09E-04
Acidification potential	kg SO2 eq	2,99E-01	4,84E-01	3,57E-01	3,01E-01	2,46E-01	2,12E-01
Eutrophication potential	kg PO4--- eq	1,05E-01	1,64E-01	1,22E-01	1,03E-01	8,69E-02	7,49E-02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	3,73E+01	3,84E+01	3,12E+01	2,86E+01	3,11E+01	2,72E+01
Global warming potential	kg CO2 eq	6,40E+01	9,51E+01	7,13E+01	6,22E+01	5,22E+01	4,50E+01
Human toxicity potential	kg 1,4-DB eq	9,11E+01	9,79E+01	8,64E+01	8,17E+01	7,85E+01	7,10E+01
Marine aquatic ecotox-icity potential	kg 1,4-DB eq	7,62E+04	8,55E+04	6,60E+04	5,83E+04	6,32E+04	5,47E+04
Ozone layer depletion potential	kg CFC-11 eq	6,92E-06	1,18E-05	8,57E-06	7,23E-06	5,65E-06	4,80E-06
Photochemical oxidation potential	kg C2H4 eq	2,54E-02	4,19E-02	3,13E-02	2,62E-02	2,10E-02	1,83E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	2,81E-01	3,53E-01	2,73E-01	2,36E-01	2,36E-01	2,05E-01

TOC

TABLE APP. C.17 Results CE-LCIA and MFA of the sensitivity analysis scenarios varying technical and functional lifespans for the P&P kitchen variant

Category	Unit	P&P					
		Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3, 5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Total import	kg	214	73	626	209	202	52
Import virgin	kg	91	63	398	133	126	38
Import non-virgin	kg	123	10	228	76	76	14
Import renewable	kg	163	54	475	158	152	40
Import non-renewable	kg	51	18	151	50	49	13
Export re-usable	kg	113	-	170	57	57	14
Export re-manufact.	kg	58	34	203	68	68	22
Export recyclable	kg	30	30	204	68	61	12
Export recovered, degraded	kg	12	8	50	17	17	4
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	12	8	50	17	17	4
Abiotic depletion potential for for elements	kg Sb eq	9,69E+02	6,05E+02	4,94E+03	1,65E+03	1,57E+03	4,23E+02
Abiotic depletion potential for fossil fuels	MJ	1,34E-03	7,52E-04	6,41E-03	2,14E-03	1,95E-03	5,37E-04
Acidification potential	kg SO2 eq	3,67E-01	2,32E-01	1,89E+00	6,30E-01	5,97E-01	1,61E-01
Eutrophication potential	kg PO4--- eq	1,30E-01	8,20E-02	6,67E-01	2,22E-01	2,10E-01	5,67E-02
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	4,56E+01	3,08E+01	2,39E+02	7,96E+01	7,46E+01	2,01E+01
Global warming potential	kg CO2 eq	7,85E+01	5,00E+01	4,01E+02	1,34E+02	1,28E+02	3,41E+01
Human toxicity potential	kg 1,4-DB eq	1,02E+02	8,23E+01	5,88E+02	1,96E+02	1,82E+02	4,93E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	9,48E+04	6,09E+04	4,86E+05	1,62E+05	1,52E+05	4,10E+04
Ozone layer depletion potential	kg CFC-11 eq	8,62E-06	5,22E-06	4,34E-05	1,45E-05	1,38E-05	3,73E-06
Photochemical oxidation potential	kg C2H4 eq	3,07E-02	2,00E-02	1,60E-01	5,34E-02	5,06E-02	1,37E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,45E-01	2,27E-01	1,80E+00	6,00E-01	5,62E-01	1,52E-01

TABLE APP. C.18 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the BAU façade variant

Category	Unit	BAU					
		Baseline	C+1	C+2	L=15	L=45	L=90
Total import	kg	801	801	801	1.602	534	267
Import virgin	kg	801	801	801	1.602	534	267
Import non-virgin	kg	-	-	-	-	-	-
Import renewable	kg	-	-	-	-	-	-
Import non-renewable	kg	801	801	801	1.602	534	267
Export re-usable	kg	-	801	801	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-
Export recyclable	kg	350	-	-	700	233	117
Export recovered, degraded	kg	138	-	-	275	92	46
Export discarded	kg	313	-	-	626	209	104
Material consumption	kg	451	-	-	901	300	150
Abiotic depletion potential for for elements	kg Sb eq	1,15E-03	7,88E-04	6,15E-04	1,58E-03	5,25E-04	2,63E-04
Abiotic depletion potential for fossil fuels	MJ	1,36E+04	9,18E+03	7,02E+03	1,84E+04	6,12E+03	3,06E+03
Acidification potential	kg SO2 eq	2,81E+00	1,94E+00	1,51E+00	3,88E+00	1,29E+00	6,46E-01
Eutrophication potential	kg PO4--- eq	5,96E-01	4,16E-01	3,28E-01	8,31E-01	2,77E-01	1,39E-01
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	2,95E+02	1,99E+02	1,52E+02	3,97E+02	1,32E+02	6,62E+01
Global warming potential	kg CO2 eq	9,78E+02	6,70E+02	5,22E+02	1,34E+03	4,47E+02	2,23E+02
Human toxicity potential	kg 1,4-DB eq	2,85E+02	1,95E+02	1,51E+02	3,90E+02	1,30E+02	6,50E+01
Marine aquatic ecotox-icity potential	kg 1,4-DB eq	1,27E+06	8,55E+05	6,53E+05	1,71E+06	5,70E+05	2,85E+05
Ozone layer depletion potential	kg CFC-11 eq	3,25E-05	2,28E-05	1,81E-05	4,56E-05	1,52E-05	7,59E-06
Photochemical oxidation potential	kg C2H4 eq	1,95E-01	1,33E-01	1,03E-01	2,66E-01	8,87E-02	4,43E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	5,87E-01	4,15E-01	3,32E-01	8,30E-01	2,77E-01	1,38E-01

TABLE APP. C.19 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the BIO façade variant

Category	Unit	BIO					
		Baseline	C+1	C+2	L=15	L=45	L=90
Total import	kg	1.488	1.488	1.488	2.806	1.048	609
Import virgin	kg	1.488	1.488	1.488	2.806	1.048	609
Import non-virgin	kg	-	-	-	-	-	-
Import renewable	kg	1.483	1.483	1.483	2.797	1.045	607
Import non-renewable	kg	4	4	4	9	3	1
Export re-usable	kg	-	1.488	1.488	-	-	-
Export re-manufact.	kg	-	-	-	-	-	-
Export recyclable	kg	-	-	-	-	-	-
Export recovered, degraded	kg	1.488	-	-	2.806	1.048	609
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	1.488	-	-	2.806	1.048	609
Abiotic depletion potential for for elements	kg Sb eq	8,02E-03	5,51E-03	4,36E-03	1,49E-02	5,72E-03	3,42E-03
Abiotic depletion potential for fossil fuels	MJ	2,87E+03	2,03E+03	1,62E+03	5,64E+03	1,94E+03	1,02E+03
Acidification potential	kg SO2 eq	2,20E+00	1,50E+00	1,16E+00	4,34E+00	1,49E+00	7,77E-01
Eutrophication potential	kg PO4--- eq	3,23E+00	2,16E+00	1,64E+00	6,43E+00	2,16E+00	1,10E+00
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	1,16E+02	7,95E+01	6,20E+01	2,27E+02	7,87E+01	4,15E+01
Global warming potential	kg CO2 eq	3,17E+02	2,16E+02	1,67E+02	6,25E+02	2,15E+02	1,13E+02
Human toxicity potential	kg 1,4-DB eq	1,25E+02	8,58E+01	6,71E+01	2,44E+02	8,52E+01	4,56E+01
Marine aquatic ecotox-icity potential	kg 1,4-DB eq	3,01E+05	2,08E+05	1,63E+05	5,91E+05	2,04E+05	1,07E+05
Ozone layer depletion potential	kg CFC-11 eq	2,81E-05	1,99E-05	1,59E-05	5,55E-05	1,90E-05	9,94E-06
Photochemical oxidation potential	kg C2H4 eq	1,65E-01	1,11E-01	8,49E-02	3,26E-01	1,11E-01	5,71E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	1,39E+00	9,83E-01	7,99E-01	2,53E+00	1,01E+00	6,35E-01

TABLE APP. C.20 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the Reclaim! façade variant

Category	Unit	Reclaim!					
		Baseline	C+1	C+2	L=15	L=45	L=90
Total import	kg	1.857	1.857	1.857	3.714	1.238	619
Import virgin	kg	4	4	4	8	3	1
Import non-virgin	kg	1.853	1.853	1.853	3.706	1.235	618
Import renewable	kg	1.752	1.752	1.752	3.504	1.168	584
Import non-renewable	kg	105	105	105	210	70	35
Export re-usable	kg	856	1.857	1.857	1.713	571	285
Export re-manufact.	kg	-	-	-	-	-	-
Export recyclable	kg	610	-	-	1.220	407	203
Export recovered, degraded	kg	391	-	-	781	260	130
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	391	-	-	781	260	130
Abiotic depletion potential for for elements	kg Sb eq	9,11E-04	8,03E-04	7,13E-04	1,82E-03	6,07E-04	3,04E-04
Abiotic depletion potential for fossil fuels	MJ	3,83E+03	3,20E+03	2,86E+03	7,66E+03	2,55E+03	1,28E+03
Acidification potential	kg SO2 eq	2,13E+00	1,84E+00	1,63E+00	4,26E+00	1,42E+00	7,10E-01
Eutrophication potential	kg PO4--- eq	5,70E-01	4,95E-01	4,34E-01	1,14E+00	3,80E-01	1,90E-01
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	1,68E+02	1,50E+02	1,32E+02	3,36E+02	1,12E+02	5,60E+01
Global warming potential	kg CO2 eq	3,36E+02	2,87E+02	2,54E+02	6,72E+02	2,24E+02	1,12E+02
Human toxicity potential	kg 1,4-DB eq	2,25E+02	1,97E+02	1,73E+02	4,51E+02	1,50E+02	7,51E+01
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	6,45E+05	5,99E+05	5,36E+05	1,29E+06	4,30E+05	2,15E+05
Ozone layer depletion potential	kg CFC-11 eq	3,60E-05	3,21E-05	2,82E-05	7,21E-05	2,40E-05	1,20E-05
Photochemical oxidation potential	kg C2H4 eq	1,55E-01	1,35E-01	1,20E-01	3,10E-01	1,03E-01	5,17E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	9,95E-01	9,02E-01	8,02E-01	1,99E+00	6,64E-01	3,32E-01

TABLE APP. C.21 Results CE-LCIA and MFA of all sensitivity analysis scenarios for the P2P façade variant

Category	Unit	P2P							
		Baseline	C-2	C-1	C+1	C+2	L15	L45	L90
Total import	kg	987	987	987	987	987	1.974	658	329
Import virgin	kg	329	795	329	329	329	658	219	110
Import non-virgin	kg	658	192	658	658	658	1.316	439	219
Import renewable	kg	-	-	-	-	-	-	-	-
Import non-renewable	kg	987	987	987	987	987	1.974	658	329
Export re-usable	kg	899	181	271	987	987	1.799	600	300
Export re-manufact.	kg	-	-	-	-	-	-	-	-
Export recyclable	kg	87	760	716	-	-	175	58	29
Export recovered, degraded	kg	-	47	-	-	-	-	-	-
Export discarded	kg	-	-	-	-	-	-	-	-
Material consumption	kg	-	47	-	-	-	-	-	-
Abiotic depletion potential for for elements	kg Sb eq	2,86E-02	4,95E-02	3,27E-02	2,85E-02	2,50E-02	5,73E-02	2,24E-02	1,29E-02
Abiotic depletion potential for fossil fuels	MJ	6,27E+03	9,22E+03	6,94E+03	5,74E+03	5,20E+03	1,25E+04	4,85E+03	2,78E+03
Acidification potential	kg SO2 eq	2,31E+00	3,94E+00	2,63E+00	2,19E+00	1,98E+00	4,63E+00	1,84E+00	1,07E+00
Eutrophication potential	kg PO4--- eq	7,35E-01	1,18E+00	8,19E-01	7,08E-01	6,35E-01	1,47E+00	5,70E-01	3,25E-01
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	6,49E+03	6,63E+03	6,52E+03	6,47E+03	5,56E+03	1,30E+04	4,35E+03	2,19E+03
Global warming potential	kg CO2 eq	5,33E+02	7,97E+02	5,91E+02	4,86E+02	4,42E+02	1,07E+03	4,04E+02	2,27E+02
Human toxicity potential	kg 1,4-DB eq	4,88E+02	6,63E+02	5,21E+02	4,60E+02	4,20E+02	9,76E+02	3,62E+02	2,00E+02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	2,74E+06	3,28E+06	2,83E+06	2,65E+06	2,35E+06	5,48E+06	1,94E+06	1,03E+06
Ozone layer depletion potential	kg CFC-11 eq	3,38E-05	5,85E-05	3,71E-05	3,17E-05	2,81E-05	6,76E-05	2,75E-05	1,62E-05
Photochemical oxidation potential	kg C2H4 eq	1,38E-01	2,30E-01	1,57E-01	1,30E-01	1,19E-01	2,77E-01	1,09E-01	6,34E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	1,35E+00	2,08E+00	1,48E+00	1,30E+00	1,17E+00	2,71E+00	1,04E+00	5,87E-01

TABLE APP. C.22 Results CE-LCIA and MFA of the sensitivity analysis scenarios varying number of use cycles for the P&P façade variant

Category	Unit	P&P				
		Baseline	C-2	C-1	C+1	C+2
Total import	kg	1.731	1.731	1.731	1.731	1.731
Import virgin	kg	518	518	518	518	518
Import non-virgin	kg	1.213	1.213	1.213	1.213	1.213
Import renewable	kg	1.035	979	1.035	1.035	1.035
Import non-renewable	kg	696	737	696	696	696
Export re-usable	kg	1.416	842	1.416	1.731	1.731
Export re-manufact.	kg	-	-	-	-	-
Export recyclable	kg	206	354	79	-	-
Export recovered, degraded	kg	109	534	236	-	-
Export discarded	kg	-	-	-	-	-
Material consumption	kg	109	534	236	-	-
Abiotic depletion potential for for elements	kg Sb eq	5,92E-03	6,54E-03	5,99E-03	5,22E-03	5,08E-03
Abiotic depletion potential for fossil fuels	MJ	4,11E+03	4,76E+03	4,18E+03	3,71E+03	3,34E+03
Acidification potential	kg SO2 eq	1,64E+00	1,88E+00	1,69E+00	1,48E+00	1,35E+00
Eutrophication potential	kg PO4--- eq	7,43E-01	9,13E-01	7,82E-01	6,72E-01	6,13E-01
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	1,83E+03	2,08E+03	1,85E+03	1,60E+03	1,57E+03
Global warming potential	kg CO2 eq	3,78E+02	4,31E+02	3,87E+02	3,42E+02	3,11E+02
Human toxicity potential	kg 1,4-DB eq	5,79E+02	6,80E+02	6,07E+02	5,32E+02	4,90E+02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	1,37E+06	2,14E+06	1,50E+06	1,24E+06	1,15E+06
Ozone layer depletion potential	kg CFC-11 eq	4,74E-05	5,92E-05	4,84E-05	4,27E-05	3,82E-05
Photochemical oxidation potential	kg C2H4 eq	1,39E-01	1,68E-01	1,46E-01	1,25E-01	1,15E-01
Terrestrial ecotoxicity potential	kg 1,4-DB eq	1,79E+00	2,38E+00	1,89E+00	1,63E+00	1,48E+00

TABLE APP. C.23 Results CE-LCIA and MFA of the sensitivity analysis scenarios varying technical and functional lifespans for the P&P façade variant

Category	Unit	P&P					
		L=15	L=45	L=90	Lf=15	Lf=45	Lf=90
Total import	kg	3.461	1.154	577	3.452	1.157	583
Import virgin	kg	1.036	345	173	1.026	665	518
Import non-virgin	kg	2.425	808	404	2.425	492	65
Import renewable	kg	2.069	690	345	2.069	690	345
Import non-renewable	kg	1.392	464	232	1.383	467	238
Export re-usable	kg	2.831	944	472	3.452	842	268
Export re-manufact.	kg	-	-	-	-	-	-
Export recyclable	kg	412	137	69	-	206	206
Export recovered, degraded	kg	218	73	36	-	109	109
Export discarded	kg	-	-	-	-	-	-
Material consumption	kg	218	73	36	-	109	109
Abiotic depletion potential for for elements	kg Sb eq	1,18E-02	4,08E-03	2,16E-03	8,81E-03	4,41E-03	2,59E-03
Abiotic depletion potential for fossil fuels	MJ	8,22E+03	2,99E+03	1,67E+03	5,84E+03	3,36E+03	2,32E+03
Acidification potential	kg SO2 eq	3,27E+00	1,19E+00	6,72E-01	2,39E+00	1,35E+00	9,28E-01
Eutrophication potential	kg PO4--- eq	1,49E+00	5,41E-01	3,02E-01	1,08E+00	6,21E-01	4,33E-01
Fresh water aquatic ecotoxicity potential	kg 1,4-DB eq	3,65E+03	1,24E+03	6,41E+02	2,70E+03	1,34E+03	7,70E+02
Global warming potential	kg CO2 eq	7,57E+02	2,75E+02	1,56E+02	5,47E+02	3,10E+02	2,14E+02
Human toxicity potential	kg 1,4-DB eq	1,16E+03	4,36E+02	2,78E+02	9,37E+02	4,69E+02	3,31E+02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	2,74E+06	1,01E+06	5,60E+05	2,02E+06	1,15E+06	8,53E+05
Ozone layer depletion potential	kg CFC-11 eq	9,49E-05	3,46E-05	1,90E-05	6,63E-05	3,90E-05	2,77E-05
Photochemical oxidation potential	kg C2H4 eq	2,77E-01	1,03E-01	5,99E-02	2,04E-01	1,17E-01	8,45E-02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,58E+00	1,33E+00	7,75E-01	2,67E+00	1,52E+00	1,12E+00

APP. C.11 Additional analysis of contribution of materials and processes to CE-LCIA and MFA results

Which materials or processes contribute most to the results varies per material flow category. Looking at the material import in the kitchens over the RSP, the majority share originates from the wood-based materials used in the panels, fronts, infill and/or finishing parts: in the baseline scenarios, this is 76% for the BAU, Reclaim! and P&P, 81% for the LIFE+ and 95% for the BIO kitchen. The share is larger for variants with no, or little coating materials. For the BAU, P2P and P&P façades, the finishing contributes significantly to the total material import over the RSP: in the baseline scenarios, the share of cement, mortar and brick-strips is 82% in the BAU; for the ceramic tiles in the P2P, this is 71%; for the P&P, the plywood boards, cement and brick-strips make up 44%. In the BIO, Reclaim! and P&P façade baselines, wood-based materials make up 36%, 61% and 41%, respectively. For the BIO façade baseline, the share of hemp-based materials in the total import is 28% and 31% for clay.

Which materials or processes contribute most to the environmental impacts varies per impact category. In most instances the majority of impacts originates from materials with high shares in the import. However, several materials and processes made disproportional contributions. In the P&P kitchen, the recycling process 'chipping for OSB production' results in a high share of impacts, especially in the abiotic depletion for elements category. Considering the limited mass of the stainless steel, aluminium and coatings (i.e., melamine), we found that these materials contribute disproportionally to the total impacts, especially for the toxicity categories. In both the kitchen and façades, most of the impact originates from material production, VRPs, or disposal processes; transport played a limited role.

TOC

APP. C.12 Ranking of design variants based on the percentual savings in the CE-LCA and MFA to the BAU (baseline scenario)

TABLE APP. C.24 Ranking of BAU kitchen scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	BAU					
		Baseline	C+1	C+2	L=7	L=40	L=80
Total import	%-saved	0%	0%	0%	-200%	50%	75%
Import virgin	%-saved	0%	0%	0%	0%	0%	0%
Import non-renewable	%-saved	0%	0%	0%	0%	0%	0%
Export reused, remanufact. or recycled	%-saved	0%	100%	100%	0%	0%	0%
Material consumption	%-saved	0%	100%	100%	-200%	50%	75%
Savings in MFA	%-saved	0%	40%	40%	-80%	20%	30%
Abiotic depletion potential for fossil fuels	%-saved	0%	31%	46%	-200%	50%	75%
Abiotic depletion potential for elements	%-saved	0%	31%	46%	-200%	50%	75%
Acidification potential	%-saved	0%	30%	45%	-200%	50%	75%
Eutrophication potential	%-saved	0%	30%	45%	-200%	50%	75%
Fresh water aquatic ecotoxicity potential	%-saved	0%	27%	40%	-200%	50%	75%
Global warming potential	%-saved	0%	30%	44%	-200%	50%	75%
Human toxicity potential	%-saved	0%	21%	31%	-200%	50%	75%
Marine aquatic ecotoxicity potential	%-saved	0%	29%	43%	-200%	50%	75%
Ozone layer depletion potential	%-saved	0%	32%	47%	-200%	50%	75%
Photochemical oxidation potential	%-saved	0%	29%	42%	-200%	50%	75%
Terrestrial ecotoxicity potential	%-saved	0%	27%	40%	-200%	50%	75%
Savings in LCA (average on all categories)	%-saved	0%	29%	43%	-200%	50%	75%
Savings in LCA (GWP)	%-saved	0%	30%	44%	-200%	50%	75%
Savings in LCA (Shadow costs)	%-saved	0%	26%	39%	-200%	50%	75%
Rank - average savings in LCA (all cat.) and MFA		**33**	**24**	**16**	**41**	**23**	**8**
Rank - average savings in LCA (GWP) and MFA		**34**	**22**	**17**	**41**	**23**	**9**
Rank - average savings in LCA (Shadow costs) and MFA		**34**	**23**	**20**	**41**	**22**	**9**

TABLE APP. C.25 Ranking of BIO kitchen scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	BIO						
		Baseline	C+1	C+2	L=7	L=20	L=40	L=80
Total import	%-saved	-60%	-60%	-60%	-139%	20%	60%	80%
Import virgin	%-saved	-43%	-43%	-43%	-43%	-43%	-43%	-43%
Import non-renewable	%-saved	100%	100%	100%	100%	100%	100%	100%
Export reused, reman-ufact. or recycled	%-saved	-7%	100%	100%	-7%	-7%	-7%	-7%
Material consumption	%-saved	-71%	100%	100%	-157%	14%	57%	79%
Savings in MFA	%-saved	-16%	39%	39%	-49%	17%	33%	42%
Abiotic depletion potential for fossil fuels	%-saved	4%	37%	52%	-43%	52%	76%	88%
Abiotic depletion potential for elements	%-saved	-10%	27%	45%	-65%	45%	72%	86%
Acidification potential	%-saved	-17%	22%	41%	-76%	41%	71%	85%
Eutrophication potential	%-saved	-11%	27%	45%	-66%	45%	72%	86%
Fresh water aquatic ecotoxicity potential	%-saved	57%	71%	78%	35%	78%	89%	95%
Global warming potential	%-saved	19%	46%	60%	-21%	60%	80%	90%
Human toxicity potential	%-saved	70%	80%	85%	55%	85%	93%	96%
Marine aquatic ecotox-icity potential	%-saved	38%	59%	69%	7%	69%	85%	92%
Ozone layer depletion potential	%-saved	-39%	8%	31%	-108%	31%	65%	83%
Photochemical oxidation potential	%-saved	21%	47%	60%	-19%	60%	80%	90%
Terrestrial ecotoxicity potential	%-saved	-35%	11%	33%	-102%	33%	66%	83%
Savings in LCA (average on all cate-gories)	%-saved	9%	40%	54%	-37%	54%	77%	89%
Savings in LCA (GWP)	%-saved	19%	46%	60%	-21%	60%	80%	90%
Savings in LCA (Shadow costs)	%-saved	42%	62%	71%	13%	71%	86%	93%
Rank - average savings in LCA (all cat.) and MFA		**34**	**18**	**14**	**37**	**22**	**6**	**2**
Rank - average savings in LCA (GWP) and MFA		**33**	**16**	**12**	**37**	**20**	**7**	**2**
Rank - average savings in LCA (Shadow costs) and MFA		**32**	**12**	**8**	**36**	**16**	**4**	**2**

TABLE APP. C.26 Ranking of Reclaim! kitchen scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	Reclaim!						
		Baseline	C+1	C+2	L=7	L=20	L=40	L=80
Total import	%-saved	-100%	-100%	-100%	-200%	0%	50%	75%
Import virgin	%-saved	100%	100%	100%	100%	100%	100%	100%
Import non-renewable	%-saved	0%	0%	0%	0%	0%	0%	0%
Export reused, reman-ufact. or recycled	%-saved	0%	100%	100%	0%	0%	0%	0%
Material consumption	%-saved	-100%	100%	100%	-200%	0%	50%	75%
Savings in MFA	%-saved	-20%	40%	40%	-60%	20%	40%	50%
Abiotic depletion potential for fossil fuels	%-saved	14%	16%	24%	-30%	57%	78%	89%
Abiotic depletion potential for elements	%-saved	20%	21%	28%	-20%	60%	80%	90%
Acidification potential	%-saved	11%	13%	22%	-34%	55%	78%	89%
Eutrophication potential	%-saved	11%	14%	23%	-34%	55%	78%	89%
Fresh water aquatic ecotoxicity potential	%-saved	-13%	-2%	9%	-69%	44%	72%	86%
Global warming potential	%-saved	-1%	6%	18%	-51%	50%	75%	87%
Human toxicity potential	%-saved	-30%	-22%	-12%	-95%	35%	67%	84%
Marine aquatic ecotox-icity potential	%-saved	-1%	7%	17%	-51%	50%	75%	87%
Ozone layer depletion potential	%-saved	15%	16%	24%	-27%	58%	79%	89%
Photochemical oxidation potential	%-saved	7%	9%	18%	-39%	54%	77%	88%
Terrestrial ecotoxicity potential	%-saved	0%	4%	12%	-50%	50%	75%	87%
Savings in LCA (average on all cate-gories)	%-saved	3%	7%	17%	-46%	51%	76%	88%
Savings in LCA (GWP)	%-saved	-1%	6%	18%	-51%	50%	75%	87%
Savings in LCA (Shadow costs)	%-saved	-10%	-3%	7%	-65%	45%	72%	86%
Rank - average savings in LCA (all cat.) and MFA		**35**	**26**	**25**	**38**	**21**	**4**	**1**
Rank - average savings in LCA (GWP) and MFA		**35**	**26**	**25**	**38**	**24**	**6**	**1**
Rank - average savings in LCA (Shadow costs) and MFA		**35**	**28**	**25**	**38**	**24**	**6**	**1**

TABLE APP. C.27 Ranking of LIFE+ kitchen scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	LIFE+								
		Base-line	C+1	C+2	Lf=40-20-7-20	Lf=40-20-20-20	L= 7-7-7-7	L=20-10-7-10	L=80-40-20-40	L=80-80-80-80
Total import	%-saved	13%	13%	13%	-2%	28%	-192%	-59%	56%	76%
Import virgin	%-saved	-29%	-29%	-29%	-31%	-26%	-31%	-28%	-29%	-31%
Import non-renewable	%-saved	14%	14%	14%	22%	4%	7%	10%	14%	7%
Export reused, remanufact. or recycled	%-saved	0%	100%	100%	-1%	2%	0%	1%	0%	0%
Material consumption	%-saved	13%	100%	100%	-3%	29%	-191%	-58%	57%	76%
Savings in MFA	%-saved	2%	40%	40%	-3%	7%	-81%	-27%	20%	26%
Abiotic depletion potential for fossil fuels	%-saved	30%	51%	61%	24%	35%	-163%	-35%	65%	78%
Abiotic depletion potential for elements	%-saved	38%	56%	65%	28%	48%	-76%	-14%	69%	85%
Acidification potential	%-saved	22%	45%	56%	15%	29%	-184%	-49%	61%	76%
Eutrophication potential	%-saved	20%	44%	55%	12%	28%	-194%	-52%	60%	76%
Fresh water aquatic eco-toxicity potential	%-saved	29%	47%	55%	26%	32%	-150%	-38%	65%	79%
Global warming potential	%-saved	27%	48%	58%	22%	32%	-167%	-40%	64%	78%
Human toxicity potential	%-saved	17%	32%	39%	15%	19%	-169%	-64%	58%	78%
Marine aquatic ecotoxicity potential	%-saved	31%	50%	59%	27%	36%	-150%	-33%	66%	79%
Ozone layer depletion potential	%-saved	23%	47%	59%	15%	31%	-185%	-46%	61%	76%
Photochemical oxidation potential	%-saved	20%	43%	53%	15%	26%	-198%	-54%	60%	75%
Terrestrial ecotoxicity potential	%-saved	8%	33%	44%	-3%	19%	-204%	-73%	54%	75%
Savings in LCA (average on all categories)	%-saved	24%	45%	55%	18%	30%	-167%	-45%	62%	78%
Savings in LCA (GWP)	%-saved	27%	48%	58%	22%	32%	-167%	-40%	64%	78%
Savings in LCA (Shadow costs)	%-saved	25%	43%	51%	21%	29%	-163%	-47%	62%	78%
Rank - average savings in LCA (all cat.) and MFA		**30**	**15**	**13**	**32**	**28**	**39**	**36**	**17**	**10**
Rank - average savings in LCA (GWP) and MFA		**31**	**15**	**13**	**32**	**28**	**40**	**36**	**19**	**11**
Rank - average savings in LCA (Shadow costs) and MFA		**31**	**17**	**15**	**33**	**29**	**40**	**37**	**18**	**11**

TABLE APP. C.28 Ranking of P&P kitchen scenarios varying number of use cycles based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	P&P					
		Baseline	C-3	C-2	C-1	C+1	C+2
Total import	%-saved	24%	24%	24%	24%	24%	24%
Import virgin	%-saved	11%	-43%	-3%	11%	11%	11%
Import non-renewable	%-saved	19%	19%	19%	19%	19%	19%
Export reused, remanu-fact. or recycled	%-saved	91%	-3%	27%	63%	100%	100%
Material consumption	%-saved	93%	21%	44%	72%	100%	100%
Savings in MFA	%-saved	48%	3%	22%	38%	51%	51%
Abiotic depletion potential for fossil fuels	%-saved	56%	30%	49%	56%	64%	70%
Abiotic depletion potential for elements	%-saved	37%	75%	81%	83%	47%	54%
Acidification potential	%-saved	50%	19%	40%	50%	59%	65%
Eutrophication potential	%-saved	53%	26%	45%	54%	61%	66%
Fresh water aquatic ecotoxicity potential	%-saved	55%	54%	62%	66%	62%	67%
Global warming potential	%-saved	57%	36%	52%	58%	65%	70%
Human toxicity potential	%-saved	50%	46%	53%	55%	57%	61%
Marine aquatic ecotox-icity potential	%-saved	55%	50%	61%	66%	63%	68%
Ozone layer depletion potential	%-saved	48%	10%	35%	45%	57%	64%
Photochemical oxidation potential	%-saved	50%	18%	39%	49%	59%	64%
Terrestrial ecotoxicity potential	%-saved	43%	28%	45%	52%	52%	58%
Savings in LCA (average on all cate-gories)	%-saved	50%	36%	51%	58%	59%	64%
Savings in LCA (GWP)	%-saved	57%	36%	52%	58%	65%	70%
Savings in LCA (Shadow costs)	%-saved	53%	44%	55%	60%	61%	66%
Rank - average savings in LCA (all cat.) and MFA		**11**	**27**	**20**	**12**	**7**	**5**
Rank - average savings in LCA (GWP) and MFA		**10**	**30**	**21**	**14**	**5**	**4**
Rank - average savings in LCA (Shadow costs) and MFA		**13**	**26**	**21**	**14**	**7**	**5**

TABLE APP. C.29 Ranking of P&P kitchen scenarios varying technical and functional lifespans based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	P&P					
		Lf=80-40-7-40, Lt=80-40-40-40	Lf=80-40-40-40, Lt=80-40-40-40	Lt=7-7-7-7, Lf=7-7-3, 5-7	Lt=20-20-20-20, Lf=20-20-10-20	Lt=40-20-20-20, Lf=40-20-10-20	Lt=80-80-80-80, Lf=80-80-40-80
Total import	%-saved	-62%	45%	-375%	-58%	-53%	60%
Import virgin	%-saved	39%	-24%	9%	9%	11%	-5%
Import non-renewable	%-saved	22%	17%	21%	21%	19%	21%
Export reused, remanufact. or recycled	%-saved	94%	88%	92%	92%	91%	92%
Material consumption	%-saved	90%	93%	60%	87%	87%	97%
Savings in MFA	%-saved	37%	44%	-39%	30%	31%	53%
Abiotic depletion potential for fossil fuels	%-saved	46%	67%	-173%	9%	13%	77%
Abiotic depletion potential for elements	%-saved	14%	52%	-313%	-38%	-26%	65%
Acidification potential	%-saved	39%	61%	-216%	-5%	0%	73%
Eutrophication potential	%-saved	41%	63%	-201%	0%	5%	74%
Fresh water aquatic eco-toxicity potential	%-saved	45%	63%	-188%	4%	10%	76%
Global warming potential	%-saved	47%	66%	-171%	10%	14%	77%
Human toxicity potential	%-saved	44%	55%	-223%	-8%	0%	73%
Marine aquatic ecotoxicity potential	%-saved	44%	64%	-186%	5%	11%	76%
Ozone layer depletion potential	%-saved	35%	60%	-229%	-10%	-4%	72%
Photochemical oxidation potential	%-saved	40%	61%	-214%	-5%	1%	73%
Terrestrial ecotoxicity potential	%-saved	30%	54%	-265%	-22%	-14%	69%
Savings in LCA (average on all categories)	%-saved	39%	61%	-216%	-5%	1%	73%
Savings in LCA (GWP)	%-saved	47%	66%	-171%	10%	14%	77%
Savings in LCA (Shadow costs)	%-saved	44%	61%	-198%	1%	7%	75%
Rank - average savings in LCA (all cat.) and MFA		**19**	**9**	**40**	**31**	**29**	**3**
Rank - average savings in LCA (GWP) and MFA		**18**	**8**	**39**	**29**	**27**	**3**
Rank - average savings in LCA (Shadow costs) and MFA		**19**	**10**	**39**	**30**	**27**	**3**

TABLE APP. C.30 Ranking of BAU façade scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	BAU					
		Baseline	C+1	C+2	L15	L45	L90
Total import	%-saved	0%	0%	0%	-100%	33%	67%
Import virgin	%-saved	0%	0%	0%	0%	0%	0%
Import non-renewable	%-saved	0%	0%	0%	0%	0%	0%
Export reused, reman-ufact. or recycled	%-saved	0%	100%	100%	0%	0%	0%
Material consumption	%-saved	0%	100%	100%	-100%	33%	67%
Savings in MFA	%-saved	0%	40%	40%	-40%	13%	27%
Abiotic depletion potential for elements	%-saved	0%	31%	46%	-38%	54%	77%
Abiotic depletion potential for fossil fuels	%-saved	0%	33%	49%	-35%	55%	78%
Acidification potential	%-saved	0%	31%	46%	-38%	54%	77%
Eutrophication potential	%-saved	0%	30%	45%	-39%	54%	77%
Fresh water aquatic ecotoxicity potential	%-saved	0%	33%	48%	-35%	55%	78%
Global warming potential	%-saved	0%	31%	47%	-37%	54%	77%
Human toxicity potential	%-saved	0%	32%	47%	-37%	54%	77%
Marine aquatic ecotox-icity potential	%-saved	0%	33%	49%	-34%	55%	78%
Ozone layer depletion potential	%-saved	0%	30%	44%	-40%	53%	77%
Photochemical oxidation potential	%-saved	0%	32%	47%	-36%	55%	77%
Terrestrial ecotoxicity potential	%-saved	0%	29%	43%	-41%	53%	76%
Savings in LCA (average on all cate-gories)	%-saved	0%	31%	47%	-37%	54%	77%
Savings in LCA (GWP)	%-saved	0%	31%	47%	-37%	54%	77%
Savings in LCA (Shadow costs)	%-saved	0%	32%	48%	-35%	55%	77%
Rank - average savings in LCA (all cat.) and MFA		**16**	**8**	**6**	**23**	**9**	**2**
Rank - average savings in LCA (GWP) and MFA		**34**	**25**	**24**	**36**	**26**	**15**
Rank - average savings in LCA (Shadow costs) and MFA		**22**	**14**	**9**	**29**	**15**	**8**

TABLE APP. C.31 Ranking of BIO façade scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	BIO					
		Baseline	C+1	C+2	L15	L45	L90
Total import	%-saved	-86%	-86%	-86%	-250%	-31%	24%
Import virgin	%-saved	0%	0%	0%	0%	0%	0%
Import non-renewable	%-saved	100%	100%	100%	100%	100%	100%
Export reused, reman-ufact. or recycled	%-saved	-78%	100%	100%	-78%	-78%	-78%
Material consumption	%-saved	-230%	100%	100%	-522%	-133%	-35%
Savings in MFA	%-saved	-59%	43%	43%	-150%	-28%	2%
Abiotic depletion potential for elements	%-saved	-600%	-381%	-281%	-1203%	-400%	-199%
Abiotic depletion potential for fossil fuels	%-saved	79%	85%	88%	59%	86%	93%
Acidification potential	%-saved	22%	47%	59%	-54%	47%	72%
Eutrophication potential	%-saved	-442%	-262%	-175%	-978%	-263%	-84%
Fresh water aquatic ecotoxicity potential	%-saved	61%	73%	79%	23%	73%	86%
Global warming potential	%-saved	68%	78%	83%	36%	78%	88%
Human toxicity potential	%-saved	56%	70%	76%	15%	70%	84%
Marine aquatic ecotox-icity potential	%-saved	76%	84%	87%	54%	84%	92%
Ozone layer depletion potential	%-saved	13%	39%	51%	-70%	41%	69%
Photochemical oxidation potential	%-saved	16%	43%	57%	-67%	43%	71%
Terrestrial ecotoxicity potential	%-saved	-138%	-67%	-36%	-332%	-73%	-8%
Savings in LCA (average on all cate-gories)	%-saved	-72%	-17%	8%	-229%	-19%	33%
Savings in LCA (GWP)	%-saved	68%	78%	83%	36%	78%	88%
Savings in LCA (Shadow costs)	%-saved	57%	70%	77%	15%	71%	85%
Rank - average savings in LCA (all cat.) and MFA		**26**	**14**	**10**	**34**	**21**	**13**
Rank - average savings in LCA (GWP) and MFA		**33**	**10**	**7**	**37**	**29**	**21**
Rank - average savings in LCA (Shadow costs) and MFA		**24**	**5**	**2**	**34**	**18**	**10**

TABLE APP. C.32 Ranking of Reclaim! façade scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	Reclaim!					
		Baseline	C+1	C+2	L15	L45	L90
Total import	%-saved	-132%	-132%	-132%	-364%	-55%	23%
Import virgin	%-saved	100%	100%	100%	100%	100%	100%
Import non-renewable	%-saved	94%	94%	94%	94%	94%	94%
Export reused, remanufact. or recycled	%-saved	63%	100%	100%	63%	63%	63%
Material consumption	%-saved	13%	100%	100%	-73%	42%	71%
Savings in MFA	%-saved	28%	52%	52%	-36%	49%	70%
Abiotic depletion potential for elements	%-saved	20%	30%	38%	-59%	47%	73%
Abiotic depletion potential for fossil fuels	%-saved	72%	77%	79%	44%	81%	91%
Acidification potential	%-saved	24%	35%	42%	-51%	50%	75%
Eutrophication potential	%-saved	4%	17%	27%	-91%	36%	68%
Fresh water aquatic ecotoxicity potential	%-saved	43%	49%	55%	-14%	62%	81%
Global warming potential	%-saved	66%	71%	74%	31%	77%	89%
Human toxicity potential	%-saved	21%	31%	39%	-58%	47%	74%
Marine aquatic ecotoxicity potential	%-saved	49%	53%	58%	-1%	66%	83%
Ozone layer depletion potential	%-saved	-11%	1%	13%	-122%	26%	63%
Photochemical oxidation potential	%-saved	21%	31%	39%	-59%	47%	74%
Terrestrial ecotoxicity potential	%-saved	-70%	-54%	-37%	-239%	-13%	43%
Savings in LCA (average on all categories)	%-saved	22%	31%	39%	-56%	48%	74%
Savings in LCA (GWP)	%-saved	22%	31%	39%	-56%	48%	74%
Savings in LCA (Shadow costs)	%-saved	17%	27%	35%	-65%	45%	72%
Rank - average savings in LCA (all cat.) and MFA		**11**	**7**	**4**	**25**	**3**	**1**
Rank - average savings in LCA (GWP) and MFA		**20**	**9**	**4**	**35**	**6**	**1**
Rank - average savings in LCA (Shadow costs) and MFA		**13**	**7**	**6**	**26**	**4**	**1**

TABLE APP. C.33 Ranking of P2P façade scenarios based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	P2P							
		Baseline	C-2	C-1	C+1	C+2	L15	L45	L90
Total import	%-saved	-23%	-23%	-23%	-23%	-23%	-146%	18%	59%
Import virgin	%-saved	67%	19%	67%	67%	67%	67%	67%	67%
Import non-renewable	%-saved	0%	0%	0%	0%	0%	0%	0%	0%
Export reused, reman-ufact. or recycled	%-saved	100%	92%	100%	100%	100%	100%	100%	100%
Material consumption	%-saved	100%	90%	100%	100%	100%	100%	100%	100%
Savings in MFA	%-saved	49%	36%	49%	49%	49%	24%	57%	65%
Abiotic depletion potential for fossil fuels	%-saved	-2400%	-4218%	-2752%	-2392%	-2081%	-4900%	-1859%	-1026%
Abiotic depletion potential for elements	%-saved	54%	32%	49%	58%	62%	8%	64%	80%
Acidification potential	%-saved	18%	-40%	7%	22%	30%	-64%	34%	62%
Eutrophication potential	%-saved	-23%	-98%	-37%	-19%	-6%	-147%	4%	45%
Fresh water aquatic ecotoxicity potential	%-saved	-2102%	-2148%	-2111%	-2095%	-1787%	-4305%	-1377%	-643%
Global warming potential	%-saved	45%	18%	40%	50%	55%	-9%	59%	77%
Human toxicity potential	%-saved	-71%	-132%	-82%	-61%	-47%	-242%	-27%	30%
Marine aquatic ecotox-icity potential	%-saved	-115%	-158%	-123%	-108%	-85%	-331%	-53%	19%
Ozone layer depletion potential	%-saved	-4%	-80%	-14%	3%	13%	-108%	15%	50%
Photochemical oxidation potential	%-saved	29%	-18%	20%	33%	39%	-42%	44%	68%
Terrestrial ecotoxicity potential	%-saved	-131%	-254%	-152%	-121%	-99%	-361%	-77%	0%
Savings in LCA (average on all cate-gories)	%-saved	-427%	-645%	-469%	-421%	-355%	-955%	-288%	-113%
Savings in LCA (GWP)	%-saved	45%	18%	40%	50%	55%	-9%	59%	77%
Savings in LCA (Shadow costs)	%-saved	-143%	-186%	-151%	-136%	-108%	-386%	-71%	10%
Rank - average savings in LCA (all cat.) and MFA		**33**	**36**	**35**	**32**	**30**	**37**	**29**	**20**
Rank - average savings in LCA (GWP) and MFA		**19**	**28**	**22**	**17**	**16**	**31**	**11**	**3**
Rank - average savings in LCA (Shadow costs) and MFA		**32**	**35**	**33**	**31**	**28**	**37**	**25**	**12**

TABLE APP. C.34 Ranking of P&P façade scenarios varying number of use cycles based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category		P&P				
		Baseline	C-2	C-1	C+1	C+2
Total import	%-saved	-116%	-116%	-116%	-116%	-116%
Import virgin	%-saved	70%	70%	70%	70%	70%
Import non-renewable	%-saved	60%	57%	60%	60%	60%
Export reused, reman-ufact. or recycled	%-saved	89%	45%	76%	100%	100%
Material consumption	%-saved	76%	-19%	48%	100%	100%
Savings in MFA	%-saved	36%	8%	27%	43%	43%
Abiotic depletion potential for elements	%-saved	-417%	-471%	-423%	-356%	-343%
Abiotic depletion potential for fossil fuels	%-saved	70%	65%	69%	73%	76%
Acidification potential	%-saved	42%	33%	40%	47%	52%
Eutrophication potential	%-saved	-25%	-53%	-31%	-13%	-3%
Fresh water aquatic ecotoxicity potential	%-saved	-520%	-604%	-529%	-442%	-433%
Global warming potential	%-saved	61%	56%	60%	65%	68%
Human toxicity potential	%-saved	-103%	-138%	-113%	-86%	-71%
Marine aquatic ecotox-icity potential	%-saved	-8%	-68%	-18%	3%	10%
Ozone layer depletion potential	%-saved	-46%	-82%	-49%	-31%	-18%
Photochemical oxidation potential	%-saved	29%	14%	25%	36%	41%
Terrestrial ecotoxicity potential	%-saved	-205%	-305%	-222%	-178%	-151%
Savings in LCA (average on all cate-gories)	%-saved	-102%	-141%	-108%	-80%	-70%
Savings in LCA (GWP)	%-saved	61%	56%	60%	65%	68%
Savings in LCA (Shadow costs)	%-saved	-21%	-64%	-29%	-9%	-2%
Rank - average savings in LCA (all cat.) and MFA		**22**	**27**	**24**	**19**	**18**
Rank - average savings in LCA (GWP) and MFA		**18**	**27**	**23**	**14**	**13**
Rank - average savings in LCA (Shadow costs) and MFA		**21**	**27**	**23**	**20**	**19**

TABLE APP. C.35 Ranking of P&P façade scenarios varying technical and functional lifespans based on the percentual savings in the LCA and MFA to the BAU (baseline scenario)

Category	Unit	P&P					
		L=15	L=45	L=90	Lf=15	Lf=45	Lf=90
Total import	%-saved	-332%	-44%	28%	-331%	-44%	27%
Import virgin	%-saved	70%	70%	70%	70%	43%	11%
Import non-renewable	%-saved	60%	60%	60%	60%	60%	59%
Export reused, reman-ufact. or recycled	%-saved	89%	89%	89%	100%	83%	67%
Material consumption	%-saved	52%	84%	92%	100%	76%	76%
Savings in MFA	%-saved	-12%	52%	68%	0%	43%	48%
Abiotic depletion potential for elements	%-saved	-935%	-256%	-88%	-669%	-285%	-126%
Abiotic depletion potential for fossil fuels	%-saved	40%	78%	88%	57%	75%	83%
Acidification potential	%-saved	-16%	58%	76%	15%	52%	67%
Eutrophication potential	%-saved	-150%	9%	49%	-82%	-4%	27%
Fresh water aquatic ecotoxicity potential	%-saved	-1139%	-322%	-118%	-814%	-354%	-161%
Global warming potential	%-saved	23%	72%	84%	44%	68%	78%
Human toxicity potential	%-saved	-305%	-53%	3%	-228%	-64%	-16%
Marine aquatic ecotox-icity potential	%-saved	-116%	21%	56%	-58%	9%	33%
Ozone layer depletion potential	%-saved	-192%	-6%	41%	-104%	-20%	15%
Photochemical oxidation potential	%-saved	-42%	47%	69%	-4%	40%	57%
Terrestrial ecotoxicity potential	%-saved	-510%	-127%	-32%	-355%	-160%	-91%
Savings in LCA (average on all cate-gories)	%-saved	-304%	-44%	21%	-200%	-58%	-3%
Savings in LCA (GWP)	%-saved	23%	72%	84%	44%	68%	78%
Savings in LCA (Shadow costs)	%-saved	-142%	12%	50%	-81%	2%	31%
Rank - average savings in LCA (all cat.) and MFA		**31**	**15**	**5**	**28**	**17**	**12**
Rank - average savings in LCA (GWP) and MFA		**32**	**8**	**2**	**30**	**12**	**5**
Rank - average savings in LCA (Shadow costs) and MFA		**36**	**16**	**3**	**30**	**17**	**11**

APP. C.13 Analysis percentual savings circular design options in assessment results

TABLE APP. C.36 Analysis percentual savings of applied circular design options in assessment results

		Adding 1 reuse cycle for virgin material			Adding 2 reuse cycles for virgin material			Adding 1 reuse cycle for non-virgin material			Adding 2 reuse cycles for non-virgin material		
		[% reduction]			[% reduction]			[% reduction]			[% reduction]		
		Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.
MFA	**Total import**	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%
	% Virgin	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%
	% Non-renewable	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%	0%	**0%**	0%
	% Biodegr., recov., disc.	100%	**100%**	100%	100%	**100%**	100%	100%	**100%**	100%	100%	**100%**	100%
	Material consumption	100%	**100%**	100%	100%	**100%**	100%	100%	**100%**	100%	100%	**100%**	100%
LCA	**Aver. all imp. categories**	28%	**31%**	34%	41%	**45%**	50%	4%	**8%**	12%	14%	**18%**	22%
	GWP	29%	**31%**	34%	42%	**46%**	50%	7%	**11%**	14%	19%	**21%**	24%
	Shadow costs	24%	**30%**	34%	36%	**44%**	50%	7%	**8%**	10%	16%	**18%**	20%
	number of underlying comparisons	5			5			2			2		
	Underlying comparisons	(1,2,3) CIK - BAU-BIO-LIFE+ - C+1 to baseline (4,5) Facade - BAU-BIO - C+1 to baseline			(1,2,3) CIK - BAU-BIO-LIFE+ - C+2 to baseline (4,5) Facade - BAU-BIO - C+2 to baseline			(1) CIK - Reclaim! - C+1 to baseline (2) Facade - Reclaim! - C+1 to baseline			(1) CIK - Reclaim! - C+2 to baseline (2) Facade - Reclaim! - C+2 to baseline		

TABLE APP. C.37 (Continued) Analysis percentual savings of applied circular design options in assessment results

		Substituting with bio-based material			Substituting with non-virgin material			Increasing Lt-Lf in parallel (i.e., 2x)			Incr. Lf (i.e, 2x)		
		[% reduction]			[% reduction]			[% reduction]			[% reduction]		
		Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.
MFA	**Total import**	-86%	**-33%**	20%	-132%	**-66%**	0%	42%	**49%**	50%	28%	**39%**	50%
	% Virgin	-43%	**-22%**	0%	100%	**100%**	100%	0%	**0%**	0%	-55%	**-47%**	-39%
	% Non-renewable	100%	**100%**	100%	0%	**47%**	94%	0%	**1%**	14%	-3%	**-2%**	-1%
	% Biodegr., recov., disc.	-78%	**-42%**	-7%	0%	**31%**	63%	0%	**0%**	0%	-98%	**-68%**	-39%
	Material consumption	-230%	**-108%**	14%	0%	**7%**	13%	0%	**44%**	50%	0%	**0%**	0%
LCA	**Aver. all imp. categories**	-72%	**-9%**	54%	22%	**37%**	51%	44%	**48%**	50%	20%	**26%**	31%
	GWP	60%	**64%**	68%	50%	**58%**	66%	43%	**48%**	50%	22%	**26%**	31%
	Shadow costs	57%	**64%**	71%	45%	**46%**	47%	30%	**48%**	50%	17%	**47%**	77%
	number of underlying comparisons	2			2			10			2		
	Underlying comparisons	(1) CIK- BIO - L20 to BAU - baseline (2) Fac. BIO - baseline to BAU - baseline			(1) CIK- Reclaim! - L20 to BAU - baseline (2) Fac. Reclaim! - baseline to BAU - baseline			(1) CIK - BAU - L40 to baseline; (2,3) CIK - BIO & Reclaim! - L20 to baseline; (4) CIK - LIFE+- L80-40-20-40 to baseline; (5) CIK - P&P - Baseline to L40-20-10-20; (6,7,8, 9,10) Fac. - BAU-BIO-Reclaim!-P2P-P&P - L90 to L45			(1) CIK - P&P - Lf=80-40-40-40 to Lf=80-40-20-40; (2) Fac. P&P Lf90 to Lf45		

APP. C.14 Effect of circular design options on the CE-LCIA and MFA parameters

In this appendix, we analyze how different circular design options influenced each parameter in the kitchen and façade assessments. We analyzed the effect of 5 circular design options: (1) applying bio-based and biodegradable materials, (2) applying non-virgin materials, (3) realizing multiple use cycles of parts and materials after use in the building component, (4) prolonging the technical and functional lifespan of the building component, its parts and materials in parallel and (5) increasing the functional lifespan of parts. We refer to Appendix C.1 for an explanation of all the CE-LCIA and MFA equations and parameters.

Our analysis of the effect of the applied circular design options on the MFA and CE-LCA parameters in the kitchen and façades assessments is summarized in Table App.C.38.

TABLE APP. C.38 Effect circular design options on MFA and CE-LCIA parameters

Circular design option	Influenced parameters	Case		Effect circular design option on parameter in kitchen and façade assessments
Applying bio-based, biodegradable materials	$\frac{AI_x}{unit}$	BIO kitchen	↓	Lower impact/unit compared to non-renewable materials (e.g., uncoated laminated timber boards)
		BIO façade	↑↓	Shift of burdens between impact categories.
	$M_{mat., x}$	BIO kitchen	–	Mass of renewable materials per kitchen remained comparable to the non-renewable material in BAU.
		BIO façade	↑	More renewable materials were required compared to non-renewable materials to fulfil the same function (e.g., insulation and structural materials).
	$r\ renew._{mat., x}$	BIO kitchen and façade	↑	Percentage of renewable materials increased.
	$r\ biodegr._{mat., x}$	BIO kitchen and façade	↑	Percentage of biodegraded materials increased.
	R	BIO kitchen	↑	Doubling of replacement rate due to lower assumed technical lifespan renewable material
		BIO façade	–	Similar replacement rate façade (30 years) compared to façade of non-renewable material.
Applying non-virgin, materials	$\frac{AI_x}{unit}$	Reclaim! façade	↓	Alternative non-virgin material is applied with lower impact/unit compared to virgin materials (e.g., recycled paper wool insulation)
	Af	Reclaim! kitchen	↓	Material in second use cycle has a lower share of impacts allocated to the use cycle of the building component.
	AI	Reclaim! kitchen	↑	Reuse processes for the non-virgin materials result in additional transport related impacts.
		Reclaim! façade	↑	Reuse and/or recycling processes for the non-virgin materials result in additional transport and process related impacts.
	$M_{mat., x}$	Reclaim! kitchen	–	Mass of non-virgin materials per kitchen remained comparable to the mass of virgin material in BAU.
		Reclaim! façade	↑	More non-virgin materials were needed than virgin materials to fulfil the same function (e.g., for non-virgin insulation a reduced insulation value needs to be used in calculations; more material is required to have the same insulation value).
	$r\ non-vrigin._{mat., x}$	Reclaim! kitchen and façade	↑	Percentage of non-virgin materials increased.
	R	Reclaim! kitchen	↑	Doubling of replacement kitchen rate due to lower assumed technical lifespan non-virgin material
		Reclaim! façade	–	Similar replacement rate façade (30 years) compared to façade of virgin material.

>>>

TOC

TABLE APP. C.38 Effect circular design options on MFA and CE-LCIA parameters

Circular design option	Influenced parameters	Case	Effect circular design option on parameter in kitchen and façade assessments	
Increasing technical and function lifespan in parallel	R	All kitchens and façades	↓	A higher technical and functional lifespan of a component, parts and materials reduced the number of replacements of materials over the RSP.
Increasing functional lifespan	R	LIFE+ kitchen, P&P kitchen and façade	↓	A higher functional lifespan reduced the number of material replacements over the RSP (e.g., finishing parts).
	Af	P&P kitchen and façade	↑	A higher functional lifespan reduced the number of reuse cycles which reduced the total number of cycles; this increased the share of impacts allocated to the use cycle of the kitchen or façade (e.g., finishing parts).
Increasing number of cycles in material life cycle	Af	All kitchen and façade variants	↓	More use cycles reduce the share of impacts allocated to the use cycle of the building component.
	AI	All kitchen and façade variants	–	Low impact, direct reuse cycles result in low (or no) additional transport- and process-related impacts.
		Reclaim!, P2P, P&P façade and P&P kitchen,	↑	High-impact recycling cycles result in high additional transport- and process-related impacts.
	$r\ reuse_{mat.,x}$	All kitchen and façade variants	↑	For reuse cycles, the percentage of reused material flows increases 100%.

APP. C.15 List of lessons learned on environmental design of circular building components

TABLE APP. C.39 List of lessons learned on environmental design of circular building components

1.	**Consider not only the present placement and maintenance, but consider all future cycles.** During design, do not only consider the initial placement of the building component in the project. Also consider (re)placements in the future and consider what happens after the component, parts and materials leave the building.
2.	**Consider building components as a composite of parts and materials with different and multiple use cycles.** Determine the expected lifespan, usecycle(s), and value retention processes (VRPs) for each material and part applied in the building component.
3.	**Combine circular design options to facilitate multiple Value Retention Processes as opposed to focussing on a single one.** Environmental performance often improves most by combining circular design options to narrow, slow and close cycles simultaneously, instead of focusing on one.
4.	**(Re)design the technical, industrial and business model integrally and in co-creation with involved stakeholders.** The environmental performance of building components is dependent on the ability to design, determine, guarantee and realise multiple cycles.
5.	**Consider all circular design parameters in interrelation with each other.** Trade-offs and changes in assumptions can cause tipping points. Applying circular design options could also result in higher environmental impacts and resource use. For example, merely substituting linear materials with more circular materials (e.g., biological, low-impact, reused or recycled) does not necessarily result in a more circular building component.
6.	**Prioritize impacts from material production and recycling processes over transport.** Most of the environmental impacts are linked to material production and recycling: increasing transport to realise VRPs is preferable over placing a new building component. Unless the component is bulky or heavy, then, transport should be kept to a minimum.

>>>

TABLE APP. C.39 List of lessons learned on environmental design of circular building components

7.	**Components with a shorter service life benefit from prioritizing circular design options which slow and close future cycles, and components with a longer service life from reducing resources now and slowing loops on site.** • **For a circular building component with a short service life (e.g., circular kitchen) the better environmentally performing design could apply the following circular design options:** — The component is designed (as efficient as possible) modular, facilitating partial replacements such as technical repairs and functional and aesthetic updates to keep the whole building component in use longer; — The building component applies materials with long technical lifespans; — Multiple cycles are facilitated, organised and incentivised after EoU to prolong the period of use (e.g., repair, reuse, and refurbishment), and after EoL to close the loop (e.g., biodegrading, recycling); — Non-virgin materials, and/or bio-based, biodegradable materials are applied if they show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials. • **For a circular building component with a medium service life (e.g., circular façade) the better environmentally performing design could apply the following circular design options:** — Non-virgin materials, and/or bio-based, biodegradable materials are applied which show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials; — The building component applies materials with long technical lifespans; — If it can be done efficiently, the component is designed modular, facilitating partial replacement such as technical repairs and functional and aesthetic updates to keep the whole building component in use longer; — Multiple cycles are facilitated, organised and incentivised after EoU to prolong the period of use (e.g., repair, reuse, and refurbishment), and after EoL to close the loop (e.g., biodegrading, recycling);
8.	**If future cycles cannot be organised in the supply chain and incentivised in the business model, then the best environmentally performing design for a circular building component with a short or medium service life (e.g., circular kitchen and façade) applies the following circular design options:** — The building component is an efficient, lightweight solution; — The building component is kept in use as long as possible; — Non-virgin materials, and/or bio-based, biodegradable materials are applied if they show a favourable balance between environmental impacts/kg, technical lifespan, and quantity needed compared to virgin, non-renewable materials; — The building component applies materials which are open-loop biodegradable or recyclable.

APP. D Appendix Chapter 7

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

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

Author & Year	Goal of study	Methods	Results	Level	Context	Focal topics
(Adams et al., 2017)	Analyse the circular economy awareness, challenges and enablers in the construction industry	Survey and workshop	Awareness, barriers and enablers	Construction industry	UK	
(Akinade et al., 2020)	Identify barriers and improvement strategies for DfD in UK construction industry	Literature review + 6 focus groups with different industry stakeholders	Barriers	Construction industry	UK	Design for Disassembly
(Azcarate-Aguerre et al., 2022)	Analyse technical implementation challenges for façade industry to adopt performance-based contracts; propose a multi-stakeholder systematic model for development and application of façade technology capable of overcoming the barriers for performance-based contracts for integrated façades	Targeted literature review, and research through design by reflection on pilot with stakeholder involvement	Barriers, model	Façade	NL	Focus on façade servitisation

>>>

TOC

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

Author & Year	Goal of study	Methods	Results	Level	Context	Focal topics
(Azcarate-Aguerre et al., 2018)	Outline the main drivers and barriers to the commercial application of the Façade-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 of relevant stakeholders	Barriers and drivers	Façade	NL	Focus on façade servitisation
(Chang & Hsieh, 2019)	Identify status quo, barriers and enablers of CE in building industry and BIM applications in Taiwan	1 in-depth interview and 1 case-study analysis	Barriers and enablers	Construction industry	Taiwan	Circular design options and BIM; Technical, functional and organisational
(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 of multiple stakeholders	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)
(Condotta & Zatta, 2021)	Identify vacuum and inconsistencies in legal framework for reuse processes in architectural field	Literature review and interviews with multiple stakeholders	Barriers	Construction industry	EU	Regulation and legislation
(Cruz Rios et al., 2021)	Identify barriers and enablers for circular building design in US	13 interviews with architects	Barriers and enablers	Building design	US	N/A
(Galle et al., 2021)	Investigate how we can exploit the opportunities of the CE in construction to make the housing market more accessible?	Longitudinal case study of singular pilot	3 lessons learned	Building	Flanders (BE)	Scale and scalability, values, knowledge

>>>

TOC

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

Author & Year	Goal of study	Methods	Results	Level	Context	Focal topics
(Ghisellini et al., 2018)	Evaluate if the adoption of the CE framework is environmentally and economically sustainable, given that the recovery of waste materials requires investments of resources.	Literature review	Barriers, solutions and success factors	Construction industry	World	C&DW
(Giorgi et al., (2022)	Analyse level of application of circular strategies in building industry across 5 EU countries, identifying barriers and enablers	Interviews with different stakeholders in 5 countries	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
(Guerra & Leite, 2021)	Investigate US 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 US	Mixed-methods approach: online survey and interviews with multiple stakeholders	Awareness, challenges and enablers	Construction industry	US (multiple regions)	N/A
(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	Industry-wide practices and firm activities	Construction industry	LU, SE	EU policies and local practices
(Huang et al., 2018)	Analyse CD&W management by using the 3R principle	40 semi-structured interviews	Barriers and proposals to improve current situation	Building industry	CN	Construction & demolition waste; Legislation

>>>

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

Author & Year	Goal of study	Methods	Results	Level	Context	Focal topics
(Kanters, 2020)	Identify the barriers and drivers of the transformation towards a circular building sector	12 semi-structured interviews with architects and consultants that have engaged in circular building design	Barriers and drivers	Comments on all levels	NL, UK, DK, BE	N/A
(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	Barriers and enablers	Construction industry	DK	N/A
(Torgautov et al. 2021)	Identify the construction trends and perform a barrier and opportunity analysis to develop CE principles in the construction sector	PEST study and stakeholder interviews using semi-structured surveys	Awareness, barriers and opportunities	Construction industry	KZ	N/A

References

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Akinade, O., Oyedele, L., Oyedele, A., Davila Delgado, J. M., Bilal, M., Akanbi, L., … Owolabi, H. (2020). Design for deconstruction using a circular economy approach: barriers and strategies for improvement. *Production Planning and Control*, *31*(10), 829–840. https://doi.org/10.1080/09537287.2019.1695006

Azcarate-Aguerre, Juan F., Klein, T., Konstantinou, T., & Veerman, M. (2022). Façades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope. *Applied Sciences (Switzerland)*, *12*(3). https://doi.org/10.3390/app12031267

Azcarate-Aguerre, Juan Francisco, Klein, T., den Heijer, A., Vrijhoef, R., Ploeger, H., & Prins, M. (2018). Façade Leasing: Drivers and barriers to the delivery of integrated Façades-as-a-Service. *Real Estate Research Quarterly*, *17*(3), 11–22.

Chang, Y. T., & Hsieh, S. H. (2019). A Preliminary Case Study on Circular Economy in Taiwan's Construction. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012069

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production*, *285*, 124854. https://doi.org/10.1016/J.JCLEPRO.2020.124854

Condotta, M., & Zatta, E. (2021). Reuse of building elements in the architectural practice and the European regulatory context: Inconsistencies and possible improvements. *Journal of Cleaner Production*, *318*(January 2020), 128413. https://doi.org/10.1016/j.jclepro.2021.128413

Cruz Rios, F., Grau, D., & Bilec, M. (2021). Barriers and Enablers to Circular Building Design in the US: An Empirical Study. *Journal of Construction Engineering and Management*, *147*(10), 04021117. https://doi.org/10.1061/(asce)co.1943-7862.0002109

Galle, W., Debacker, W., De Weerdt, Y., Poppe, J., & De Temmerman, N. (2021). Can Circularity Make Housing Affordable Again? Preliminary Lessons About a Construction Experiment in Flanders Taking a Systems Perspective. *Smart Innovation, Systems and Technologies*, *203*, 151–160. https://doi.org/10.1007/978-981-15-8783-2_12

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five european countries policies and practices. *Journal of Cleaner Production*, *336*(January), 130395. https://doi.org/10.1016/j.jclepro.2022.130395

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/J.RESCONREC.2021.105617

Hjaltadóttir, R. E., & Hild, P. (2021). Circular Economy in the building industry European policy and local practices. *European Planning Studies*, *29*(12), 2226–2251. https://doi.org/10.1080/09654313.2021.1904838

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., & Ren, J. (2018). Construction and demolition waste management in China through the 3R principle. *Resources, Conservation and Recycling*, *129*(April 2017), 36–44. https://doi.org/10.1016/j.resconrec.2017.09.029

Kanters, J. (2020). Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector. *Buildings*, *10*(77), 1–16. https://doi.org/10.3390/buildings10040077

Selman, A. D., & Gade, A. N. (2020). Barriers of incorporating circular economy in building design in a Danish context. *ARCOM 2020 - Association of Researchers in Construction Management, 36th Annual Conference 2020 - Proceedings*, 665–674.

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, *11*(11). https://doi.org/10.3390/buildings11110501

APP. D.2

Barriers for the implementation of CE (design) options identified in literature

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

Feasibility category	##		Barriers	Total	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
Environmental	5		Potential environmental benefits of reuse are not certain	1								x									
			Building components are commonly downcycled	1								x									
			Not all materials can be effectively recycled	1								x									
			Circular design options have trade-offs between each other	1								x									
			Increased transport for VRPs can increase environmental burden	1						x											
Financial & economic	55	Initial costs & profit	Circular design options and materials require higher initial investment	5						x			x	x		x					x
			Additional time, labour and cost to design and construct circular design options	7		x				x		x			x	x			x		x
			Fragmented supply chain lead to misalignment incentives	4	x					x		x								x	
			Lack of financial incentive to design for slowing and closing loops	1	x																
			High availability of virgin material and low virgin material prices	4						x		x		x	x						
			Additional time and costs of non-virgin materials testing or recertification (due to lack of CE marking or certification)	4		x				x	x				x						

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Financial & economic	55	Initial costs & profit	Innovative circular design requires technical certification which takes long and is costly	1						x											
			Contract set-up and management costs	1				x													
			R&D investment for circular design options	2				x		x											
			Lower up-front profit for leased components	1				x													
			Costs of complying to legal frame-works of reuse and recycle	1										x							
			Cost of material storage	1						x											
			Initial costs are conditional above other aspects	1						x											
			Low landfill fees	1						x											
			Increased costs of circular tools	1						x											
			Increased cost for storage and transportation	1						x											
			Costs of careful disassembly are not outweighed by savings from reusing or reselling reclaimed materials	1											x						
			Linear processes like demolition, downcycling and disposal are less costly than demounting and circular VRPs	3						x					x			x			
			Increased cost and time in disassem-bly process due to lack of information on materials in existing stock	1							x										
		Life cycle costs	Low or uncertain end value of products and materials	3	x					x										x	
			Increased operational costs for CE service	1									x								
			Constructing with non-standard tech-niques increases insurance costs	1						x											

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Financial & economic	55	Life cycle costs	Increased costs for new roles/activities in process	1						x											
			Long lifespan of building pushes circular business models beyond the scope of current supply chain (lease is impossible)	1											x						
			Lease premiums might be too high in the beginning (as risks are overestimated)	1				x													
			Lease business model accessible only to clients with high cashflow	1				x													
			Stakeholders favour short-term profit	3						x		x								x	
		Risk	Lack of scale and scaling potential	1									x								
			Risk, doubts on safety and quality when applying non-virgin materials	6		x				x	x	x		x	x						
			Lacking certification or low performance guarantee for non-virgin materials	5		x					x				x			x		x	
			Modular buildings, DfD could compromise building resilience, durability and safety	3		x				x		x									
			Risk or unwillingness to pay for long term financial benefits of CE that may not occur (whilst up-front investment is needed now)	4		x				x			x							x	
			Lease business model leads to fragmented ownership of real-estate (is risky investment for banks)	2				x							x						
			High competitiveness of market inhibits circular innovations	1						x											
			Difficult to enter reclaimed materials into established markets dominated by industrial products	1						x											

>>>

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

Feasibility category	##		Barriers	Total	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
Financial & economic	55	Risk	Underdeveloped market salvaged components and reclaimed materials	3						x		x								x	
			Increased risk in process due to uncertainty in estimating time for disassembly and VRPs, causing scheduling issues	1						x											
			Less choice in manufacturers, contractors and suppliers (not everyone offers CE solutions)	1						x											
			Lack of alternative circular components and materials available on the market (e.g., bio-based materials)	3								x			x				x		
			Financing model sensitive to global material commodities market trends	1				x													
			Difficult to identify market for salvaged components and reclaimed materials	1											x						
			Market for prefabrication heavily dependant on import	1								x									
			Lack of application circular business models in practice (there are no examples)	1											x						
			Only examples of lease for short-life building components (e.g., furniture and heating)	1											x						
			Only examples of take-back schemes for valuable materials	1											x						
			Virgin resource-rich countries have less urgency to transition to CE	1											x						
			Lack of alignment between demand and supply (of non-virgin materials)	4						x			x					x	x		

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Financial & economic	55	Value proposition	Stakeholders financially favour narrowing resource and energy use over slowing and closing future cycles	1																x	
			Unclear or unviable financial and/or business case	6	x							x	x		x					x	x
			(Ultimately) unwillingness to pay for circular design options	1						x											
			Wait and see response of stakeholders who do not face an immediate need for a circular alternative or do not value its advantages	1									x								
			Lack of client demand for circular design options	3						x					x						x
			Recycled or reclaimed materials are not (significantly) cheaper than virgin materials	1						x											
			Difficulty to quantify the benefits of CE hinders sales	1						x											
			Lack of marketing plan or poor marketing for reclaimed materials	1						x											
Societal & cultural	14		Lack of interest in CE and circular design options	3						x		x		x							
			Poor perception of non-virgin materials and preference for virgin materials	4		x				x				x							x
			Rigid financial and corporate structure	1			x														
			Competitive fragmented supply chain	1								x									
			Conservative construction industry resistant to risk and change	6						x		x	x		x		x		x		
			Lack of CE leadership by designers	1								x									
			Uncertainty about future spatial needs	1								x									

>>>

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

Feasibility category	##	Barriers	Total	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
Societal & cultural	14	Modern consumerism culture (waste is considered as inevitable)	2						x										x	
		Users value authenticity and exclusivity which hinders CE	1																x	
		Customs of users and supply-chain partners	3						x			x							x	
		Building sector is linked to many different other sectors and practices inhibiting change	2									x						x		
		Focus on EoL solutions rather than preventive solutions (nobody wants to consume less)	1										x							
		Difficulty changing take-make-use industry (entire system and mindset needs to be changed)	3						x	x				x						
		Construction industry associates sustainability with durability	1						x											
Behavioural	10	Lack of trust in reclaimed material suppliers	1								x									
		Scepsis on future benefits of circular design options (e.g., reusing materials in future)	2						x		x									
		Habits of users and supply-chain partners and resistance to change	2						x										x	
		Luck of trust in quality, properties and durability of reclaimed materials	4						x	x			x	x						
		Pressure to get the project done	1						x											
		Trust in conventional construction materials	1						x											
		Lack of trust in innovative and non-conventional materials and designs	1						x											
		Lack of trust in accuracy of existing data on buildings	1						x											

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Behavioural	10		Lack of trust in the builders intentions (e.g., when using a circular material)	1						x											
			Lack of separate collection process for reclaimed materials negatively influences end-user perception	1							x										
Governmental & regulatory	37		Lack of ambiguous legislation and regulation for CE and circular design options	8		x					x	x		x	x	x			x	x	
			Limited subsidies or tax levies for circular building	2								x		x							
			Lack of taxes on virgin materials (e.g., environmental costs tax)	2							x				x						
			Policies ignore and/or do not discourage resource extraction and demand	2							x	x									
			Building product, construction and safety regulations could impair applying circular design options	2								x								x	
			Building and design codes favour virgin materials	1		x															
			Assessment methods do not credit circular design options sufficiently	2		x						x									
			Environmental performance assessment and certification is not commonly promoted in legislation nor applied	1											x						
			Lack of standardisation, grading systems and certification to establish quality, performance and technical characteristics of non-virgin materials	3		x						x			x						
			Insurance constraints and legal warranties of non-virgin materials	2		x						x									
			Industry standards need to change for circular building	1		x															

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Governmental & regulatory	37		New contracts are needed in CE business models	1			x														
			Data security and privacy issues in material passports	2				x												x	
			Policy focussed on recycling leads to downcycling	1								x									
			Anti-trust legislation impedes collaboration needed for circularity	1								x									
			Current policies favour linear economy models	2											x					x	
			Existing legislation favours ownership	1									x								
			Environmental costs and environmental value are not considered in policy	2										x	x						
			Difficult to hold stakeholders responsible over the long term	1						x											
			Lack of specific use requirements makes that reclaimed materials do not fulfil terms in End of Waste law, hindering reuse	1							x										
			Reclaimed materials not mentioned in the assessment procedures to obtain CE-marking	1							x										
			Unclear if reclaimed materials need to comply to legislation (e.g., CE marking or other certification processes)	2							x				x						
			Lack of CE marking inhibits reuse by increasing risk, costs and doubt on quality and safety	1							x										
			Construction Product Regulation legally prevents reclaimed material reuse in other function than original one	1							x										

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Governmental & regulatory	37		Regulatory inconsistencies increase construction time, process costs, performance assessment issues and negative end-user perception	1							x										
			Reusable components and materials are ‘first’ considered as waste in legislation, then requiring proof that they are not	1							x										
			End of Waste hinders reuse of material flows which do not yet have a developed market	1							x										
			Predemolition audits are not mandatory by law	1							x										
			Legislation focusses on avoiding landfilling	1											x						
			Lack of EU coordination in CE legislation	1											x						
			Ambiguous and lack of common definition of waste in legislation	1											x						
			Lack of detailed waste qualification codes inhibits separation of waste flows	1											x						
			Requirements to waste can be fulfilled by focussing on inert waste (lighter waste does not need to be considered to comply)	1											x						
			Legislation does not promote use of material passports or provide common framework and definitions	1											x						
			Difficult to obtain a permit for a modular and demountable building	1											x						
			BIM is only mandatory in public building processes	1											x						
			Fiscal barriers for buildings which have fragmented ownership (due to leasing components)	1											x						

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Technical	21		Complexity of buildings	2	x							x									
			Damage to materials during disassembly	3		x						x			x						
			Construction methods need to change	2		x				x											
			High complexity product requires technological integration which hinders circular design	1			x														
			Current buildings were not designed for disassembly, and composites hinder reuse	4							x	x			x					x	
			Non-virgin materials may contain hazardous materials or be contaminated	5		x				x	x	x								x	
			Uncertainty about lifespan and EoL	1								x									
			Industrialisation of bio-based materials hinders biodegradability	1								x									
			Over dimensioning is needed when using non-virgin materials	1								x									
			Lack of standardisation of building components	1								x									
			Lack of transportability of building components	1								x									
			Changing requirements inhibit reuse of components in future	1								x									
			Interface design between virgin and non-virgin materials and products differ	1								x									
			Large scale retail lowers costs, but leads to poor technical quality	1								x									
			Lack of sorting and processing technology for non-virgin materials	2								x						x			
			Fast-paced technology adds uncertainty of future reuse	1								x									

>>>

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

Feasibility category	##		Barriers	Total	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
Technical	21		Non-virgin and bio-based materials have less applications due to lower technical properties	2										x							x
			Recycling often requires additional virgin materials due to loss of material mass or quality (immature recycling technology)	2						x								x			
			New equipment or factories are needed to manufacture circular design	1						x											
			Limited site access and dimensions hinder disassembly and/or reuse	1						x											
			In existing components, the finishing has a short lifespan and cannot be easily separated causing premature obsolescence	1						x											
Functional & aesthetic	2		Perceived lack of aesthetics of non-virgin materials	3		x				x		x									
			Modular buildings, DfD compromises aesthetics	2		x				x											
Supply chain	11		Lack of reverse logistical mechanisms for recovery and VRPs	6	x	x	x					x			x						x
			Storage capacity needed for reuse of materials	4		x				x		x			x						
			Transport needed for VRPs	2		x						x									
			Development of new roles and processes required in supply chain	3				x		x					x						
			Lack of technology to assess non-virgin materials	1								x									
			Lack of processing plants & factories for VRPs	1						x											

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Supply chain	11		More collaboration needed between supply chain partners	3											x		x	x			
			A designated employee (per stake-holder) required which safeguards circularity throughout the process	1											x						
			Need for material passport specialist along the process	1											x						
			Circular supply-chain models not applied in practice	1											x						
			Temporary, project-wise building processes hinder finding synergies between supply chain partners	2											x						x
Information, skills & educational	33		Lack of awareness, consideration or concern of CE amongst stakeholders	5	x				x	x		x									x
			Lack of circular economy knowledge	3	x							x		x							
			Lack of concrete knowledge and proof of performance and benefits of circular design options	5						x		x		x	x	x					
			Lack of information about recover-able materials / material flows are not mapped	4		x					x				x						x
			Lack of disassembly information and cost-effective material separation methods	1		x															
			Lack of information exchange for non-virgin materials (e.g., cross-stakeholder material platforms)	2		x									x						
			Lack of information in design stage	1																x	
			Lack of CE assessment methods or CE consideration in existing tools	4		x						x							x	x	
			Existing CE tools are not BIM compliant	3		x			x			x									
			Data collection issues	1				x													

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Information, skills & educational	33		Lack of knowledge about which information needs to be stored and shared on circular components	1					X												
			Confusion between reuse and recycling	2							X	X									
			Lack of clear and common definitions on CE and circular design options	5						X		X			X		X			X	
			Lack of CE experience and skills by stakeholders	4				X				X			X					X	
			Lack of empirical knowledge on CE barriers	1								X									
			Lack of CE education in school curricula	1								X									
			Lack of lifecycle and long-term thinking	3						X		X			X						
			Lack of information about availability and quality of non-virgin materials	3							X	X		X							
			Lack of tools to identify and classify salvageable materials (e.g., during predemolition audit)	6		X				X	X	X			X					X	
			Lack of information on materials during refurbishment and demolition	4							X			X	X					X	
			Limited visualisation capability for CE strategy	2		X						X									
			Need to trace material over lifecycle and update information in material passport over time	2											X					X	
			Handling huge amount of data of materials passports	1																X	
			Harmonised, material passport technology needs to be developed	3							X				X					X	
			Use of BIM is not widespread	2											X					X	
			Lack of understanding of circular design options	3						X					X			X			

>>>

TOC

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

Feasibility category	##		Barriers	Total	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
Information, skills & educational	33		Lack of holistic and systems thinking	1						x											
			Lack of understanding of link between materials and health of indoor space (air quality)	1						x											
			Design approach needs to include circular design options and materials from the start	2						x	x										
			Lack of local, site-specific design and building approaches	2							x				x						
			Lack of structural information sharing between stakeholders over lifecycle (e.g., on available reclaimed materials)	1											x						
			Lack of urban-planning skills lead to premature obsolescence of buildings	1														x			
			Material platforms and passports only consider material quantity and location not environmental impacts	1											x						

References

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Akinade, O., Oyedele, L., Oyedele, A., Davila Delgado, J. M., Bilal, M., Akanbi, L., … Owolabi, H. (2020). Design for deconstruction using a circular economy approach: barriers and strategies for improvement. *Production Planning and Control*, *31*(10), 829–840. https://doi.org/10.1080/09537287.2019.1695006

Azcarate-Aguerre, Juan F., Klein, T., Konstantinou, T., & Veerman, M. (2022). Façades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope. *Applied Sciences (Switzerland)*, *12*(3). https://doi.org/10.3390/app12031267

Azcarate-Aguerre, Juan Francisco, Klein, T., den Heijer, A., Vrijhoef, R., Ploeger, H., & Prins, M. (2018). Façade Leasing: Drivers and barriers to the delivery of integrated Façades-as-a-Service. *Real Estate Research Quarterly*, *17*(3), 11–22.

Chang, Y. T., & Hsieh, S. H. (2019). A Preliminary Case Study on Circular Economy in Taiwan's Construction. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012069

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production*, *285*, 124854. https://doi.org/10.1016/J.JCLEPRO.2020.124854

Condotta, M., & Zatta, E. (2021). Reuse of building elements in the architectural practice and the European regulatory context: Inconsistencies and possible improvements. *Journal of Cleaner Production*, *318*(January 2020), 128413. https://doi.org/10.1016/j.jclepro.2021.128413

Cruz Rios, F., Grau, D., & Bilec, M. (2021). Barriers and Enablers to Circular Building Design in the US: An Empirical Study. *Journal of Construction Engineering and Management*, *147*(10), 04021117. https://doi.org/10.1061/(asce)co.1943-7862.0002109

Galle, W., Debacker, W., De Weerdt, Y., Poppe, J., & De Temmerman, N. (2021). Can Circularity Make Housing Affordable Again? Preliminary Lessons About a Construction Experiment in Flanders Taking a Systems Perspective. *Smart Innovation, Systems and Technologies*, *203*, 151–160. https://doi.org/10.1007/978-981-15-8783-2_12

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five european countries policies and practices. *Journal of Cleaner Production*, *336*(January), 130395. https://doi.org/10.1016/j.jclepro.2022.130395

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, *170*, 105617. https://doi.org/10.1016/J.RESCONREC.2021.105617

Hjaltadóttir, R. E., & Hild, P. (2021). Circular Economy in the building industry European policy and local practices. *European Planning Studies*, *29*(12), 2226–2251. https://doi.org/10.1080/09654313.2021.1904838

Huang, B., Wang, X., Kua, H., Geng, Y., Bleischwitz, R., & Ren, J. (2018). Construction and demolition waste management in China through the 3R principle. *Resources, Conservation and Recycling*, *129*(April 2017), 36–44. https://doi.org/10.1016/j.resconrec.2017.09.029

Kanters, J. (2020). Circular Building Design: An Analysis of Barriers and Drivers for a Circular Building Sector. *Buildings*, *10*(77), 1–16. https://doi.org/10.3390/buildings10040077

Selman, A. D., & Gade, A. N. (2020). Barriers of incorporating circular economy in building design in a Danish context. *ARCOM 2020 - Association of Researchers in Construction Management, 36th Annual Conference 2020 - Proceedings*, 665–674.

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, *11*(11). https://doi.org/10.3390/buildings11110501

APP. D.3 Summary of the development process of the circular kitchen and resulting designs

In this appendix we included the description of the development process of the circular kitchen (CIK) provided in Wouterszoon Jansen, van Stijn, Gruis and van Bortel (2022, Appendix C). Although this description is elaborate, it should not be understood as exhaustive. Wouterszoon Jansen et al. (2022) describe how the development took place, the type of choices made and show the resulting designs. For the sake of comparability between other cases, we have added Table App.D.3.

In social housing, the kitchen consists of cabinets from melamine-coated chipboard panels which are glued together. The 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, environmental 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 subparagraphs.

APP. D.3.1 Initial project goal & start up

In the project's initiation phase, researchers explored the interest of stakeholders in the social-housing kitchen supply chain to develop a circular kitchen. They posed questions related to the business model of kitchens, and the possibility to transition to a lease kitchen. A consortium was formed that would explore the possibilities of a lease kitchen. This consortium agreed to start a one-year project to create a proof of principle for a circular kitchen (the CIK).

APP. D.3.2 Proof of principle phase

In the proof of principle phase, the goal for the CIK was redefined as 'developing an exemplary circular building component: The Circular Kitchen', initially for adoption by Dutch housing associations. 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 for implementing circular principles. Gaining this understanding was necessary to develop potentially feasible proposals.

In the second part, five potentially feasible variants of the CIK were designed. To develop these variants the different choices to be made – parameters – for the technical, industrial and business model were listed using brainstorms, literature and precedent cases. Consequently, several variants for the CIK were developed by 'mixing and matching' these options, employing them as building blocks: (1) the 'green kitchen', where chip board 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 repair, reuse, 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 recycle 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.D.1.

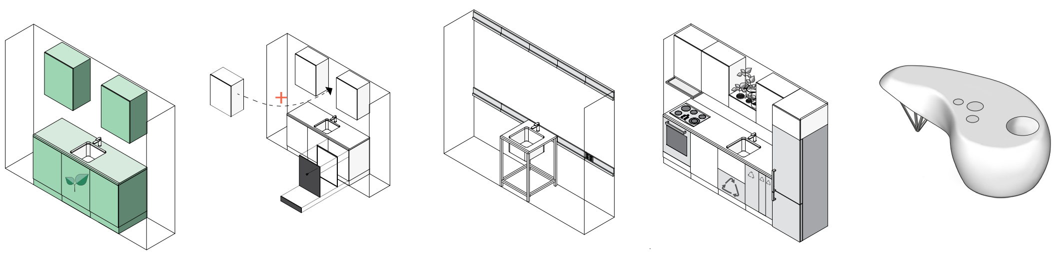


FIG. APP. D.1 The five sketch design variants for the circular kitchen. Front left to right: the 'green kitchen', the 'basic+ kitchen', the 'plug-and-play' kitchen, the 'all CE-kitchen' and the '3D kitchen'

In the third part, the proof of principle of the CIK was developed further and tested for feasibility in an iterative co-creation process with TU Delft, AMS, housing associations and parties from the industry. The stakeholders 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 ideally needed to be combined with the plug-and-play model. For the reasoning of stakeholders on the feasibility of each of design variant, we refer to Table App.D.3.

TABLE APP. D.3 Stakeholder reasoning on the feasibility of the 5 circular kitchen design variants

The green kitchen	+ Close to current BAU and technical capabilities + Promising variant + Design has clear circular pathways - Composting is not right EoL for long-lasting bio-based materials: we should keep bio-based materials at highest utility and value
Basic+ kitchen	+ Simple component design + Customization options for user + Increases user awareness of the costs of changing kitchen parts will make them take better care of their kitchen + Close to current BAU and technical capabilities + Promising variant - Is based on 'old' and 'linear' values - Difficult to find a standard-size that fits all dwellings
P&P kitchen	+ Most of the kitchen will have a long life + Flexible system to adjust style and layout of the kitchen to changing needs + Partial replacements possible + Interesting from life cycle cost perspective + Ideal and versatile design + Easy and fast to make adjustments + Great to combine with sustainable materials
ALL CE kitchen	+ Goes beyond the kitchen: smart to take all flows of the kitchen into account - Less promising variant: it has too many parts - Complex
3D Boiler	+ Clear circular concept design - Dream scenario - Not possible with current techniques

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

The final proof of principle of the CIK combined the all-CE and plug-and-play variants and can be seen in Figure App.D.2. The kitchen consists of a docking station in which modules can be plugged in and out. The kitchen modules themselves are also divided in 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.D.3 a variant with a return street, in which the producer would re-distribute and lightly refurbish kitchen modules, was considered a feasible option.

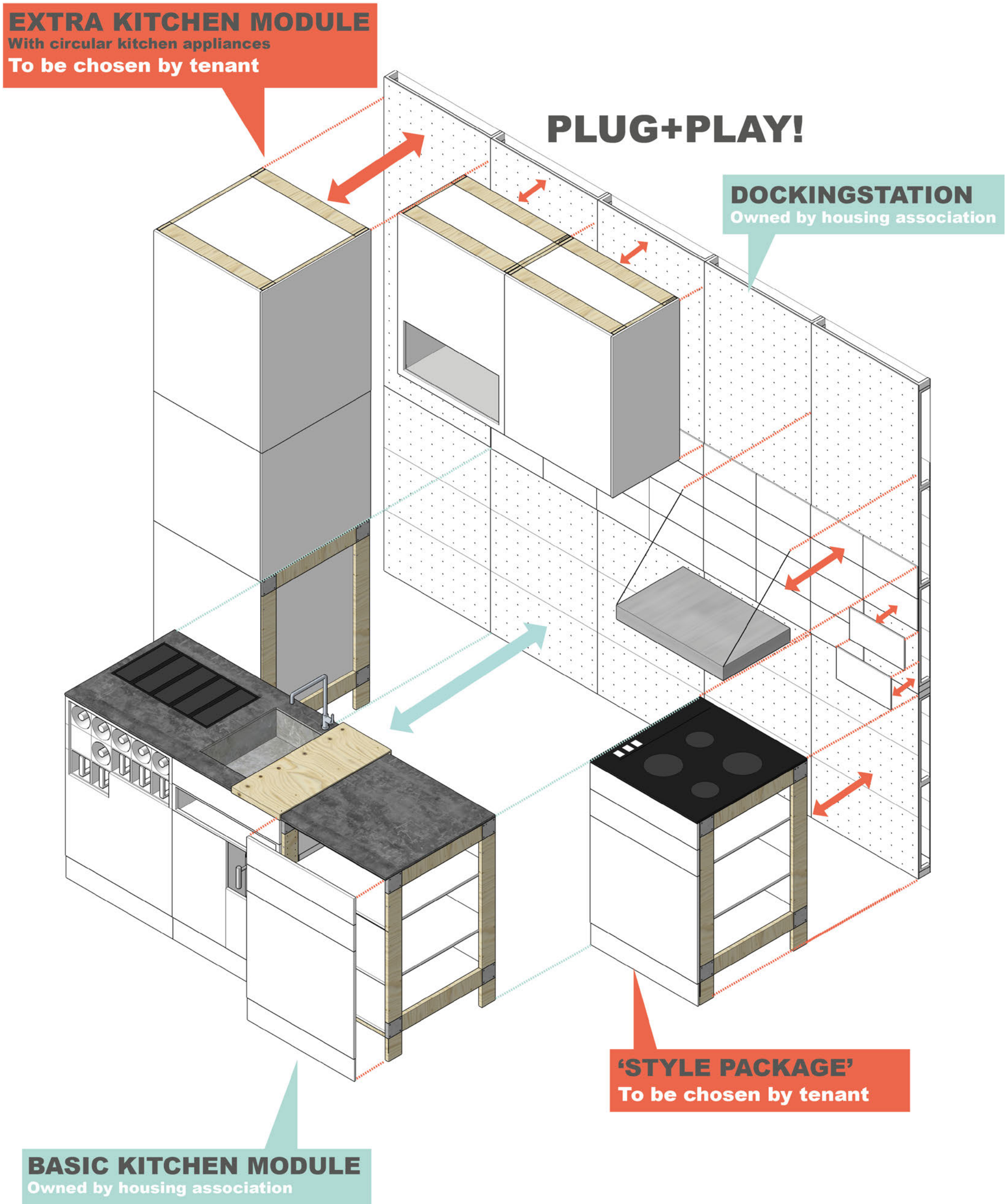


FIG. APP. D.2 The technical model of the proof of principle CIK

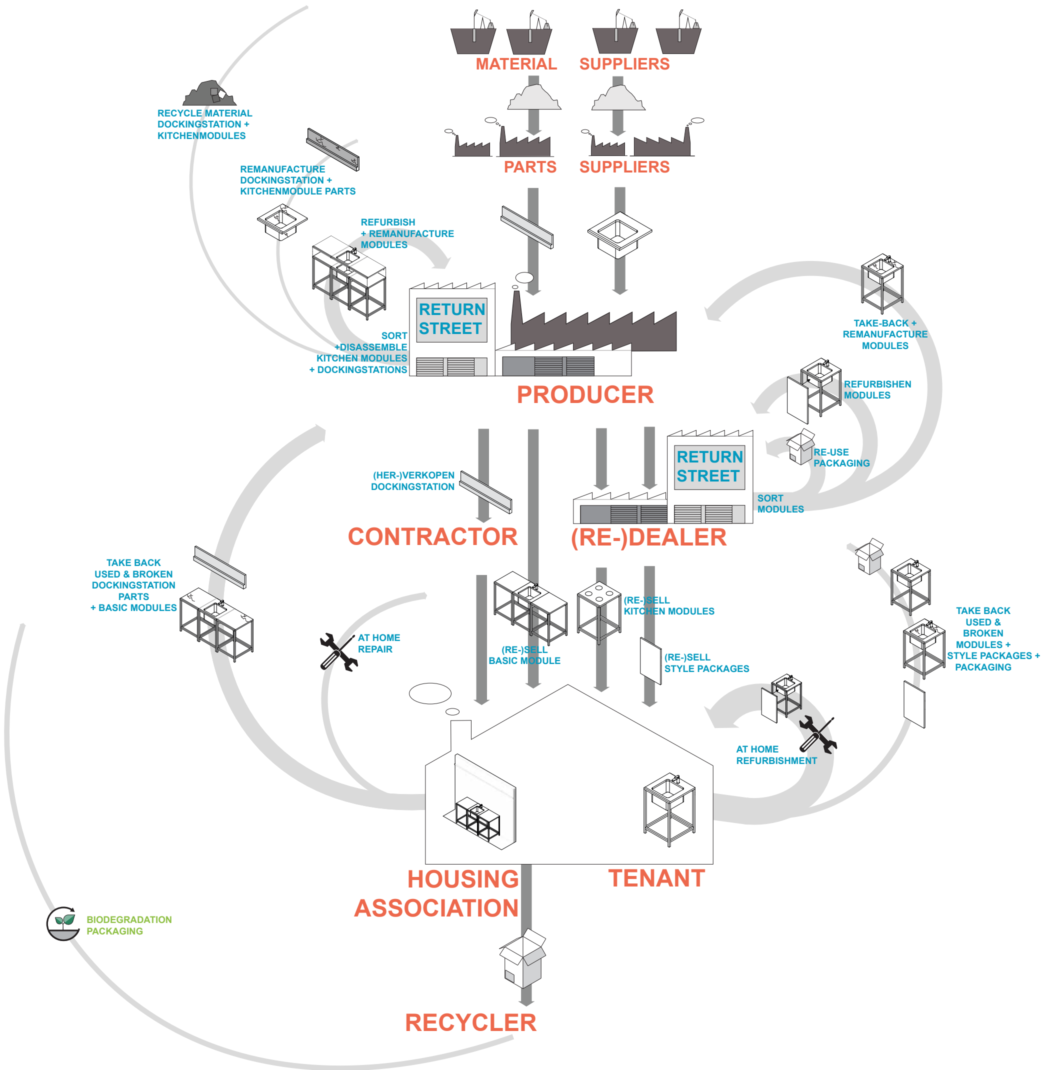


FIG. APP. D.3 The industrial model of the proof of principle CIK

APP. D.3.3 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

TOC

team. They developed the proof of principle further to a proof of concept in multiple work sessions. Their ideas were then discussed and improved in workshops with the larger stakeholder group.

In their work-sessions, the small team defined by which criteria the kitchen should be assessed: functional requirements, circular performance and economic performance. The functional requirements were determined by a housing association (HA) and the kitchen manufacturer, the circular performance would be determined by life cycle analysis (LCA) and the economic performance by Total Cost of Ownership (TCO). 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 in the larger group. A number of focus areas were identified as well. (1) The materials used should be available on the long term to avoid future incompatibility of the design and available material. (2) 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 a docking station. However, towards the first prototype, 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 to a prototype. However, hanging frame-based wall cabinets was foreseen to raise too many issues, and these were therefore constructed of solid panels. Third, the style package was selected to be positioned outside of the frame (i.e., covering the frame). This was preferent over a style package placed inside the frame, since a covered frame was found to 'look more recognizable to the general public', offer more space, and have 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; 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 system. 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 in 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 kitchen manufacturer: a sustainable plywood or bamboo panels with a detachable high-pressure laminate (HPL) finishing.

APP. D.3.4 Prototypes

The prototype phase consisted of two sub-phases. In a 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 Figures App.D.4-5. Since chipboard is generally used in the kitchen, most of the connectors offered by the standard suppliers were less suited for other material 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 kitchen manufacturer. This tool-free connector was then further tested in a mock-up of a 60 cm 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 Figures App.D.6-7). 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, a sustainable plywood was seen as the best option.

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

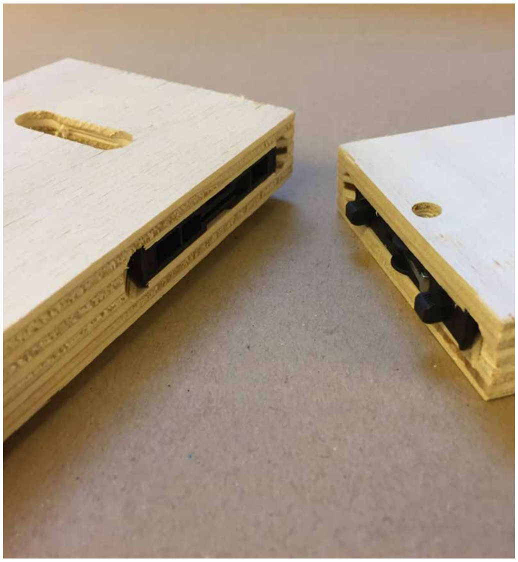


FIG. APP. D.5 A mock-up for the connector used in CIK prototype 1

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

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

In the second sub-phase, the production of the first prototype was prepared and the first prototype was manufactured. The first CIK prototype consisted 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. 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 kitchen manufacturer's own facilities, which are equipped for mass production only. The production of the prototype was therefore outsourced to a third party. Figures App.D.8 and App.D.9 show the assembly of the prototype.

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

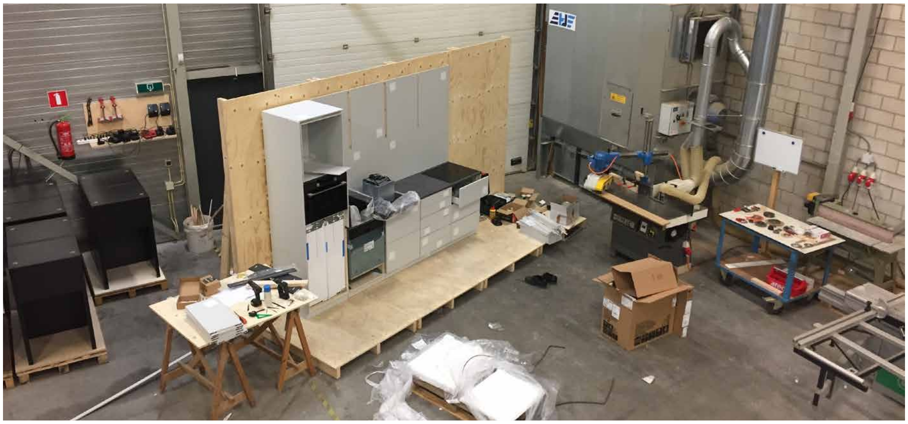


FIG. APP. D.9 CIK prototype 1 being assembled with a grey style package

In January 2019, the first full scale prototype of the CIK was presented and discussed with (future) clients and end-users (see Figures App.D.10-11). The goal of this event was to give both clients, 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 the 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 then for an un-sustainable one. However, the price of the first prototype was marked too high.

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

FIG. APP. D.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 clients were used to evaluate prototype 1. From this evaluation, further steps were formulated and planned in a number of co-creation workshops. Table App.D.4 shows the workshops during this next phase.

TABLE APP. D.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 10th of January 2019, the Dutch CIK project partners gathered to evaluate the prototype. A document with points to reevaluate was presented and steps were formulated to work towards prototype 2. This included reevaluating a number of design choices made for prototype 1 that will be elaborated on in the next section.

APP. D.3.5 Demonstrator

After prototype 1, a number of design decisions were evaluated. Most notably, the docking station had to be adapted 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 was reconsidered. Last, the connectors used were reconsidered.

In the second workshop, on the 3rd of may 2019, the Dutch project partners gathered to discuss the development towards the CIK demonstrator. Here, a number of variants for the demonstrator were presented as seen in Figure App.D.12.

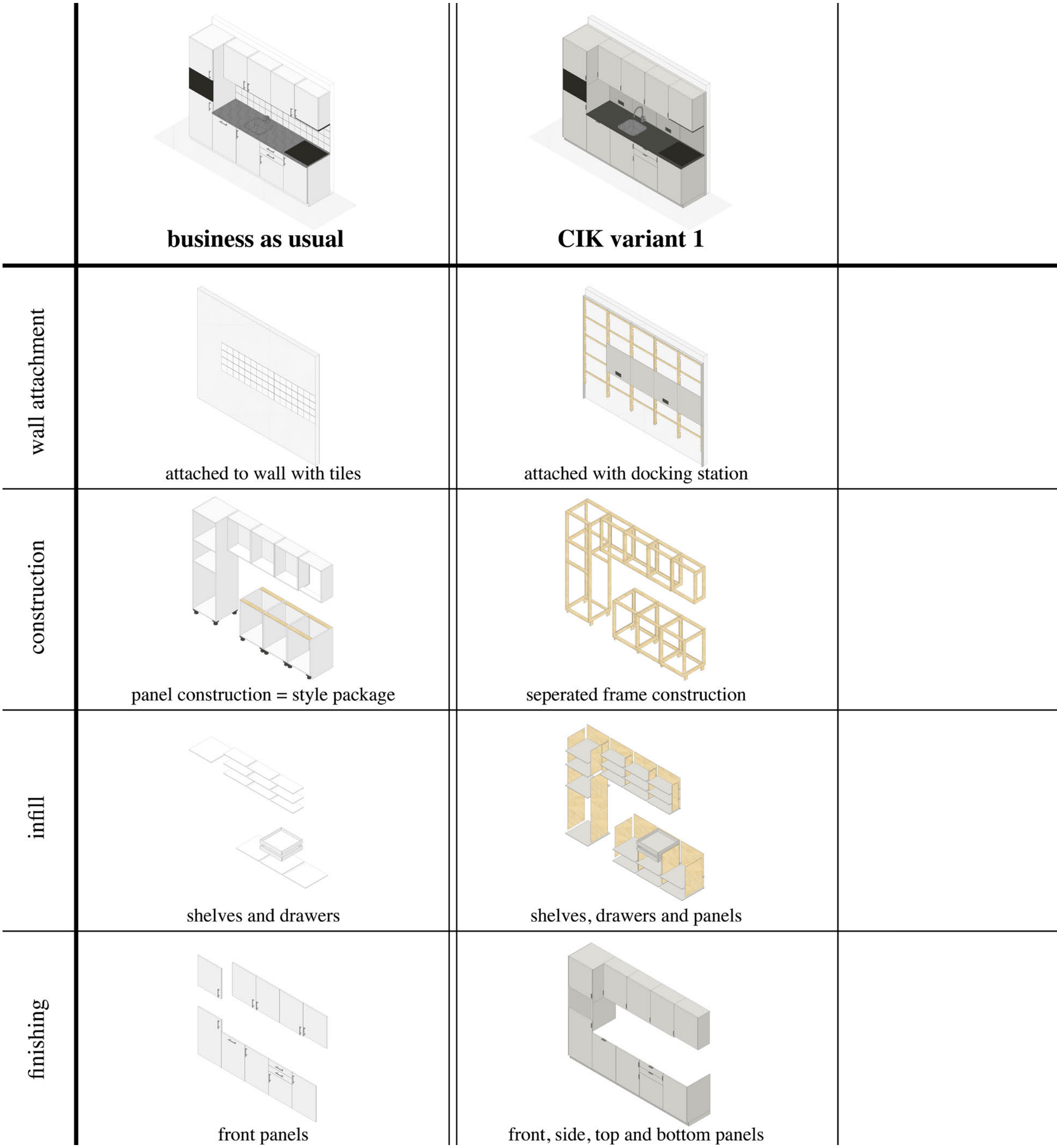
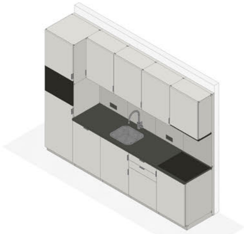
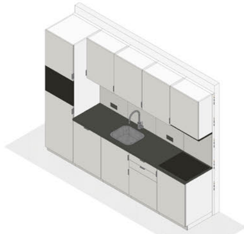
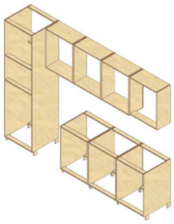
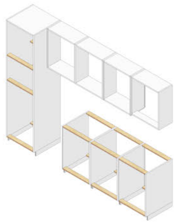
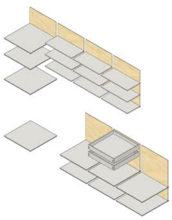
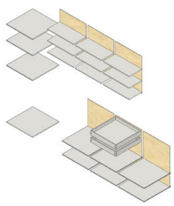
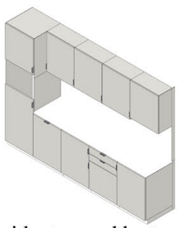
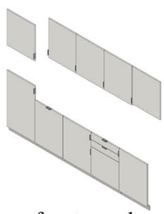


FIG. APP. D.12 Variants for the CIK demonstrator as presented during the workshop on the 3rd of may 2019

TOC

	 **CIK variant 2**	 **CIK variant 3**
	 attached with docking station	 attached with docking station
	 seperated panel construction	 panel construction = style package
	 shelves, drawers and panels	 shelves, drawers and panels
	 front, side, top and bottom panels	 front panels

Variant 1 consists of a frame construction (including the wall cabinets), while variants 2 and 3 consist of a 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.

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 CO_{2eq} emissions). The project group was asked to rank the 4 kitchens from 1st choice to 4th choice to gain insight on their purchasing preference if these kitchens would be available for purchase now. Table App.D.5 shows the results of the votes including the remarks. The number of votes from the HA 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. The business and industrial model was not altered compared to prototype 1.

TOC

TABLE APP. D.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 CO_2 footprint (HA) - No option for a sus-tainable future (HA) - CO_2 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 environmen-tal impact savings (HA) - Costs per CO_2 saved (HA) - High price (HA) - More material changes		
Variant 2	1 (1)	8 (2)	4 (2)	2 (1)	15 (6)
remarks		+/- Costs per CO_2 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 CO_2 saved (HA) + Lowest difference purchase price & TCO + Most durable - 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)	

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

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 a number of workshops, CIK partners divided these kitchens amongst the HAs. The remaining demonstrators would be placed in showrooms and used for events. Furthermore, there have been numerous requests from outside of the consortium to purchase the CIK. 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 prototype 2.0, placed in the showroom at one of the HAs, was planned in 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 the same time, a number of people involved in the project long term became less involved and others took over their role.

FIG. APP. D.13 CIK demonstrator as placed in a house provided by a housing association

In spite of the regulations, the kitchen manufacturer 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 were placed against a half wall, meaning the docking station had to be adapted to fit. The kitchen manufacturer was able to adapt these prototypes and has placed the kitchens successfully. This first placement provided some valuable input, for example that 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.D.13. This placement provided useful feedback needed to further develop the prototype to a market ready circular kitchen. A number of key issues were identified: (1) the kitchen did not allow for enough space behind the docking station for plumbing (see Figure App.D.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.D.15).

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

FIG. APP. D.15 CIK demonstrator upper cabinet without a door, showing the cabinet's interior

APP. D.3.6 Towards market implementation

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 repair of parts in local shops. Instead of plywood, a more circular variant of the current chip-board is used.

References

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

APP. D.4 Summary of the development process of the circular skin and resulting designs

In this appendix we describe the development process of the circular skin case including renovation façade and roof components. Although this description is elaborate, it should not be understood as exhaustive. We describe how the development took place, the type of choices we made and show the resulting designs.

APP. D.4.1 Start up: a search for the goal and approach (July 2017 - October 2018)

In the 'REHAB' research project, researchers of the Delft University of Technology and Amsterdam Institute for Advanced Metropolitan Solutions aimed to learn how to develop feasible circular building components for the renovation of Dutch social housing by co-developing and testing them together with practice. Over the course of one and a half year, the researchers formed three teams centred around the development of different circular building components.

The researchers met with contractor Dura Vermeer and – separately – housing association Ymere. Separately, both parties expressed interest in learning more on circular renovation. However, Dura Vermeer already worked with Ymere as a co-maker on their renovation projects. Co-makers have a long-term collaboration with the housing association which is aimed at renovating more efficiently. Together they committed to the REHAB project to start learning about circularity in renovation and innovate together. Two meetings on management level took place to discuss circular economy and circular design. In these meetings we explored what to develop (goal), how to develop (the process), and to align expectations. The idea was to develop a scalable modular renovation concept which could improve the dwelling quality and energy performance, consisting of multiple circular building components. The entire concept would be developed to the level of concept; one or several circular building components would be developed further. A renovation project would be found in which the development of one or more circular component(s) would take place. The choice of building components would depend on what interventions would be needed in the selected project. It was decided that the researcher would join the project team but would also continue to have meetings with the management team to discuss the progress. Together a suitable renovation project was selected and the researcher joined the project team. However, after one meeting, the project team and researcher decided that the project was already too far along to start the development of a circular building component. The concept design had already been made and the team was in the engineering phase. So, only small optimizations could still be made to the plan. During the next management meeting the decision was made to look for another project, one which was still in the initiative phase.

APP. D.4.2 Developing a principle design (October 2018 – December 2018)

Three co-creation workshops were scheduled with the contractor to jumpstart the development of the modular renovation concept and circular building components.

First co-creation workshop: status quo and first sketch design

During a first co-creation workshop, the researcher and contractor discussed the status quo in renovations: which types of renovation are often done by the contractor; how do they do it; what are the challenges they experience. In nearly all renovation projects, measures which improve the (technical) quality of the dwelling are combined with measures which improve the energy efficiency. Determining the best approach to improving the energy efficiency was found challenging. Some projects are renovated to 'energy label B' whilst others are renovated to net zero energy. A 'Net Zero Energy Building (NZEB) renovation' - in Dutch 'Nul op de Meter' (NOM) – is often done by applying standardized, NZEB renovation concepts. These can be replicated in many projects and propose a combination of renovation measures for a certain dwelling type. These measures are sometimes also prefabricated to limit the renovation time on site. Often, the existing skin of the dwelling is insulated from the exterior; insulating glazing, PV panels and a heat pump are placed. The NZEB approach makes the dwelling compliant to the energy-requirements for 2050. It requires a high initial investment which can be earned back over 30 years. The contractor stated that renovations with lower energy ambition levels – such as 'energy label B' renovations – are more common. An energy label B approach is developed on a project basis. The energy performance is optimized by applying one or more measures such as installing double glazing, insulating the roof from the inside, placing a more energy-efficient gas boiler and/or insulating the cavity wall. The dwellings are made compliant to current regulations for a lower investment. However, when requirements in regulation increase, further improvements become harder to justify (creating a lock-in). During this workshop the goal for the development was formulated as follows: *to make the exterior skin of an NZEB renovation circular.* This was considered a logical next step for the development of the NZEB concepts.

The researcher then presented several circular building approaches. By identifying and combining interesting existing solutions, an initial direction for a circular skin was proposed: a modular skin combined with a digital customization, exchange and return platform. This direction was both considered circular and an interesting business proposition for renovation. See Figure App.D.16, for a quick sketch of this proposition.

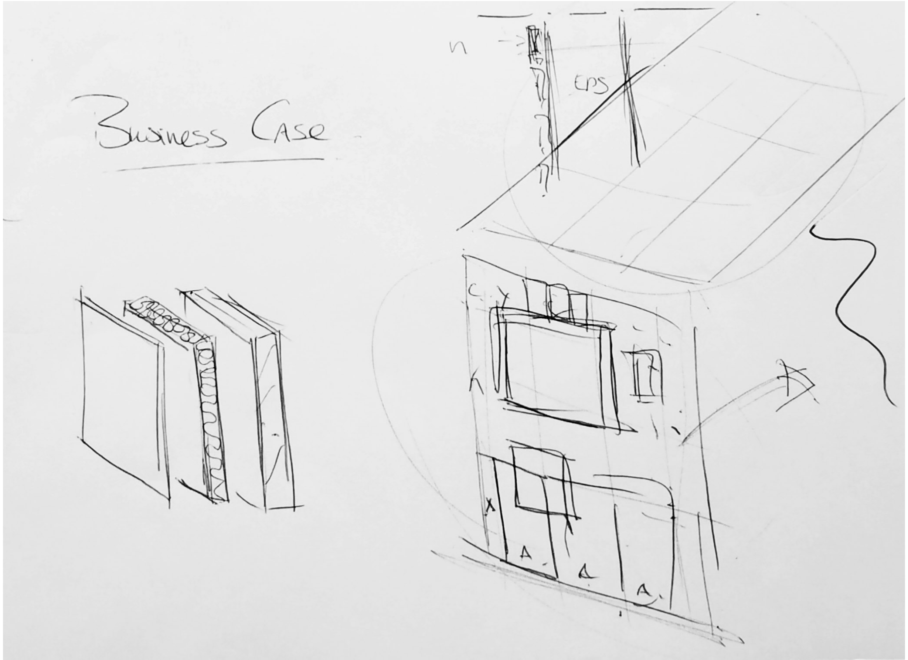


FIG. APP. D.16 First sketch design of a modular circular skin

Second co-creation workshop: renovation scenarios, design variants and questions

The contractor took the researcher to the construction site of an on-going NZEB renovation project. Using the input from the previous meetings, the researcher

TOC

then developed three renovation scenarios distinguishing different energy-efficiency ambitions: light-, mid- and deep renovation. The modular, circular renovation concept could be applied in each scenario, bridging the current gap between the more project-wise ‘energy label B’ renovation and the concept-wise, NZEB renovation. For the latter two scenarios, the exterior renovation skin components could be applied. The researcher developed two design variants for a circular, exterior-renovation façade: the (1) RECYCLE ME! and the (2) Plug+play façade (see Figure App.D.17). The first variant narrows and closes resource loops by changing the materials to low-impact, recyclable and reused materials. The supporting business and supply-chain models remain similar to existing models. The Plug+play variant has an additional emphasis on slowing resource loops through modularization, standardization, customisation, and facilitating partial replacements. The business and supply-chain models were diversified by offering additional services, including update, repair, customisation and reuse services.

Rather than being understood as finished designs, these variants explored what type of technical questions different circular designs would raise. For example, the following questions were identified: how to choose a module size; how to make modules demountable without causing a ‘thermal bridge’ in the insulation; how to align the measurements of existing façades with the new modules? The scenarios, design variants and identified questions were presented to the contractor in a second co-creation workshop. The latter variant was considered both the most circular and offering the most interesting value proposition to the contractor. The technical challenges were extensively discussed, not to solve them but to explore ‘the problem scape’ of the design.

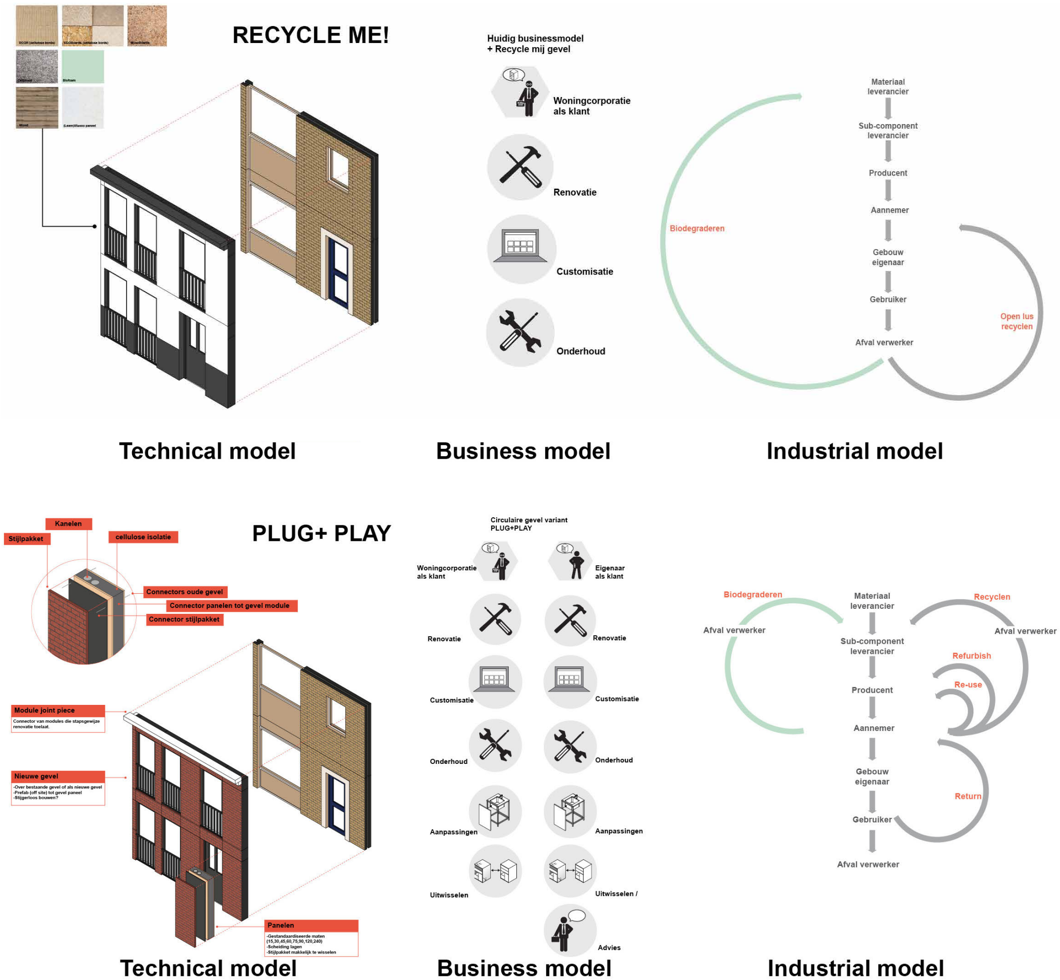


FIG. APP. D.17 Two design variants for a circular façade including technical, business and supply-chain model. From top to bottom: (1) Recycle me! and (2) Plug+Play

Third co-creation workshop: principle design and technical drawings

The researcher further detailed the preferent design variant and included a circular roof component (see Figure App.D.18). The principle design of the circular skin is based on a plug-and-play system. It consists of a prefabricated roof and façade component. These components can be installed in just a few crane movements, minimizing construction time and inconvenience on site. The façade and roof components consist of modules with standard dimensions. These can easily be clicked in and -out of a 'docking station'. The modules themselves consist of a timber-frame filled with insulation material and a 'style package' (finishing). The style package is mounted to the timber frame by means of accessible, detachable and remountable connections.

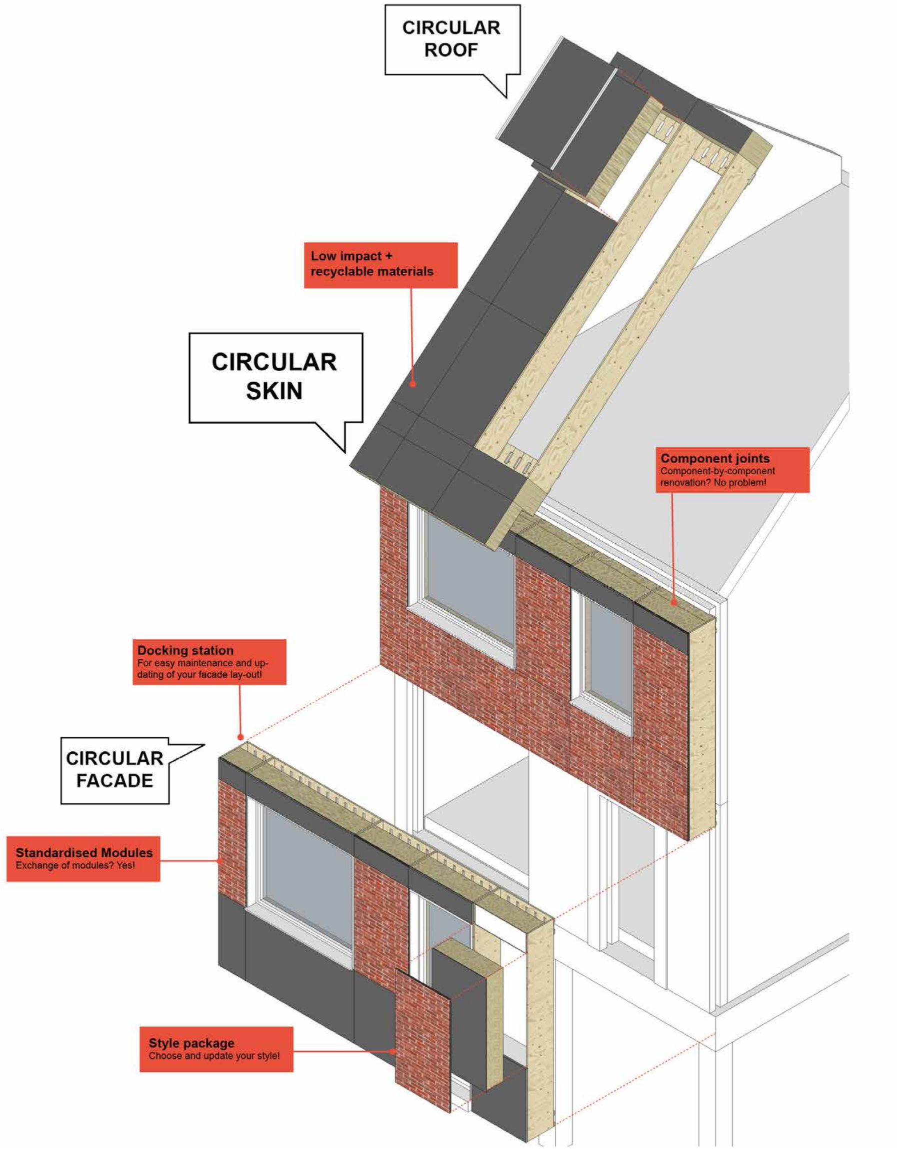


FIG. APP. D.18 Principle design of the circular skin

TOC

This design makes the skin flexible to use during renovation. Due to the far-reaching modularisation, this standard renovation concept can be easily adapted to the renovation ambition of an individual project such as 'energy label B' or NZEB renovation. Due to the modular construction, the renovation can be built up step-by-step (see Figure App.D.19). The design also makes the skin adaptable to the various renovation wishes of housing associations, tenants and owner-occupiers. The circular skin is easy to repair: all parts remain accessible and can be disassembled. It is also adaptable and 'upgradable' to the housing needs of the future. Modules and parts are interchangeable and reusable in other renovation projects. Finally, by applying separable biological and technological materials, the skin can be recycled at the end of life (EoL).

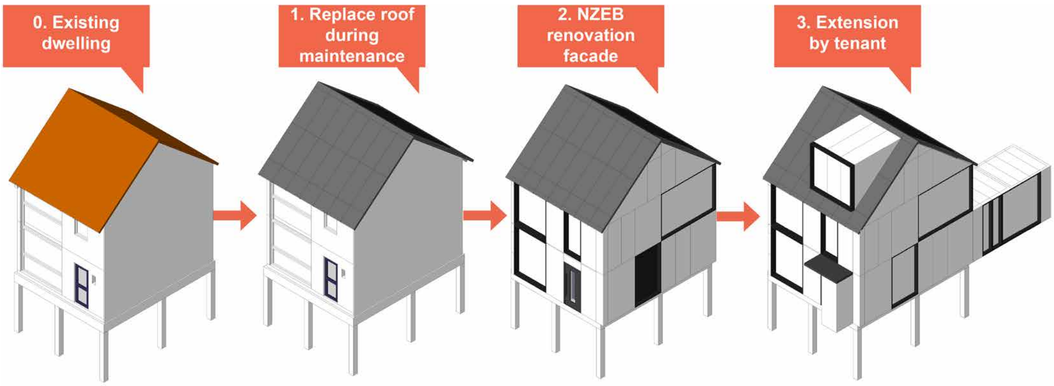


FIG. APP. D.19 Step-by-step renovation using the circular skin

The researcher also developed technical drawings (including 1:20 vertical sections and principle details) to explore technical questions. For example, how to facilitate step-by-step placement of building components and what is the sequence of de- and remounting façade modules?

During the third workshop, the refined principle design and technical drawings were discussed with the contractor. The developed design principle was considered to facilitate circularity and provide additional functional and economic benefits. The outcome of the discussion was a list of technical questions, including: can we replace the finishing of the roof with PV panels (to prevent double material use); how do vertical and horizontal gaps in modular components influence the performance (aesthetic, thermal, waterproofing, lifespan); which margins are needed between the modules; how can we account for measurement differences? At this stage, the contractor and researcher concluded that more stakeholders would be needed to develop the circular skin components further. For example, a roof and façade manufacturer, connector suppliers, building physics consultant, designer, and cost-specialist. This further development would be organized in co-creation sessions which would be linked and run in parallel to the renovation project in which the circular skin would be tested. Additionally, the contractor and researcher suggested to involve more housing associations into the development to increase the scaling-potential of the circular skin.

APP. D.4.3 Testing the principle design and creating a plan for a next step (December 2018- February 2019)

The background, goal and principle design was presented to the management team of the housing association. During the development of the principle design with the contractor, the management team had partially been renewed. The housing association suggested to focus on creating as much circularity as simple and low-cost as possible. And, to find out what challenges this creates. A new project was selected which would (likely) apply (some form of) insulation in the skin in ±600 dwellings. This project also matched the timeframe of the research project. It was decided the researcher would join the project team to see to what extend the principle design of the skin could be implemented.

The researcher presented the background, goal and circular skin principle to the project team. The team decided that four co-creation sessions would be planned to start the development of the circular skin. A roof and façade manufacturer and architect would need to be selected soon, so they could join these sessions.

The researcher then met the project lead of the contractor and their innovation manager to elaborate on the background of the developed principle design. Together a plan of approach was made for the development of the circular skin.

APP. D.4.4 Comparing more circular skin variants (April 2019)

During a communal workshop with the stakeholders involved in the circular skin, circular dwelling extension and NZEB-light cases, the researcher presented five circular skin variants (Figure App.D.20). In the development of the initial design principle for the circular skin, (only) two design variants had been compared. A relatively quick choice was made on a preferent design variant resulting in a ‘quick’ principle design. These 5 variants were used as a ‘step back’ from the developed principle design to facilitate discussion between stakeholders on the feasibility of different design pathways.

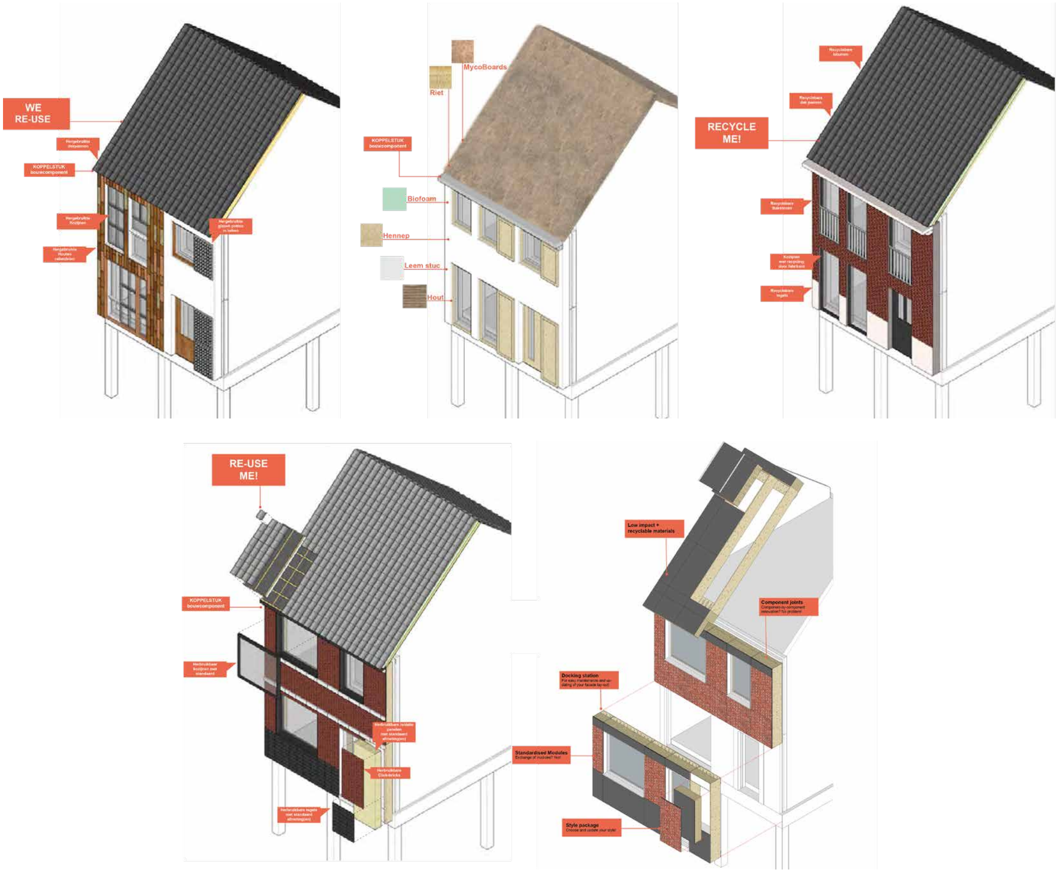


FIG. APP. D.20 5 Circular skin design variants. From top left to bottom right: (1) Reclaim! skin, (2) Bio skin, (3) Recycle me! skin, (4) Product2Product skin, and (5) Plug-and-play skin

The ‘Reclaim! skin’ applies non-virgin materials, meaning either directly reused or recycled materials. For example, reused rooftiles, reclaimed wooden cladding, reused window frames. But plastic food containers and glass bottles could also serve as façade ornamentation. The skin is sold to the housing association. At EoL, the housing association can have the skin disassembled and can directly reuse materials in a new project or have them recycled or incinerated.

The ‘Bio-skin’ (BIO) applies bio-based and biodegradable materials. For example, façade and roof panels consisting of wooden timber frames with straw, hemp of flax insulation. For the façade finishing, wooden or clay-plaster finishing could be used. The roof could be thatched with straw or reeds. The skin is sold to the housing association. At EoL, the materials are industrially composted.

The ‘Recycle me! skin’ applies materials which could be recycled back into the same product at EoL. The joints between different materials are demountable to allow their separation into pure recycling flows. For example, materials such as bricks, aluminum frames, EPS insulation and ceramic tiles are applied. The skin is sold to the housing association and at EoL the skin is disassembled into different waste flows for recycling. This variant remains closest to the current supply-chain and business model.

The ‘Product2Product (P2P) skin’ is based on direct reuse and the high end-value of building products: it consists of building products with a long technical lifespan, applying standardized sizes and connectors which allow for easy dis-, and re-assembly. For example, click brick- or ceramic tile façade finishing, rooftiles, and aluminum window frames are applied. In the P2P skin, the façade and roof are sold to the housing association. At end of use, the skin can be disassembled, resold (e.g., on a building material platform), and re-assembled at another dwelling.

The ‘Plug-and-play (P&P) skin’ applies a combination of circular design options to slow and close loops. The P&P skin is modular, separating parts based on their functional and technical lifespan. The skin consists of de- and re mountable insulation modules in standard sizes. These facilitate future changes in lay-out and reuse of the modules on another dwelling. For the finishing of the skin, a wide variety of standard-sized panels can be easily (de-, and re-) attached using click connections. The P&P skin is either leased, sold with (prepaid) buy-back guarantee, or take-back guarantee. If sold, an accompanying maintenance subscription and update services are offered by the provider. This business model provides an incentive for the provider (i.e., manufacturer and contractor) to realize a skin which is easy to repair, update, reuse or recycle.

The stakeholders evaluated the feasibility of the circular design variants. See Table App.D.6 for the reasoning of the stakeholders on the feasibility of these variants. The group decided that the Plug-and-play skin should be combined with the Reclaim! skin and Bio-skin variants.

TABLE APP. D.6 Perceived feasibility of circular design variants for the circular skin

Reclaim! skin	+ Reduction of virgin materials and embodied impact now + Feasible on short term + Initial costs lower (hindsight: not always the case) - Reclaimed materials have limited supply and need to be made available (e.g., central database) - Unknown if quality of reclaimed materials is controlled and/or if guarantees are provided - Unknown if these materials have shorter lifespan - Possibly leads to increased costs for maintenance
Bio-skin	+ Reduction of non-renewable materials and embodied impacts now - Not always bio-based alternative for materials (e.g., there is no bio-based glass) - Not enough land to produce bio-based materials for mass-application + Bio-based materials have feel-good factor + Use of bio-based materials fits in current supply chain - Higher initial costs; unknown costs; no savings in life cycle costs - Information lacking on certification and compliance to building code of bio-based materials - Bio-based materials are non-proven solution
Recycle me! skin	-Does not reduce material use or impacts now or prevents material use in future (by slowing loops) + Recycling materials fits in current supply chain: close to business as usual - Only feasible on large scale in long loops
Product2product skin	+ Facilitates future reuse of building products and materials - Does not reduce material use or impacts now - Standard sizes are required to facilitate reuse + Relatively large certainty that there will be a future market for these products - Disassembly is not part of current supply-chain activities - Database is needed to align supply and demand
Plug-and-play skin	+ Facilitates future repair, adjustments, reuse at highest utility and value - Does not reduce material use or impacts now - Only circular if loops can be guaranteed - (Large) standard-sizes are required which is likely only possible for new built + Customization and flexibility speaks to the market + Opportunities for industrial production - Too innovative: 'dream' which is not yet possible - Uncertain that there is reuse potential for these modules in the future market - Requires big adjustment in supply chain, way of designing, long-term thinking and change of building culture - Increases technical challenges such as demountability, air-tightness, rigidity

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

APP. D.4.5 Developing a proof of concept within a renovation project (March 2019–June 2019)

The renovation project in which the circular skin was developed was coordinated by the project leader of the contractor in close collaboration with the project leader of the housing association. Simultaneously, management meetings for the circular skin development took place every month.

The renovation project had just started up. The team discussed the overall approach and planning. Simultaneously, they tried to find a way to integrate the development of the circular skin in the project approach. Early on, the team found that integrating the circular skin development was a challenge. The project was already large and complex; the activities needed to develop the circular skin were not clear yet. The development of the skin added more risk to the project. Furthermore the tempo needed for the circular skin development did not match the project planning.

The project team developed three options for the circular skin development and discussed these during the management meeting. The first option was to integrate the development in the circular skin in the project. The business-as-usual (BAU) skin would be optimised as much as possible on circularity through quick-wins. The advantage of this option is that it limited the risk in terms of costs, quality and time for the project. However, it was considered that optimising the BAU variant might limit the level of circularity that could be achieved. For example, if an exterior skin would be applied, the BAU façade consists of EPS-foam boards and brick strips glued onto the façade. The development might end up making an inherently non-circular solution just a bit more circular. Contrary, the second option was to develop an innovative circular skin and apply this in the entire project. The large scale of the project might motivate the supply chain to invest time in the innovation. However, this approach entailed a larger risk to the cost, quality and time for the renovation project. This was unacceptable to the stakeholders. The third was a 'compromise variant' in which two circular skin solutions would be developed. For one part of the renovation, a more innovative circular skin would be developed; for the other part a variant would be applied which optimises the BAU skin on circularity. The project could be cut into different phases or one pilot block could be selected. This approach would limit the risk whilst facilitating more radical innovation. However, it would increase the complexity: two solutions needed to be engineered. Furthermore, it might also result in two different street views in one neighbourhood, a neighbourhood known for its uniform design. The stakeholders felt this might raise issues at the permitting stage. Following this discussion, the team initially decided to apply an innovative circular skin in one block as a 'separate' pilot and to apply quick-wins throughout the entire renovation to reduce risks in the project. Additionally, the management team of the housing association and contractor decided that the contractor should take the lead in developing the pilot. The management team indicated that a clear plan of approach was needed for the innovation including key performance indicators. Furthermore, management suggested that on regular intervals the financial feasibility and added value of the skin needed to be evaluated.

APP. D.4.6

Exploring circular design variants in prototypes: creating energy for a next step (May 2019 – November 2020)

The project lead of the contractor and the researcher decided to team up with the University of Applied Sciences in Rotterdam to develop 11 prototypes of the circular skin design variants. The reason for developing these prototypes was multi-fold. Albeit a lot of effort in the last 6 months, there were little concrete results in the development of the circular skin. The prototypes gave an opportunity to jump-start further development of the circular skin, to explore the technical feasibility of different circular design options, to create enthusiasm amongst (future) stakeholders and generate a 'buzz' in the wider sector.

The contractor and researcher concretised the 5 circular skin design variants shown in App.D.20; with the support of suppliers, these designs were further developed to detailed designs and prototypes by the students. Figure App.D.21 depicts two of these prototypes. The students tested the building-physical performance of the prototypes and tested the ease of realising the circular design options. For example, the students tested the effect on air-tightness in modular façades and the time it took to adjust a flexible façade.

FIG. APP. D.21 Prototype of the Bio façade (left) and the plug-and-play façade (right). Prototypes made by students of the University of Applied Sciences in Rotterdam.

APP. D.4.7 Transition to a pilot (June 2019 -February 2020)

The following two co-creation workshops focused on the circular business model variants and the value proposition of the circular skin. Furthermore, the contractor and researcher had developed a concrete plan of approach for the development of the circular skin, formulated goals (see Table App.D.7) and KPIs.

During the following management meeting, the plan of approach was discussed. The decision was made to separate the circular skin development fully from the renovation project. The project had been postponed (for other reasons than the development of the circular skin). The choice was made to develop the circular skin as a pilot. To test the skin, the housing association was willing to make a dwelling available during mutation. In the following months, the contractor gathered a circular skin team together with the researcher. An architect (Villanova architecten), building physics consultant (Climatic Design Consult (CDC)) and façade manufacturer (Barli) joined the team. A conscious choice was made for a façade manufacturer of timber-frame façade panels. The contractor and researcher found that a timber-frame façade was closer to the developed principle design of the circular skin than a façade panel made from EPS. A reclaimed-material broker (Repurpose) was invited to pitch their ideas. They suggested that facilitating future reusability was valuable but reuse should also be done now. It reduces the virgin material use, environmental impacts and waste generation now; and it builds the market for future reuse. The team decided that the principle design had focussed only on facilitating future VRPs. They decided that more focus should be given to integrating reclaimed materials now. So, the reclaimed-material broker was asked to join the team.

TABLE APP. D.7 Goals for the circular skin

Value	1. The circular skin can be applied in different programs of requirements and can fulfil different user re-quirements.
	2. The circular skin has at least the same functional quality as the linear NZEB renovation skin
	3. The circular skin can be installed whilst residents live in the dwelling
Sustainability	1. The circular skin allows renovation in steps to the energy performance requirements for dwellings in 2050.
	2. The circular skin uses less materials and has a low environmental impact by: a. Using less materials over the total lifespan of the skin b. Uses components and materials longer c. Minimises waste by keeping materials in the supply chain
Finance	1. The circular skin can be manufactured and applied on a large scale
	2. The circular skin has the same life cycle costs as a BAU skin and requires a maximum of 10% higher initial investment

A plan was made for the innovation process. A series of thematic workshops would be organised in which the researcher would present circular theory and the partners would share their ideas on the themes. The architect and façade manufacture would use this input to explore these themes in the design and draw up a circular skin concept design.

Half a year since the last management meeting, the developed plan was presented to the housing association. The housing association was asked to join the co-creation sessions and to start considering in which dwellings a pilot could be done. The housing association indicated that they did not see it as their role to join all these sessions. Rather, they would join at milestones and would provide information upon request. Furthermore, they found that the plan for the innovation process showed only one iteration; they suggested the development of a satisfactory skin might require more iterations. They agreed to look into possible dwelling types but that it was too soon to commit to a pilot as there was no solution ready to commit to.

APP. D.4.8 Developing a proof of concept and mock-up for the circular skin (February 2020 – June 2021)

The first co-creation session with the circular skin team was a full-day, kick-off workshop. The entire circular skin team met for the first time. Circular theory and the previous design choices were presented. The team was asked to re-assess the circularity and feasibility of the 5 circular skin design variants. The last part of the workshop focused on evaluating the key performance indicators of the circular skin. The kick-off was aimed at getting an equal level of knowledge on circularity. Additionally, the goal was to get everyone on the same page regarding the principle design and key performance indicators.

In the following workshops, the circular skin team developed the principle design into a concept design for the façade. Four thematic workshops took place between March 2020 and June 2020, focusing on the following themes: (1) modularity and standard-sizes, (2) modularity in sketch design and materialization theory, (3) building physics and materialization, and (4) panel sketch design and joints.

In another three workshops, a first comprehensive design concept was developed by combining and iteratively refining the decisions from previous workshops. The team decided to test the technical, functional and aesthetic feasibility, in a prototype of the circular façade. In June 2020 a definitive design for the façade and first drawings for the prototype were presented to the team.

As the development required a lot of choices to be considered, the co-creation initially focused only on the façade. The other building components disappeared to the background. The contractor was clear that making a circular façade was not of added value to them. They need an entire renovation concept to offer to the client. So, the contractor selected the roof manufacturer Linex to co-develop a circular roof. Linex specializes in 'hinged timber-frame roofs' and was interested in entering the renovation market. Together with the team they developed a design concept for the circular roof in several sessions. The researcher was not involved in these workshops. The partners had internalized much of the circular design knowledge from the development of the circular façade.

A detailed concept design for the skin was not finalized until January 2021 (see Figure App.D.22). The circular skin concept design is meant as an alternative for the BAU-NZEB renovation concept. Circularity is used as a means to speed-up the energy renovation. The design included (for now) two building components of the circular skin: a circular façade and a circular roof. Both are insulation solutions which are prefabricated off-site and installed by crane on top of the existing façade and roof. As such, they increase the energy performance, provide a quality upgrade whilst causing less nuisance for the resident compared to in-situ renovation. Both in the façade and roof components, circular design options to narrow, slow and close resource loops are combined. Where possible, reclaimed and bio-based materials are used and the design facilitates repair and likely future adjustments. The circular façade consists of timber-frame panels which span floor-to-floor and wall-to-wall; the circular roof consists of 6 timber-frame panels. They are made from reclaimed wooden beams and reclaimed insulation blankets. To reach the desired insulation value whilst keeping the panel thin and lightweight, the cavity between the existing and circular façade and roof are filled with recycled insulation flakes (e.g., recycled cellulose). The thickness of the cavity is adjustable so the insulation value of the façade and roof can be changed to (future) requirements. Adjusting the configuration of roof panels allows to make a dormer and raise the roof. By adjusting the placement of wooden frames in the façade panel, a dwelling extension, energy module and/or floor length windows could be placed. The façade finishing is kept as a separate layer. It is installed with wooden frames to the timber-frame panels so it can be easily dismounted for repair, updates and reuse. Different (more) circular finishing options are offered, for example, standard-sized brick-strip panels, reclaimed wood, reclaimed Trespa® or burned wood.

The mock-up of the circular façade (see Figure App.D.23) was presented to the circular skin team in June 2021 and evaluated. In this prototype several finishing materials, joints and insulation materials were tested. Furthermore, with the mock-up we aimed to 'see' what the façade looked like. The team found that making the

TOC

joints between the brick-strip panels look nice was difficult and labour intensive. The end result did not yet have the desired visual quality. The reused wood proved challenging in the production process. Even though the material was 'promised as' nail-free, the mock-up was hand-made. The manufacturer was hesitant to use the reclaimed wooden beams in the machine park. Any metals left in the wood might damage the machine or cause stops in the production process. Also, the tolerances in the beams were larger; the machines were not set up to allow for larger tolerances. The reuse of reclaimed mineral-wool insulation blankets went well. They were easy to clamp between the timber frames. Reclaimed mineral-wood insulation was also feasible from a cost perspective. Using foam insulation boards was found more labour intensive. All the boards needed to be cut to fit between the timber frames. Blowing in insulation flakes has not yet been tested.

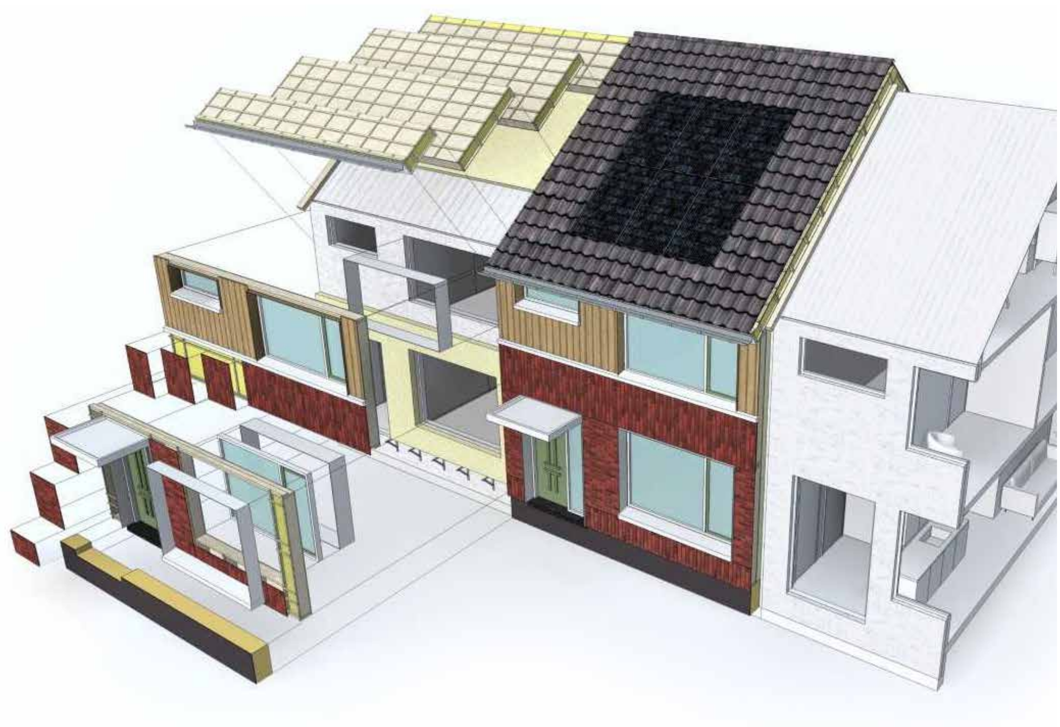


FIG. APP. D.22 Circular skin concept design (image made by Villanova architecten)

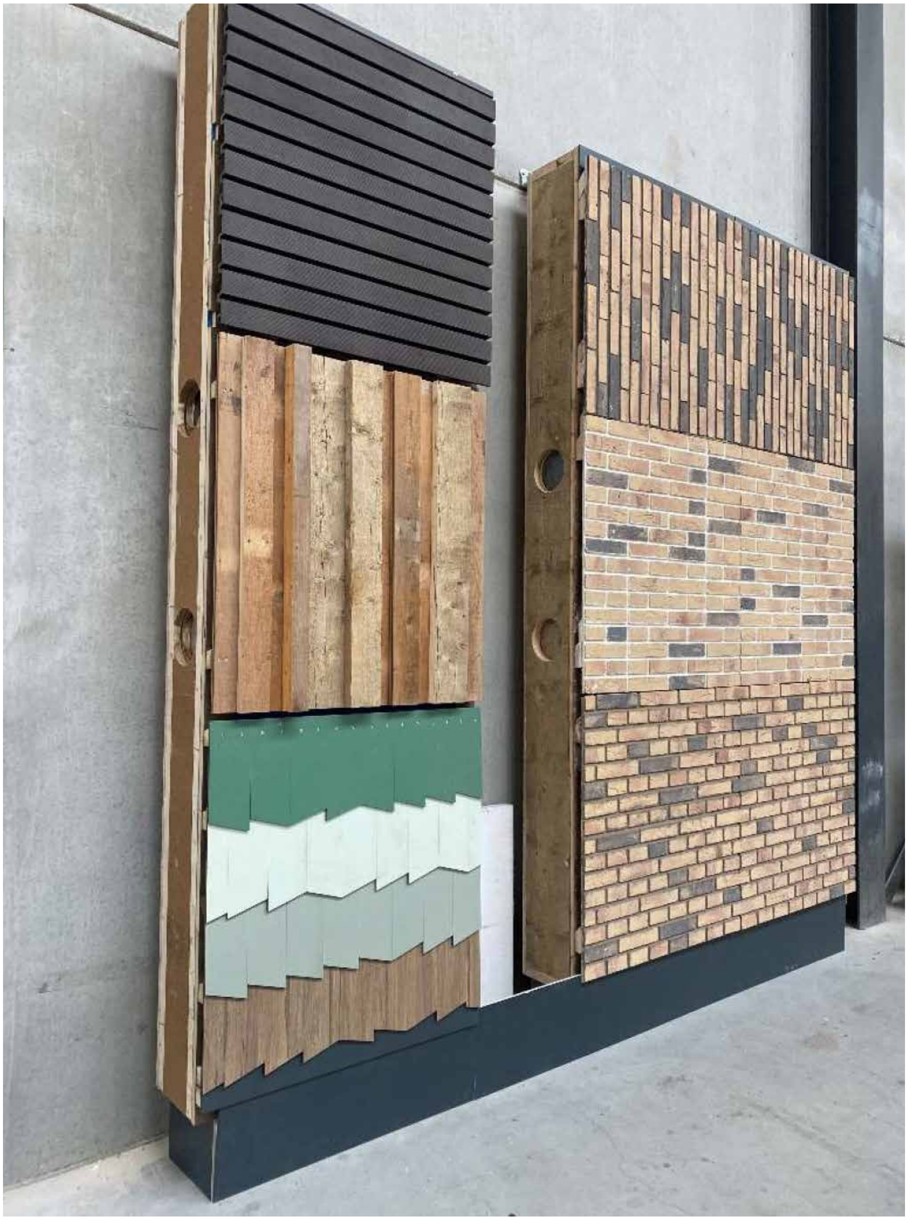


FIG. APP. D.23 Circular façade mock-up (mock-up and image made by Barli)

TOC

APP. D.4.9 Client focus group (February 2021-march 2021)

To test the feasibility of the circular skin with prospective clients and to create a potential customer base, two co-creation workshops were organised with housing associations. The development so far was presented. The concept design and the goals for the circular skin were discussed at length.

The housing associations indicated that the ability to renovate in steps towards energy neutral (2050-proof) was very important. Most housing associations were not yet ready to make the whole step right now; they preferred a step-by-step approach. They suggested that an exterior renovation façade would not likely be ‘a first step’ due to the high investment required. They suggested that the roof component would likely be applied first in combination with cavity-wall insulation and insulating glazing. The housing associations also desired support in the provision of a material passport and ‘ensuring circularity’ of the solutions they applied. Financially, keeping initial-costs low and the TCO equal to BAU was important. They considered it an additional value if the contractor supported them with applying for subsidies.

These discussions resulted in a set of new requirements for the circular skin (see Table App.D.8). Additionally, it caused a shift in emphasis in the development of the circular skin. The focus changed from the exterior façade renovation to the circular roof; the contractor wanted to start looking into developing circular components for cavity wall insulation and new insulating glazing. Although the façade might be part of the pilot home – to show the final step of the circular skin – it will likely not be applied (in mass) on the short term.

TABLE APP. D.8 New requirements for the circular skin

Added value requirements	-Integration of new climate installations in the skin -Applicable on different dwelling types -Modular renovation to achieve energy transitions: first the roof, only then the installations and exterior façade
Environmental requirements	-Realising energy neutral renovation ambition now is too ambitious -Support in documenting components and materials in passport -Ensuring circularity (but how)?
Financial re-quirements	-Keeping investment costs low -Support in applying for subsidies -Low maintenance costs can compensate for higher investment cost

APP. D.4.10 Towards implementation in a pilot (June 2021 – February 2022)

When the concept design had been developed, the contractor suggested that this circular skin design was like ‘a concept car’. Likely, when the costs would be calculated, we would find that it would be expensive; a compromise variant needed to be made. The idea was to offer alternative options within the circular skin. For example, offering thermically treated wooden window-frames could be offered as a more circular option with a higher initial investment. Recycled plastic window-frames could be offered as a less circular option but with a lower initial cost. This allows clients to pick and choose what they find more important.

Additionally, the modularity of the renovation concept became a focal point as the main added value. Rather than seeing the entire circular skin as the value proposition, the value proposition might be a strategy to make the to-be-renovated dwelling ready for the energy- and use requirements of 2050 in steps. This modular approach allows housing associations flexibility to adjust the renovation concept to their ambitions, project-specific requirements and allows them to spread costs over multiple investment cycles.

In the next steps, the contractor will focus on further development of the business model and value proposition. The concept will be evaluated on economic and environmental performance. The emphasis in technical development will be on further development of the circular roof in combination with components like circular cavity-wall insulation and new insulating glazing. Next to developing the circular skin further as a concept, the contractor is also exploring how to integrate lessons-learned on circular design into their ‘regular’ project approach.

APP. D.5

Description of the development process of the circular dwelling extension and resulting design

In this appendix we describe the development process of the circular dwelling extension. Although this description is elaborate, it should not be understood as comprehensive. We describe how the development took place, the type of choices we made and show the resulting designs.

APP. D.5.1

Interest in learning about circular renovation (March 2018 – December 2018)

In the 'REHAB' research project, researchers of the Delft University of Technology and Amsterdam Institute for Advanced Metropolitan Solutions aimed to learn how to develop feasible circular building components for the renovation of Dutch social housing by co-developing and testing them together with stakeholders from practice. Over the course of one and a half year, the researchers formed three teams centered around the development of different circular building components.

The researchers contacted housing association Eigen Haard. Eigen Haard was doing circular pilots in different parts of their organisation. They were interested in doing a pilot in circular renovation in order to learn more about it. Together a suitable renovation project was selected in which circular building component(s) could be developed: de Kuilsenhofweg and Kolfschotenstraat in Amsterdam. The researcher joined the project team. Eigen Haard did not have long-term collaboration contracts with contractors but rather selected them on a project basis. The housing association wrote a tender to select the contractor. In this tender the housing association explicitly included the ambition to realise a circular renovation. They specified that they were looking for a contractor who wanted to "learn together". Participation in the REHAB project was also included as a condition in the tender. The contractors were invited to give a pitch and ERA Contour was selected. The renovation project was organised in a 'building team': a conceptual contractor and architect joined early in the process to co-design and realise the project. All phases of the project were coordinated by the project leader of the contractor in close collaboration with the project leader of the housing association.

APP. D.5.2 Choosing a component to develop within the renovation project (March 2019 – April 2019)

The researcher provided two workshops in which circular economy, circular design theory and circular building approaches were discussed. Furthermore, the plan of approach for developing a circular renovation solution was developed. In the renovation project various building components required (re)placement. But which components were to be replaced was not yet certain as the scope of the renovation was to be determined within a feasibility study comparing multiple renovation scenarios. The contractor, housing association and researcher decided that to make all building components of the renovation 'fully' circular would not be feasible. The team chose to focus on developing one circular building component and to optimise the rest of the renovation approach on circularity where possible. Multiple components were considered, such as the roof, windows, climate installation and bathroom. The circular dwelling extension was selected for the following reasons. First, for several components it was not yet sure if they would be applied in this project. The old extension would certainly require replacement. So, developing a circular dwelling extension component made certain that the component would be applied in the project. Second, for some of the building components, the housing association and contractor found they had limited opportunities to redesign the components themselves. For example, for the climate installation and windows, the manufacturer would need to do most of the development. Third, the circular dwelling extension included various building components in one: a roof, façade, floor and windows. As such it provided an interesting learning object. Furthermore, it was also considered a safe component to experiment with as it was only a relatively small component in the entire renovation. Fourth, the dwelling extension had scale-up potential. During the renovation of their dwellings, housing associations often encounter the need to (re)place dwelling extensions. For example, they replace old entrance porches, balcony closets, dwelling extensions made by tenants or they need to place an extension for new climate installations (e.g., in an NZEB renovation). The team considered that developing a replicable circular dwelling extension could lead to significant resource-use, environmental-impacts and waste reduction.

APP. D.5.3 And then there was a plan! (March 2019 – April 2019)

Immediately a clear plan of approach was made for the development of the circular dwelling extension. As the circular dwelling extension would be part of the renovation project, the plan for the circular dwelling extension would need to follow the same milestones as the rest of the renovation plan. The plan for the renovation project would be developed following the regular building project phases. However, the team considered that the development of the circular dwelling extension might require more time. So, the contractor and researcher chose to plan a separate development process for the circular dwelling extension. A series of thematic co-creation workshops were scheduled which took place in parallel to the project meetings. Moreover, the workshops were started straight away to ensure there would be enough time for the development. It was agreed that in the early stages of the development, the researcher would take the lead whilst after the concept design the stakeholders would take over.

APP. D.5.4 The business-as-usual extension (may 2019)

In the first workshop, the researcher asked the contractor how they would 'normally' replace an old dwelling extension in a project. The contractor showed existing dwelling extension designs which they considered business-as-usual (BAU). A prefabricated shed would have been placed. This design consists of a concrete floor slab, and a construction and façade finishing of woolmanized wood. The roof would be finished with bitumen and a zinc roof molding. Together the contractor and researcher analyzed what was (not) circular in this design. They found that the BAU design does not apply a lot of material as it is quite minimalistic; this reduces resource use. But on the other hand, the applied materials are virgin and have a relatively high environmental impact. The design is made to be low maintenance but it is not demountable nor particularly easy to repair, adjust or reuse in the future. Furthermore, the BAU design is not insulated so the team found that the space does not have a high added value (or end-value).

APP. D.5.5 Design variants for the circular dwelling extension (may 2019)

An architect (DOOR architecten) was selected to join the project. They had extensive experience with circular building projects and are known for working with reclaimed materials. Furthermore, a carpenter was asked to join the development of the circular dwelling extension in a consulting role (as manufacturer).

The researcher developed 5 design variants for the circular dwelling extension: (1) the 'Reclaim! dwelling extension', (2) 'BIO-Extend', (3) 'Recycle me! dwelling extension', (4) 'Product-2-product dwelling extension', and (5) Plug-and-play dwelling extension'. See Figures App.D.24-25 for their technical designs.

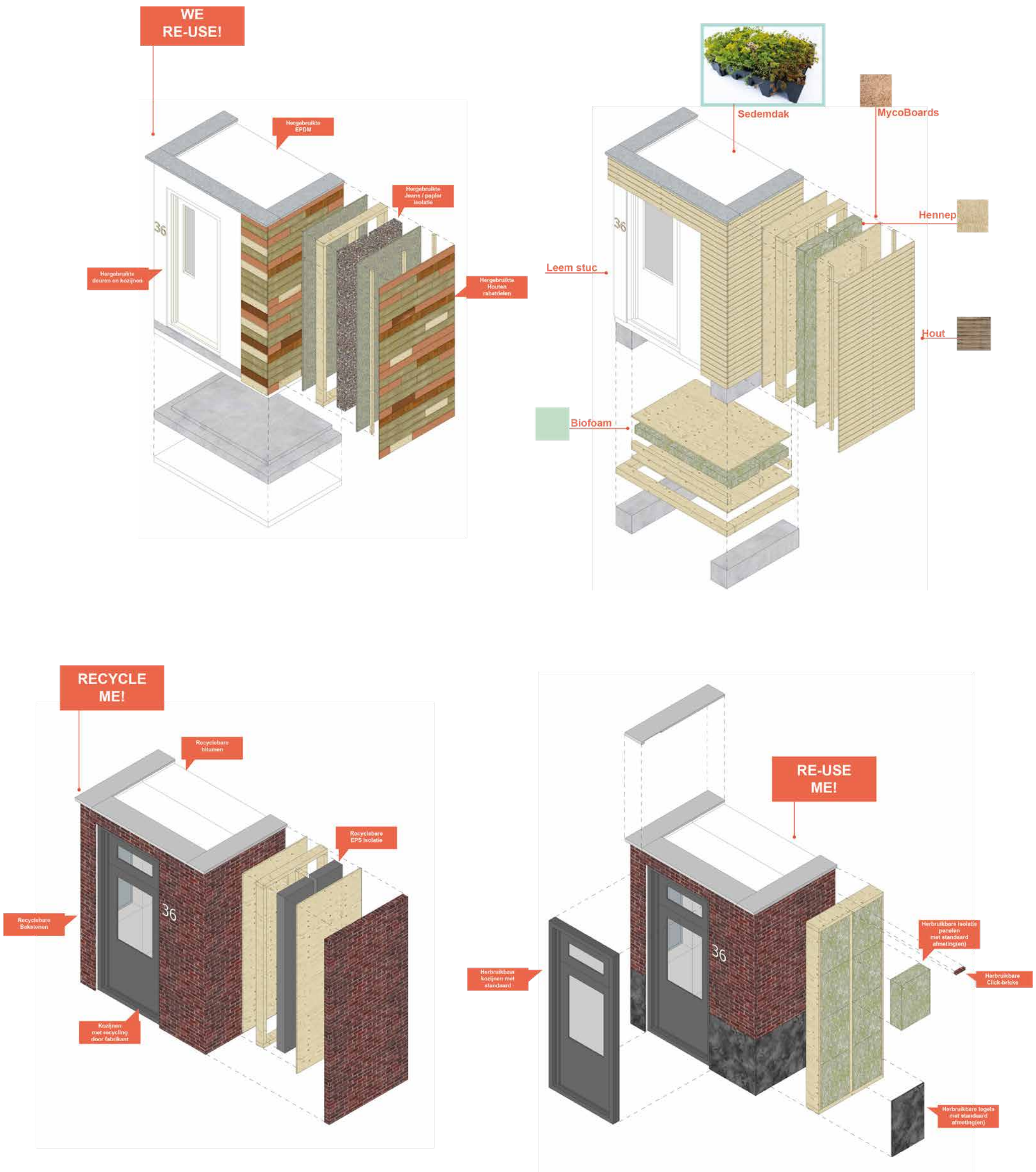


FIG. APP. D.24 Circular dwelling extension design variants (from top left to bottom right): (1) ‘Reclaim! dwelling extension’, (2) BIO-Extend, (3) Recycle me! dwelling extension, and (4) Product-2-Product dwelling extension

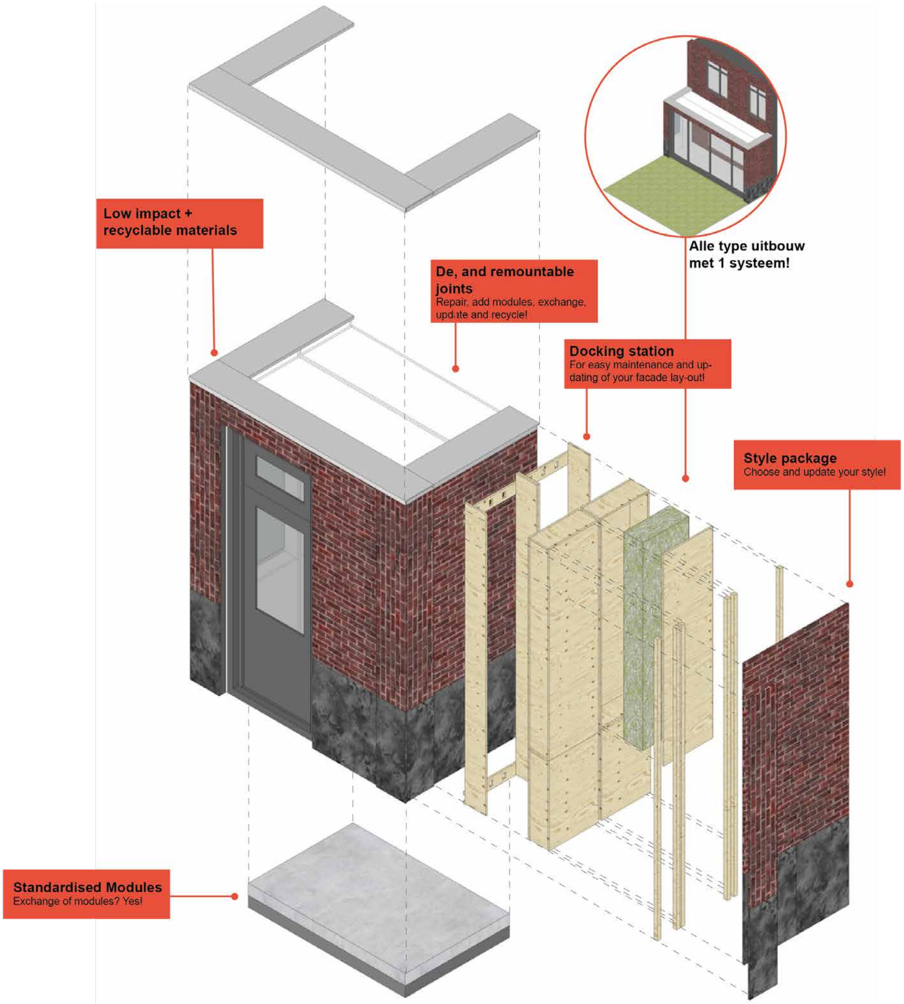


FIG. APP. D.25 Plug-and-play dwelling extension design variant

The Reclaim! dwelling extension applies non-virgin materials, either directly reused or recycled materials. It consists of a concrete floor-slab, and timber-frame roof and wall panels. The timber frame is filled with recycled cotton or cellulose insulation. The roof finishing is reused EPDM and the finishing consists of reused wood cladding. Reused doors and window frames are applied. The extension is sold to the housing association. At end of life (EoL), the housing association can have the extension disassembled and can directly reuse materials in a new project or have them recycled or incinerated.

The BIO-Extend applies bio-based and biodegradable materials. It consists of timber-frame floor, walls and roof panels. The timber frame is filled with hemp insulation. A mycelium board is attached on the exterior side of the timber frame and the façade is finished with clay plaster and wooden cladding. A sedum roof finishing is applied for the roof panel. The dwelling extension is sold to the housing association. At EoL, the materials are industrially composted.

The Recycle me! dwelling extension applies materials which could be recycled back into the same product at EoL. The joints between different materials are demountable to allow separation of materials into different recycling flows. The roof is finished with recyclable bitumen, bricks are used and EPS insulation is applied. The supply-chain and business model can remain the same as in the BAU design. The dwelling extension is sold to the housing association and at EoL the extension is disassembled into different waste flows for recycling.

The 'Product-2-Product (P2P) dwelling extension is based on direct reuse of building products: it consists of building products with a long technical lifespan, applying standardized sizes and connectors which allow for easy dis- and re-assembly. The P2P dwelling extension is constructed with a concrete floor, timber-frame walls and roof panels filled with EPS-foam boards. The façade finishing consists of click-brick strips and ceramic panels. The P2P dwelling extension's is sold to the housing association. At end of use (EoU), the extension can be dissembled, resold (e.g., on a building material platform), and re-assembled at another dwelling.

The 'Plug-and-play (P&P) dwelling extension applies a combination of circular design options to slow and close loops. The P&P dwelling extension is modular, separating parts based on their functional and technical lifespan. It consists of prefabricated floor, wall and roof modules with standard sizes. New modules can be added to adjust the extension to meet changing housing needs. Modules can also be disassembled for reuse in other dwelling extensions. The floor module consists of a concrete slab. The roof and wall modules consist of a docking station, timber-frame insulation module and finishing layer. The timber frame is filled with recycled cellulose insulation. A recycled, wood-wool board covers the exterior side of the timber frame. For the finishing of the façade, a wide variety of standard-sized panels can be easily (de-, and re-) attached using aluminium board anchors. For example, high-quality ceramic brick-strip panels or ceramic tiles. The P&P dwelling extension is either leased, sold with (prepaid) buy-back guarantee, or take-back guarantee. If sold, accompanying maintenance subscription and update services are offered. This business model provides an incentive for the provider (i.e., manufacturer and contractor) to realize a dwelling extension which is easy to repair, update, reuse or recycle. At EoU, we assume the dwelling extension or its modules can be adjusted and/or reused in the same or another dwelling. At EoL, the dwelling extension modules are disassembled and their materials are either recycled, down-cycled or incinerated.

The design variants were presented to the housing association, contractor, architect and manufacturer during a co-creation workshop. The group was asked to evaluate the design variants on their feasibility. We refer to Table App.D.9 for the reasoning of stakeholders on the feasibility of each design variant. The team decided that the plug-and-play dwelling extension should be combined with the Reclaim! dwelling extension and Bio-Extend variants.

TABLE APP. D.9 Perceived feasibility of the design variants for the circular dwelling extension

Reclaim! dwelling extension	+ Reduction of virgin materials and embodied impact now + 'Short loops' when materials are reclaimed from the project as there is not a lot of transport required + Not too innovative in terms of technique and process + With reclaimed materials circularity is apparent to people + Good for company image of stakeholders - Design does not facilitate reuse of materials in the future - Materials cannot be reused/recycled infinitely - Difficult to procure enough materials locally to manufacture just-in-time - Not innovative enough to just apply reclaimed materials: we could make it more circular - No guarantees for reclaimed materials
Bio-Extend	+ Reduction of non-renewable materials and embodied impact now + Materials do not need to be reused or recycled; this limits the amount of energy used in VRPs + Bio-based materials have a good image with people; they give a green image to projects + Fits current trend - The lifespan of these materials will likely be shorter than the service life. So, materials will look poorly over time. This is bad for the neighborhood image - It is a waste to let materials degrade over such a short time - Bio-based materials are not the final product, to make products and components technical materials will be needed (e.g., additives are needed in bio-based insulation) -Higher initial costs but no end-value (as they are applied in this design) - How to ensure that residents and our maintenance department will not paint the bio-based, biodegrad-able materials with 'normal' paint in the future? - Not enough land on earth available to grow enough bio-based materials
Recycle me! dwelling extension	+ Familiar appearance of the extension (no alternative materials) + easy to realize as it is close to current practice - Too much emphasis on material selection and recycling (i.e., closing the outer loop); there is more circular potential to prevent recycling by facilitating repair, reuse and adjustments (i.e., closing shorter loops) - This variant does not look circular - Circular on the very long term (only when materials are recycled in the future). Circularity is difficult to guarantee that way

>>>

TOC

TABLE APP. D.9 Perceived feasibility of the design variants for the circular dwelling extension

Product-2-product dwelling extension	+ Circular as it facilitates future reuse of building products and materials + Keeps products cycling at highest utility and value + Stimulates another way of doing business (not just selling more) + Familiar appearance of the extension (no alternative materials) + Vandal proof - This level of modularity facilitates reuse but not adjustments - This variant does not look circular - Circular on the long term (only when products are reused in the future). Circularity is difficult to guarantee that way
Plug-and-play dwelling extension	+ Most circular variant as it facilitates repair, adjustments and reuse by making partial replacements possible + Modularity facilitates aesthetic and functional customization now, and in the future, (this makes the design future-proof) + Due to the modularity this design is replicable on and scalable to other projects: modules become interchangeable - Having a standard module is 'a dream' which can become outdated in the future. In 20 years, a different standard module might be used. Then our system will be prematurely disposed of - This system requires a closed-loop supply chain to realize the circularity which is difficult to realize and guarantee - Not every material has the same measurement system: this might lead to production losses for one or more materials - Developing a standard module requires support from multiple supply-chain partners and the entire sector

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

APP. D.5.6 Developing a concept design (May 2019 – September 2019)

Five thematic co-creation workshops took place to develop a concept design from the chosen design variants.

The first workshop focused on 'modularity and standard measurements'. During this workshop the team discussed possible measurement systems. The group decided to work with measurements based on a 60 cm grid. They discussed the level on which modularity is realized (e.g., building component, sub-components or parts). The group decided that to cycle the dwelling extension at highest utility and value, modularity should be realized on all levels. From these discussions they proposed the main architecture of the extension. The extension would consist of standard-sized floor, wall and roof modules. The wall modules would be constructed with timber frames which consists of a docking station in which infill modules can be (re)placed. A finishing layer is mounted onto the infill modules, which can be easily clicked on and off. For the floor and roof modules, the team decided that a comparison matrix was needed to select the most optimal option.

The second workshop focused on materialization. An inventory was made of possible materials for each part of the building component. The group started to qualitatively assess their circularity and feasibility.

In the third co-creation workshop, circular assessment was discussed in more detail. A qualitative assessment matrix, based on environmental performance, economic performance and added value was developed. Three circular dwelling extension scenarios were chosen to compare the performance of the circular dwelling extension to: ‘maintain the existing dwelling extension’ scenario, ‘replace with a BAU dwelling extension’ scenario, and ‘replace with non-circular dwelling extension designed by an architect’ scenario.

In the fourth workshop, different options for windows and floor modules were compared. Also, the construction of the modular timber-frame walls was discussed further. The idea of a separate docking station was abandoned. The wall, floor and roof modules would form both the construction and insulation layer. An important discussion focused on the choice to keep the wall, roof or floor as one module or to make smaller modules within these modules. Making smaller modules (e.g., of 60 cm) would require to double the total number of vertical frames, increasing material use (see Figures App.D.26-27). The manufacturer stated that the reuse of these modules is uncertain and asked whether it would not be better to use less materials up front. The researcher indicated that this is the difference between circular design and eco-efficient design. A conscious choice to use a little more material up front can increase the lifespan and end value of the wall module. Incidentally, which variant has less impact can only be ‘proven’ through a life cycle assessment.

In a fifth workshop with the contractor, manufacturer and researcher, the choice was made to make smaller modules. Although this would increase the number of vertical timber frames, the group discussed options to minimize the thickness of the construction wood per module (Figure App.D.28).

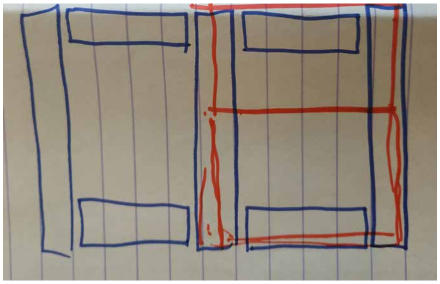


FIG. APP. D.26 Sketch of timber frame as one larger wall module

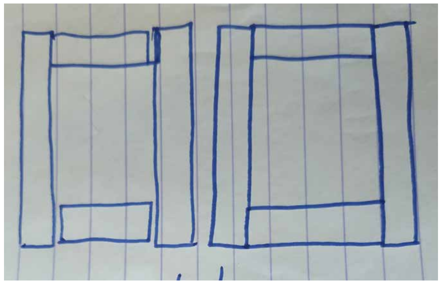


FIG. APP. D.27 Sketch of timber frames as two smaller wall modules

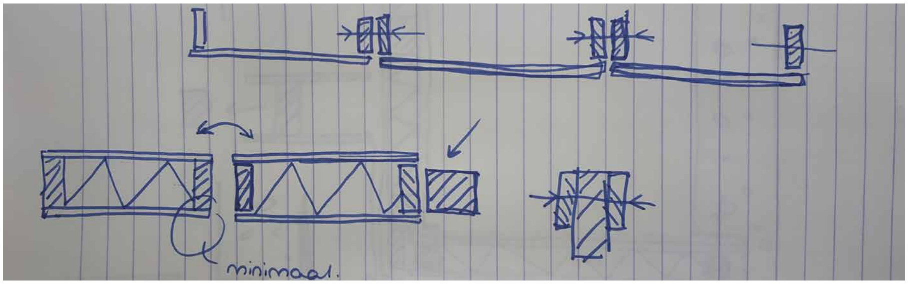


FIG. APP. D.28 Sketch of options to reduce material use in timber frames when creating smaller wall modules

From the input of these workshops, the researcher developed an initial concept design which is summarized in Figure App.D.29. The dwelling extension design is modular on component, subcomponent and part levels; the modules are standard-sized based on a 60-cm grid. In terms of materialization no definitive choices had yet been made. So, the design included (only) the suggestion that low-impact, bio-based or non-virgin materials should be used where possible.

The design was presented in a sixth co-creation workshop (July 2019) where the stakeholders reflected on the feasibility of the circular dwelling extension. In two following workshops, using this input, the concept design was compared to the other dwelling extension scenarios. For the comparison the previously-developed assessment matrix was used. The team found that maintaining the existing dwelling extension would be a bad investment. The BAU extension has high initial costs for the value it adds. The non-circular dwelling extension designed by an architect would be costly but not necessarily sustainable. The circular dwelling extension performed best of all scenarios on environmental performance, did not increase initial costs significantly compared to a BAU variant and provided added value because it was future-proof, a scalable solution and a provided a high-quality space for tenants.

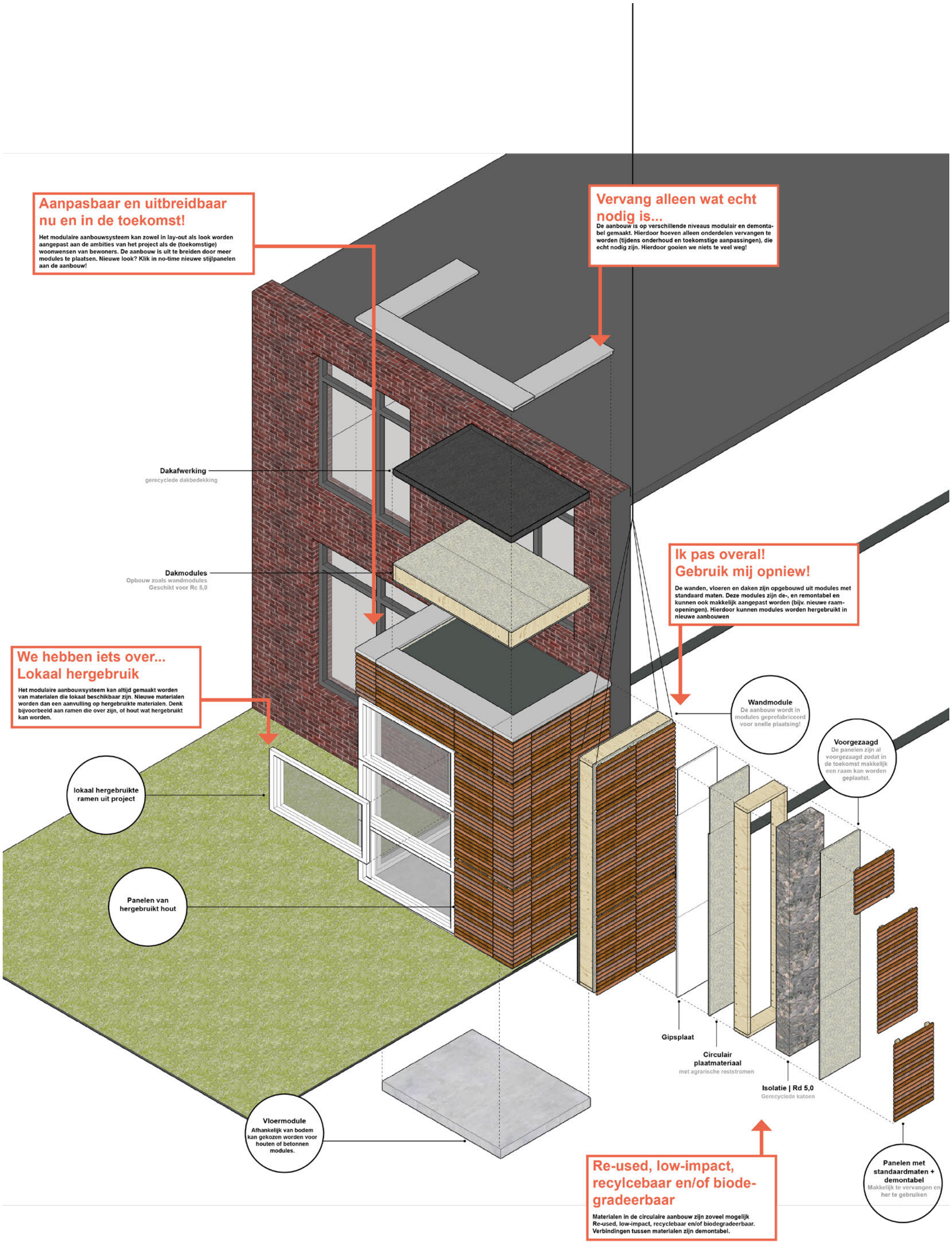


FIG. APP. D.29 Circular extension technical concept design

TOC

Parallel to these co-creation workshops, the architect developed a preliminary plan for the renovation of the project. They also included a design for the dwelling extension in their plan (see Figure App.D.30) They had made an inventory of all the materials which would be removed during renovation, including the old window frames, double glazing and wood from the pergola. They used these materials to configure the design of the dwelling extension. Notably, the principles of standardization and modularity were not (yet) pronounced in this design. The preliminary renovation plan and concept design for the circular dwelling extension were presented to the board of the housing association; approval followed several months later.

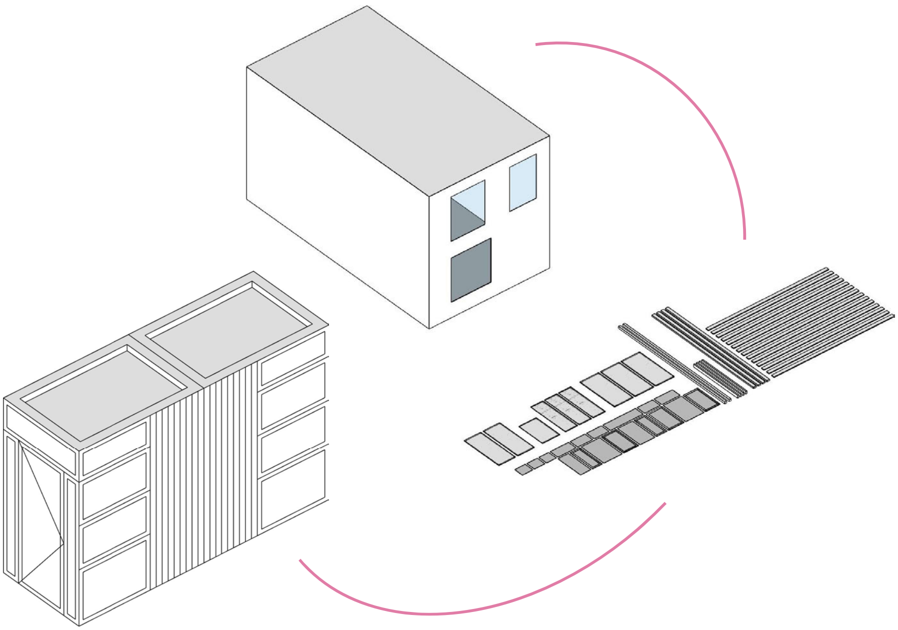


FIG. APP. D.30 Circular dwelling extension preliminary design showing material reuse from renovation project (image made by DOOR architecten)

APP. D.5.7 Starting-up the definitive design phase (December 2019-Februari 2020)

To develop the concept design for the circular dwelling extension further, a new plan of approach was written by the contractor and researcher. New co-creation workshops were scheduled which would take place in parallel to the development of a definitive design for the entire renovation. The contractor would take the lead

TOC

and the architect and manufacturer would provide the drawings as input. Moreover, a separate series of 3 workshops was planned to find a more quantitative way of assessing the circularity of the design.

The first step was to integrate the concept design (of the researcher) and preliminary design (of the architect). The team found that both designs contained desirable circular design options for the circular dwelling extension. So, during the first workshop both designs were merged. In this stage of the development new employees of the contractor ERA Contour joined the project. The manufacturer 'van den Oudenrijn' was selected to realize the dwelling extension and joined the team. The next two workshops were used as kick-off meetings. The concept design of the circular dwelling extension was explained and the lessons-learned from the previous co-creation workshops were shared. The purpose was to get the new stakeholder up to speed on circular design knowledge and align expectations.

APP. D.5.8 Developing a definitive design and preparing for the test home (March 2020-April 2020)

A series of 4 thematic co-creation workshops followed to develop a definitive design for the circular dwelling extension. In the first workshop, choices on modularity, standard-sizes and the architecture of the wall, floor and roof modules was revisited as new expertise was present in the team. Amongst all, the choice for modules on a 60-cm grid was reconfirmed. Also, the team discussed if the modules should fall outside, inside or 'on' the grid and to what extend future enlargement of the extension should already be prepared for in the foundation. In the second workshop, materials were selected. A long discussion took place on the possibility of making a wooden, timber-frame floor module rather than using a concrete slab. It was doubted that such a floor module would last long. The third and fourth workshop were used to finalize any outstanding choices and prepare the definitive design of the circular dwelling extension.

The following definitive design of the extension was included in the definitive design of the entire renovation: the circular dwelling extension is modular. Roof, floor and wall modules can be used to (re)configure different types of extensions. The modules are standard-sized – built on a 60-cm grid. In the future new modules can be added to adjust the extension to meet changing housing needs. Modules can also be disassembled for reuse in other dwelling extensions. As the extension remains outside the thermal skin, the modules did not have a very high insulation value. Higher levels of insulation were not required and this design choice reduced the material use now. In the future, an additional layer of insulation could be run in front of the module to achieve a higher insulation value if needed. The wall, floor and roof modules themselves consist of separate timber-frame modules and a finishing layer. No glue or PUR was used. This makes it possible to repair and update parts easily and facilitate reuse and recycling of materials. Where possible, reclaimed materials were used. For example, reclaimed wood from the old pergola in the renovation project was reused as façade finishing. In the renovation project, windows with double-glazing were replaced for triple-glazing. The old window frames and glazing were reused in the extension. The door was reused from another renovation project. The reclaimed door and windows did not fit in the 60 cm grid. So, a separate frame was placed into the front façade in which the reclaimed parts could be fitted. This frame functioned as an intermediary element to bridge differences in sizing between the standard-sized modules and custom measurements of reclaimed materials. The rainwater drain was also reused from another renovation project. Recycled cotton insulation and recycled roof felt were used. See Figure App.D.31, for the definitive design of the circular dwelling extension.

APP. D.5.9 Detailed design and preparing for the test home (May 2020 – October 2020)

The definitive design was further developed to a detailed design. Additional choices needed to be made on materials, suppliers, sub-contractors and how to realise the circular dwelling extension (i.e., the building processes). Also, those who would join during the realisation phase would need to be educated on what is circularity and what is different about this project. The researcher and contractor developed circular guidelines for builders, purchasers, foremen and work-planners. Additionally, new information was revealed during this stage which required adjustments of the design. For example, after consulting the structural specialist, the old foundation was found insufficient for this extension design and a new foundation was required. Circular alternatives – like reclaimed steel beams - were considered. But no suitable beams in terms of sizes and material treatments were found. So, new steel profiles were chosen. Furthermore, various choices needed to be made in the harvesting and treatment processes of the reclaimed materials. For example, the reclaimed wood from the pergola is applied as the cladding of the circular dwelling extension. After disassembly, part of the wood was found to be quite weathered and mossed. Different treatments were tested to find out which would look best and would be feasible in terms of time (see Figure App.D.32).

TOC

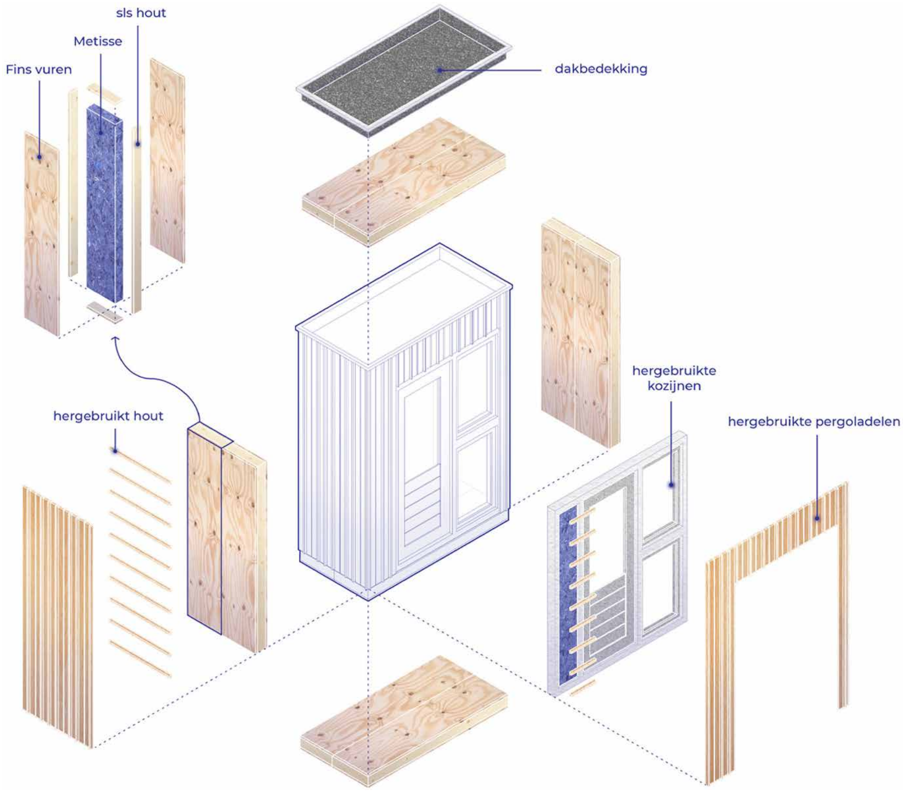


FIG. APP. D.31 Circular dwelling extension definitive design (image made by DOOR architecten)

FIG. APP. D.32 Testing multiple treatments for the reclaimed wooden façade finishing of the circular dwelling extension

The circular dwelling extension was prefabricated in the production hall of the manufacturer and installed in October 2020 in the test dwelling (see Figure App.D.33). Additionally, the circularity of the design has been assessed by an external consultant using the Building Circularity Index (BCI). The BCI suggested that the environmental performance would increase if the floor module would apply more durable materials. So, it was decided to apply reclaimed hardwood to increase the lifespan of the floor modules without increasing their environmental impact.

FIG. APP. D.33 Circular dwelling extension in test home

FIG. APP. D.34 Circular dwelling extension as realized in the renovation project (photo by DOOR architecten)

APP. D.5.10 Realisation of the renovation project, evaluation and next steps (October 2020 – August 2021)

The entire renovation plan had received the required percentage of approval from the tenants in the beginning 2021 and went through permitting in the first half of 2021. It has since been implemented in 44 dwellings of the renovation project (see Figure App.D.34). The circular dwelling extension has been evaluated in two workshops with all the stakeholders involved in design and implementation. The stakeholders evaluated what they considered had gone well and what they thought required improvement (see Table App.D.10).

TABLE APP. D.10 Stakeholder evaluation of the circular dwelling extension development and realization process

Technical design and realization	+ Beautiful design which fits with the quality that the housing associations wants for its tenants + looks like new, not like reused material + The project process went well: great collaboration and everybody was informed on the circular plans through the kick-offs and the presentations of the researcher - More quality control needed in the factory to minimize improvement points on site - Harvesting materials is a project in its own right: more time is needed for work preparation, resident communication, capacity and safety - Cleaning the reclaimed wood from the pergola took more time than calculated - The role of the material supplier moved to the manufacturer (harvesting, removing nails and cleaning materials) - Cheaper laborers should be hired to clean reclaimed wood instead of expensive skilled laborers - During harvesting, different batches of pergola wood were discovered. So, the extensions' façades will not all look uniform -More time is needed between granting the commission and start of work when materials need to be harvested -To simplify the project, it would be easier to harvest materials from other projects - Materials with non-virgin content had a longer delivery time -Quality of the floor needed to be improved to resist moisture. So, we had to use more durable materials like hardwood -If the extension becomes an on-demand option for tenants, we need alternative sources for reclaimed materials or a storage
Circularity	+ Many circular design options were implemented; this allowed us to learn a lot + Combination of circular design options which narrow, slow and close loops + A lot of reclaimed materials were applied + Future cycles have been facilitated + The BCI showed the design was very circular + (Contrary to wat was initially thought) standardizing led to little material loss during production + Assessing the design using the BCI taught us how to reach our circular ambitions + The involvement of an architect, researcher and consultant with knowledge and experience on circularity was very important to develop the circular extension - We applied virgin wood in the timber frame; we need to find a more circular alternative or apply reclaimed materials - Reuse of steel beams was challenging due to their coatings - The environmental impact of the new foundation was not considered in the scope of this project. A new foundation was required because of increasing the size of the extension due to using the 60cm grid - The technical design was developed but the organization of the future VRPs and business model has not been determined yet. When is the right moment for this?

>>>

TOC

TABLE APP. D.10 Stakeholder evaluation of the circular dwelling extension development and realization process

Costs	+ The value of the non-virgin materials rose because virgin material prices rose. This makes reuse more affordable + We were more secure of costs because we used a lot of reused materials rather than virgin materials + As this is a scalable design, we might get more certainty about costs and duration of renovation in the future + Reclaimed materials were used cost-effectively + Circular costs and benefits were compared in parallel for circular and non-circular scenarios: very insightful to see what circularity costs - Virgin material cost rose between detailed design and realization - Due to using the 60-cm grid, the extension became a bit larger. A new foundation was needed increasing the costs - End value should be made visible in cost calculation - It took a lot of labor to harvest and clean reclaimed materials, so costs were high. This could maybe be done more efficiently - The reclaimed windows were hand-painted. It would be more cost-efficient to spray-paint them -The sub-contractor for the roof felt worked on site. In the future it might be more price efficient to do this in the factory
Value	+ The quality of the space is better: it is a real room + Placement did not impact the garden too much. One row of tiles needed to be removed + The space is insulated. This is appreciated by most residents + It is quite beautiful + Standard measurements mean it is easy to enlarge later on: future proof + We can adjust the finishing layer if we reuse the modules + There are opportunities to apply the extension elsewhere: in particular to make extensions for climate installations, balcony closets and to offer as an on-demand option for tenants - The circular extension is a darker space (less windows) than the old extension. This makes the living room darker as well
Collaboration	+ Long process with high-quality workshops and meetings + Consistency in people involved + Commissioning process was great: selection on a pitch rather than a book + Involving circular experts and architect to guide stakeholders in this process + Linking a component development to a project provides pressure and capacity to do it + It was great that we focused on one component because it takes a lot of time, doing everything fully circular would not have been feasible + Client who is consistent in their circular ambition gave the market a push + Continuous involvement of the client in the development process + Clear planning and parallel co-creation sessions - In hindsight some subcontractors, the maintenance department of the housing association and a reclaimed material broker should have been involved earlier in the process - More circular material suppliers need to be found - How to guarantee future VRPs in the process? We still need to organize these

Stakeholder evaluation which increased the perceived feasibility is indicated with a '+' and evaluation which decreased the perceived feasibility is indicated with a '-'.

The next step for the contractor and housing associations is to explore how the circular dwelling extension can be replicated in following projects and how the lessons-learned can be implemented in other building components.

APP. D.6 Summary of the development process of the NZEB-light and resulting designs

In this appendix we describe the development process of the 'Net Zero Energy Building (NZEB)-light' renovation concept – or ‘Nul-Op-de-Meter (NOM)-light’ renovatie concept in Dutch. The NZEB-light concept included roof, façade and climate installation components. Although this description is elaborate, it should not be understood as exhaustive. We describe how the development took place, the type of choices we made and show the resulting designs.

APP. D.6.1 Starting the collaboration and setting goals (October 2017 – July 2018)

In the ‘REHAB’ research project, researchers of the Delft University of Technology and Amsterdam Institute for Advanced Metropolitan Solutions aimed to develop feasible circular building components for the renovation of Dutch social housing by co-developing and testing them together with stakeholders from practice. Over the course of one and a half year, the researchers formed three teams centred around the development of different circular building components.

Housing association Wonion contacted the researchers. Wonion was already doing a pilot on circular demolition and new built. They were also interested in doing a circular renovation project in order to learn more about it. A cluster of dwellings for senior citizens was up for renovation. Over the coming years, ±20 of these dwellings would be renovated per year. Wonion wanted to realize the projects with local contractors and installation service providers rather than asking a larger contractor from out of the region. For this purpose, a new ‘result oriented collaboration’ was formed between 4 local contractors and 3 local climate-installation service providers. The idea behind the collaboration was that partners would be involved long-term, allowing them to learn from each project and iteratively improve the renovation approach and reduce costs. Furthermore, in the collaboration, the aim was for the contractors and climate-installation service providers to propose the best approach to meet the requirements of the client. They take the lead in the development and could divide the work between them.

Their idea was not to develop a new approach per project, but to develop a project-transcending, sustainable renovation toolbox. This toolbox was to be filled with state-of-the-art, sustainable renovation components. By mixing and matching these components, the approach could be tailored to the various renovation projects of Wonion. Hence, the renovation approach can be continuously improved and prices reduced. An ambition document was created for the renovation approach. This document included ambitions (not goals!) for various fields of sustainability. Circularity was one of these ambitions (see Table App.D.11)

TABLE APP. D.11 Brief summary of ambitions for the to-be-developed renovation approach

Ambition		Explanation ambition
Generic approach		Can be replicated in multiple projects. With each project, the solutions will be improved and the initial costs and the average total cost of ownership reduced
Energy positive		The solution is not just energy neutral but will supply energy. It prepares us to become self-sufficient (go off-grid)
Low maintenance		Reduce future maintenance costs without high additional investments required
Life-proof approach		The dwellings should be suitable for residents in all stages of life, including seniors. So, the dwellings need to be wheelchair- or walker-proof
High tenant satisfaction		The renovation should be realised while the tenant still lives in the dwelling without causing too much nuisance. The approach should increase tenant awareness for sustainability, should be easy to use and should decrease the total costs of living for tenants
+50 years on top of service life dwelling		After renovation the dwelling needs to have an extended service life of 50 years, without needing significant additional investments or maintenance
Modular renovation approach		Most of the housing portfolio of Wonion has been maintained and updated over time. This makes NZEB renovation in which the whole exterior and interior is renovated in one go, financially unattractive. Furthermore, for blocks with fragmented ownership, such renovations are unaffordable for owner-occupiers. Therefore, the NZEB renovation approach needs to consist of 'sustainable' modules which can be applied during natural maintenance and renovation moments
Approach includes sustainability ambitions integrally	**Quality of life by living**	Ensuring we create places where people want to live and work. The renovation needs to be affordable and cause little nuisance. It should be simple to use the dwelling post-renovation (e.g., no complex climate installation system)
	Building a movement	Building sustainable awareness and scalable sustainable solutions step-by-step with our partners
	Green grows!	When dwellings are demolished or renovated, increase the green blue-networks
	Energy-rich living	Energy use needs to be reduced to NZEB-level or better; we prepare to go off-grid
	No waste: a circular built environment	Building components should be circular by narrowing, slowing and closing loops through their design, supply chain and business model
	Clean as a bike	Reduce transport-related emissions through sourcing locally, reducing transport movements and using sustainable means of transport

Setting up the collaboration, the development of the toolbox and filling the toolbox with first building components would be included in the scope of the first renovation project. For this particular project, Wonion had the goal to reduce the energy use to net zero; they wanted to integrate other sustainability goals into the applied renovation – including circularity. The role of the researcher was (1) to put circularity on the agenda during the development of the renovation approach and toolbox, and (2) to support the stakeholders in developing more circular building components for the renovation approach.

APP. D.6.2 Kick off workshop and plan of approach (July 2018 – November 2018)

The researcher organised a kick-off workshop. The researcher presented the basic theory of circular renovation and explained various circular design options. As a small exercise, the stakeholders had to generate ideas for a circular building component by applying circular design options in the span of an hour and a half. They were divided into two groups. One group worked on ideas for a more circular climate installation and one on a circular façade. Both groups presented a collection of ideas which could make both building components more circular. The researcher summarised their design ideas in Figures App.D.35-36.

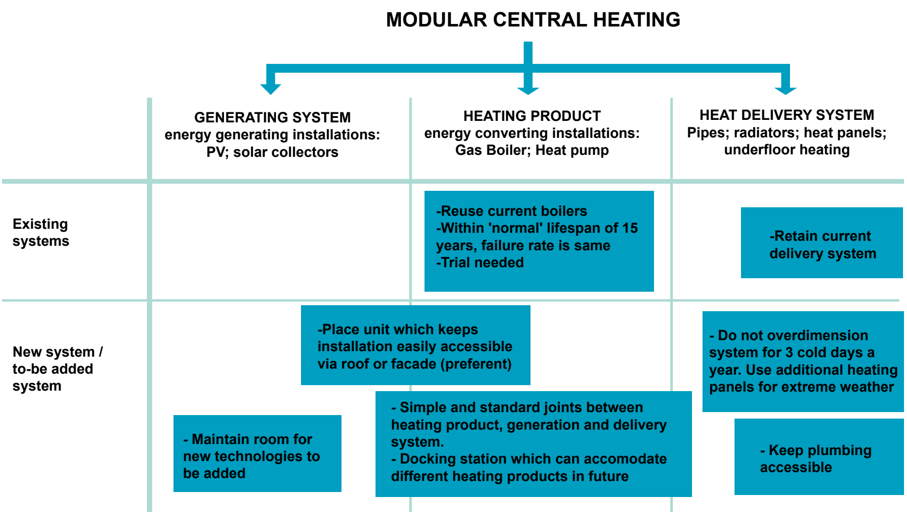


FIG. APP. D.35 First design ideas for a circular climate installation

TOC

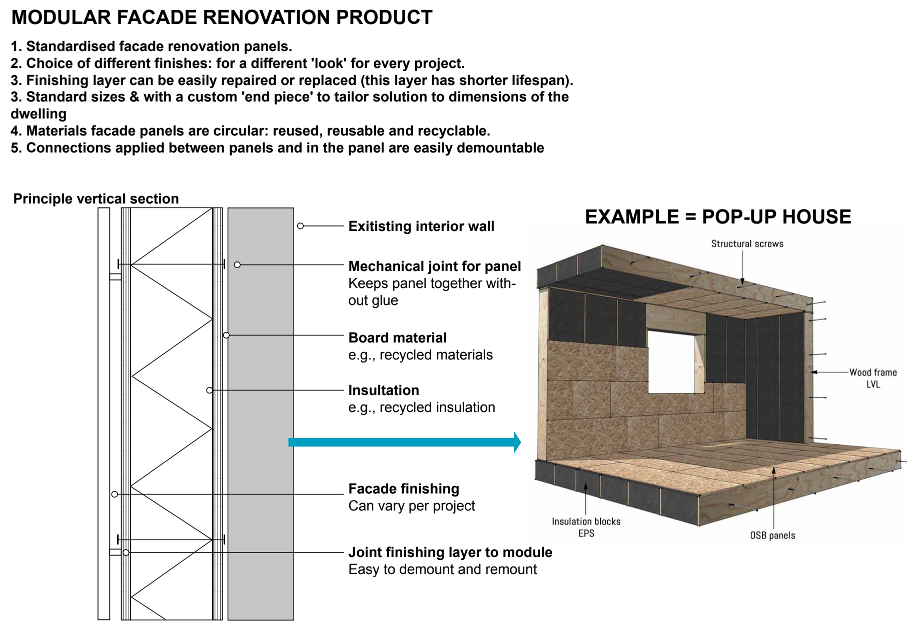


FIG. APP. D.36 First design ideas for a circular renovation façade

The stakeholders were then asked to evaluate the feasibility of these designs. See Table App.D.12 for a summary of their reasoning on the designs' feasibility. In the following period the contractors and installation service providers were to develop an approach for the first renovation project. The conclusion of the workshop was that these first design ideas could be taken into account during the development of the approach for the project.

The stakeholders started to explore renovation scenarios for the renovation project and worked on solidifying the new collaboration. The researcher and housing associations proposed a plan of approach to also develop circular renovation components. As a starting point, the decision was made to focus on developing a circular façade and roof in the scope of the first project. This was a logical choice, as both building components would likely be applied in the first renovation project. In the following project a more circular climate installation would be explored. The plan was to develop the circular roof and façade in 4 co-creation workshops which would take place in parallel to the renovation-project process.

TABLE APP. D.12 Perceived feasibility of the first ideas for a circular renovation façade and climate installation

Circular façade design	+ the design for the façade is circular because it applies the following options: • Insulation with reused materials is very circular • A façade with insulation panels and separate finishing layer • Modularity in façade panels is very circular • Standardization of the façade panels • Prefabrication • Possibilities to reuse the modular façade • Possibility to adjust the façade and finishing • De-, and remountability • The recycling opportunities • Possibility to apply bio-based materials - The measurement system of the modular façade needs to be researched: is this possible in renovation? - The plastic windows and window frames in the current project are 'only' 30 years old. Can't we keep these longer? - Where can the 2^{nd} hand materials (reused materials) come from? - Can we make this product or do we need manufacturers?
Circular climate installation design	+ the design for the circular climate installation is circular because it applies the following options: • Maintaining existing products and materials (e.g., radiators) • Modular system • No-nonsense and focus on extending lifespan • Step-by-step approach - The boiler on the upper floors is not convenient - Replacing a functioning central-heating boiler is not circular - The boiler itself is not a circular product - Is it possible to reach optimal energy performance using the existing infrastructure and radiators?

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

APP. D.6.3 Developing a circular skin (January 2019 – February 2019)

In the first co-creation workshop, the stakeholders evaluated business-as-usual (BAU) façade and roof designs. The stakeholders were divided in groups of two. Each team selected one BAU roof and façade component. The groups were then asked to 'dissect' these building components into a systems-tree. Following, they had to evaluate the circular potential of the building component using a 'circular quick scan'. This is a checklist of circular design options to narrow, slow and close the loop, developed by the researchers. The group then reflected on the results of the quick scan, determining which elements of existing components were found circular or not. The following 5 improvement points were specified: (1) standardization of the components in sizes, parts and/or panels; (2) using no adhesives, instead use de-, and remountable connections; (3) the existing components use mostly high-impact, non-reused and non-recyclable materials. The circular roof and façade components should use more circular materials; (4) make a simple design; (5) coordinate the technical, functional and economic lifespan. During the second half of the workshop, the researcher presented different circular building approaches and example cases in which circular design options were applied. The group was then asked to evaluate the feasibility of these. Furthermore, they could specify if they missed any examples. The findings are listed in Table App.D.13. The output of this workshop was taken into account in the development of circular design variant for the façade and roof components.

TABLE APP. D.13 Perceived feasibility of the circular design options as applied in example approaches and cases

Circular design options applied	Example approaches and cases	Reasoning of the feasibility by stakeholders
Separating building into components based on lifespan; standardising sizes; de- and remount-able joints	Open Building approach; shearing layers Component renovation (by Bouwhulpgroep)	+ Adjustability of Open Building is very circular + Dry joints are very circular (e.g., floating heating pipes) – Unclear what the advantage is of adjustability – Separation of 'support' and 'infill' is not possible in existing stock (they are already fused together) – The standardized measurements do not fit to measurements of the existing dwelling
Modular component; separating parts based on lifespan; standard-ising sizes; de- and remountable joints; applying bio-based and low-impact materials	Circular kitchen; BILT Huis; Circl House; PD-LAB	+ Modular sub-components and separation based on lifespan is very circular as it facilitates adjustability + Bio-based and renewable materials are very circular + Adjustability has high user value + Potentially, low cost-price – A prefab façade is not circular – Demountable building is difficult to realize – The standardized measurements are difficult to match with measure-ments in existing dwellings – Modular parts are difficult to realize
Reused materials; de- and remountable joints; component and material passports	Circl pavilion	+ Reused materials and material passports are feasible to realize – This is a very local approach and you need a lot of transport

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

The researcher developed 5 design variants for the circular renovation façade and roof (see Figure App.D.20 in Appendix D.4). During the second workshop, the researcher presented these variants and asked the stakeholders to evaluate their feasibility. The circular design options applied per design variant and the results of the evaluation have been included in Table App.D.14.

TABLE APP. D.14 Circular design options applied in 5 design variants for a circular renovation façade and roof component, and their perceived feasibility by stakeholders

Design variant and applied circular design options	Reasoning on the perceived feasibility by stakeholders
Reclaim! skin Roof and façade design based on using reclaimed materials	+ Reduction of virgin materials and embodied impacts now + 'Short loops' when materials are reclaimed from the project as there is not a lot of transport required + Can be done in the scope of a project + Starting of a material bank – Questionable sustainability of the reclaimed materials. For example, the jeans itself are not sustainable products. Then we make insulation. How can this insulation be sustainable? – Reclaiming materials from a building not designed for it can be difficult – There are multiple moments in the lifecycle of a building when materials come available (multiple collection moments) – New material costs are quite low compared to reclaimed materials. This makes choosing for reused and recycled materials difficult – There is no / not enough choice at the regular 'wholesaler'. Where do we get reclaimed materials? – Reclaimed materials / parts are already at the end of their lifespan. For example, technical (e.g., rotten window frames) or functional (e.g., single- or double-glazed windows) – There are not enough reclaimed materials
Bio-skin Roof and façade design based on using bio-based and biodegradable materials	+ Reduction of non-renewable materials and embodied impacts now + Renewable materials, so we can grow more + Bio materials provide a higher living comfort: we can make a 'breathing' building + Not feasible to change all materials to bio-based alternatives + Some bio-based materials are certified like clay plaster and straw insulation – We will need a lot of biological materials – The materials are not reusable as a product (no slowing of loops) – Do we have enough biological materials or do we need more planets to provide them? – Origin of materials unknown or far. The Netherlands does not have a lot of forests – There is no / not enough choice at the regular 'wholesaler'. Where do we get such materials? – There are probably not enough bio-materials – The maintenance costs could be higher – Is there enough acceptance with tenants for these solutions?
Recycle me! skin Roof and façade design based on using materials which can be recycled well in the future	+ Good idea for regions with reducing number of inhabitants through demolition permits – Transport, storage and degradation of recycling materials
Product2product (P2P) skin De- and remountable roof and façade design facilitating future reuse of building materials and products (e.g., brick, rooftile, window)	+ Facilitates future reuse of building products and materials: all parts are reusable multiple times and this slows the loop + If done at large scale, this could be scaled up easily + Easy to realize and implement – Limited aesthetic choices – Parts which are applied horizontally cannot be reused (they degrade too much)

>>>

TOC

TABLE APP. D.14 Circular design options applied in 5 design variants for a circular renovation façade and roof component, and their perceived feasibility by stakeholders

Design variant and applied circular design options	Reasoning on the perceived feasibility by stakeholders
Plug-and-play (P&P) skin Modular roof and façade design consisting of standard-sized blocks which facilitate repair, adjustments and future reuse of component, parts and materials	+ Standardization and demountability facilitates future repair, adjustments and reuse at highest utility and value + Possible to only replace the part that is needed; prevents premature obsolescence of the whole component + Examples already exist, such as Open Building + [Potential for mass-production] will lead to reduction of costs due to increased speed, less mistakes, lower costs – Limits design freedom – It is circular on component level but not on part level (parts are not reusable) – The existing building stock does not have standard sizes. How can we deal with measurement differences? – Can we solve the non-standard measurement through ‘custom pieces’? – Difficult to ensure thermal performance due to vertical joints – Standardization of measurement needs to be forced on the entire market for this to work. Currently this is not the norm – Does this approach fit the interests in the supply chain – How big is the exchangeable building volume? (Does this really make an impact?)

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

The stakeholders agreed that a combination of design variants would be preferent. Variant 5 should form the basis of the design; both the variants applying biological (variant 2) and reclaimed (variant 1) materials should be integrated in the P&P design. Further modularization on part level (variant 4) should also be investigated. The stakeholders raised questions which should be investigated and tested in further development. Furthermore, the group discussed the next steps for further development. The contractors felt that the development of such a circular façade and roof component is difficult; it is not their core-business. Instead, they suggested that a third-party should do this – like a manufacturer. Furthermore, they stated that a newly developed solution cannot be implemented right away. There is no pre-calculated data available for newly innovated components in their software to calculate the energy performance. In order to give any guarantees, all kinds of testing would need to be done by the contractor. Finally, the contractors and climate-installation service providers felt that the start date for the renovation project was already too soon to still develop new circular building components. They also had already found another façade renovation product which they wanted to apply in the first project. They concluded that the collaboration should focus on finding implementable solutions rather that making ideal but unfeasible solutions themselves. The group suggested the first project could be executed with existing products and for a second project a circular building component could be developed.

Following the conclusions of the second workshop, the plan of approach for the development of more circular building components was adjusted. Instead of designing new circular façade and roof components to apply in the renovation project, the focus was changed to making a more circular renovation approach using existing building products and materials. A dual plan was proposed. Some of the building components for the first renovation project had already been selected. So, with the contractors and climate-installation service provider responsible for the first project, the focus would be on optimizing their proposed approach on circularity. For the second renovation project, we would take a more 'ideal' design concept as a starting point for the circular roof and façade. Then, we would look to what extent we could realize this concept using existing building products and materials.

APP. D.6.4 Optimizing the approach for the first renovation project on circularity (march 2019-may 2019)

The first renovation project included 22 dwellings for senior citizens at Wijnwaarden in Terborg (11) and Prinses Irenestraat in Varsseveld (11). The contractors Te Mebel vastgoedonderhoud BV and Rudie Jansen, and climate-installation service provider Klein Poelhuis developed the renovation plan together with Wonion. The project consisted of 6 blocks of 4 homes each. 2 homes had been sold and were partially included in the renovation. The initial goal was to renovate these dwellings to NZEB level.

During the next team meeting, the stakeholders presented their approach for the first renovation project. The approach was evaluated by the stakeholders, identifying which aspects they considered very circular and which aspects could still be improved. The approach per building component and evaluation has been included in Table App.D.15. No product choice had yet been made for the climate installation.

TABLE APP. D.15 Perceived circularity of proposed preliminary design per building component

Description design per building component	Design aspects stakeholders perceived were already very circular (+) and not yet very circular (-)
Roof • Standardized, integrated insulation panels placed on top of the existing purlins. • Panel consisting of hardboard, EPS, foil and spruce battens – glued together.	+ The roof insulation panel is modular + The roof covering (tiles) is also modular + Joints between products are de- and remountable + The insulation panels and tiles have standardized measurements so they can be used again as a product + A smart installation plan is very important to maximize the number of whole insulation panels so they remain reusable – Integrated product consisting of glued materials. These cannot be easily demounted and recycled at EoL of the panel – EPS is an oil product – EPS is recyclable in theory but who will be responsible is not clear – The gap sealing is done with PUR and kit. This means the modularity and demountability of insulation panels is lost – No inventory has been made of what materials can be reused from the renovation.
Façade • Insulate façade cavity with EPS granules (glued after installation); • Insulate exterior of the façade using a modular, insulation system: standard-sized, EPS boards with slot- and groove connections. • Metal connectors are integrated in the boards to screw them to the façade. • Milled slots for wooden furring laths to mount façade finishing • Different façade finishes are still possible (e.g., rooftiles, wooden cladding, façade panels, boards with brick strips).	+ The façade insulation panel is modular + Most façade finishing options are very modular. Only glued brick-strips and plaster are not + Joints are de- and remountable and standardized + (Part of the) façade finishing can be easily removed for repair and updates + Metal anchors and wooden furring laths can be removed to facilitate recycling + Insulation panels have standard sizes and are easily reusable as such + A smart installation plan is very important to maximize the number of whole insulation panels so they remain reusable – Slot and groove connection inhibits demounting one panel (without removing the rest). Inhibits repair or adjustments – EPS is an oil product – EPS is recyclable in theory but who will be responsible is not clear – The gap sealing is done with PUR and kit. This means the modularity and demountability of insulation panels is lost – No inventory has been made of what materials can be reused from the renovation.
Floor • Insulate crawlspace with EPS flakes.	+ Uses less materials – After filling the crawlspace, the access to infrastructure (plumbing, sewage and wiring) is blocked – EPS is an oil product – EPS is recyclable in theory but who will be responsible is not clear
Façade openings • (Possible option) window and door frames of modified wood	+ Wood is a renewable material and has low environmental impact. As it is not painted it will have a low impact at EoL + Possibly, a standard size can be chosen, making the window frames easy to reuse in the future -Not clear if materials can be separated at EoL

Realized interventions and circular design options in the first renovation project

The preliminary design was put forward for evaluation by the housing association and found not financially feasible. The ratio of façade, roof and floor surface requiring insulation was high compared to the gross rentable floor area. The complex geometry of the skin at the rear of the dwelling increased the initial costs even further.

The stakeholders chose to lower the energy ambitions to make the renovation feasible. They tried to get as close to NZEB-level as financially feasible. The floor, façade and roof were insulated. The dwelling was taken of the gas, installing an all-electric heating system. See Figure App.D.37 for the result of the renovation.

The façades were not insulated using exterior panels as the costs were found too high. Instead, the façade cavity was filled with insulation. The stakeholders chose to do this with EPS granulate to avoid the use of PUR. The existing window-frames were kept and refitted with HR++ glass. The Trespa® panels used as façade finishing had weathered. Instead of replacing them, the stakeholders chose to flip them to make them look as new. Only those which were in poor condition were replaced. The crawlspace of the floor was insulated using EPS flakes which can be removed and reused in the future. The roof was insulated using an integrated PIR-insulation panel. These have been installed using screws and no PUR has been used for gap sealing. Rather a swelling tape has been applied to ensure demountability and reusability. The Trespa® fascia boards needed to be moved upwards due to the new insulation layer. By carefully considering the detail, the old boards could be reused as they were still in a good state. The Trespa® fascia panels have been cleaned, reused and secured with Trespa® screws from another project. The skylights in the roof were removed to make space for the solar panels. These skylights were placed in storage so they can be used elsewhere. A great deal of attention has been paid to realizing gap sealing without using PUR. The high-efficiency boiler has been replaced by an air-to-water heat pump. The high-efficiency boilers had only been used a short while so they were reused in other properties of Wonion. The boilers were reused in the following days to prevent the water retained within the boiler to cause erosion. A new heat recovery unit has been installed for ventilation.

FIG. APP. D.37 (On the right) more circular nearly-NZEB renovation

APP. D.6.5 Developing a NZEB-light renovation approach and pilot project (August 2019-September 2020)

The second renovation project focused on the Koningin Emmastraat in Terborg and consisted of 25 single-family homes. The contractors Lenferink, De Variabele and climate-installation service provider Wassink took the lead in this project. Before the project team had started with the design process, the researcher proposed a new plan of approach for developing a more circular roof and façade. The plan proposed a two-day pressure cooker to kick-start the development. However, no common dates could be found for such a kick-off. During the first project team meetings in November and December, a choice was made to address circularity within the project team meetings rather than organizing a parallel process.

In the following meetings, it became apparent that the project team had the ambition to develop a more cost-efficient NZEB renovation solution. In NZEB renovations the heat load is usually reduced to 30 kWh/m^2/year. The team found that reducing the heat load from 50 kWh/m^2/year to 30 kWh/m^2/year is relatively expensive compared to reducing the first ±100 kWh/m^2/year. Furthermore, research on user behavior showed that residents in very energy-efficient housing do not actually use less energy than those in slightly less energy-efficient housing. In other words, they considered the last 20 kWh/m^2/year reduction as theoretical and costly. So the team

TOC

was motivated to develop a NZEB home with a heat load of 50 kWh/m^2/year which could be realized using as little interventions as possible. At this value the tenant's energy bill would be significantly lowered, their living comfort increased and the cost of renovation would be lower. Furthermore, an energy performance fee could still be asked from tenants to recuperate the investment of the renovation over time. Circularity would be taken into account as well but focusing efforts on (1) reducing material use by doing less and (2) exploring circular alternatives for materials which needed to be added.

In each of the project team meeting, circularity of various project decisions was considered. Different contractors and climate-installation service providers where in the lead of this project and involved personnel had also changed. So, to give the team more concrete support in choosing more circular products and materials, the researcher organized a second workshop on the evaluation of circularity of existing products and materials. This workshop had a similar set-up and purpose as the one organized a year earlier.

In the following meetings a proof of concept for an NZEB-light renovation was developed. As this was not yet a proven design, the team decided to realize two pilot dwellings rather than renovating all 25 dwellings straight away. In the realized pilot, the heat load was reduced to 50kWh/m^2/year. Instead of insulating the exterior of the dwelling skin, the existing skin was insulated as much as possible. The measures differed slightly per dwelling, depending if the dwelling was a corner or terraced house. A corner house needs more measures to lower the heat demand than terraced housing. The existing façade cavity insulation was insulated again where needed, as the previously-installed insulation flakes had sagged over the years. New glass panes (partly HR++ and partly HR+++) have been placed within the existing window frames. The Tonzon floor insulation consisting of foil insulation pillows had been partially eaten by rats. Although an inquiry had been made to repair the existing insulation, it was more cost-efficient and less risky to replace it with new Tonzon floor insulation. The roof was insulated from the inside by clamping flax insulation between the rafters. The team researched if the rooftiles really needed replacement. In this case, the rooftiles needed replacement. The team first explored if reclaimed rooftiles could be placed. However, reclaimed rooftiles are offered to the market for the renovation of period properties; purchasing reclaimed rooftiles was found too costly. So, a low-impact virgin rooftile which cleans exhaust gases (NOx) from the air was selected. It turned out that the roof battens also needed to be replaced (see Figure App.D.38). A water-to-water heat pump was placed with a vertical drill hole of 270 m deep. Originally it was the intention to connect 4 homes to 1 drillhole. During the drilling, the last part of the drilling was more difficult than expected, increasing the drill time. Perhaps, 1 drill-hole per home which is less deep would be more cost-effective as it can be carried out with a smaller drill. The current heating delivery system (e.g., radiators and plumbing) could be maintained. A heat recovery ventilation unit has been installed in the attic. A lot of attention was also paid to the gap sealing using flexible PUR, kit and tapes. See Figure App.D.39 for the NZEB-light pilot homes during renovation.

FIG. APP. D.38 Low-impact virgin rooftiles

FIG. APP. D.39 Aerial view of construction site NZEB-light pilot homes (on the left)

APP. D.6.6

Evaluation, documentation and next steps of the projects (September 2020 - December 2020)

The researcher and housing association organized two meetings to evaluate the circular innovation process within both projects, to document the reasons for taking certain choices and determine next steps.

The first meeting focused on evaluation. The stakeholders were asked to inventory what they thought went well in the developed approaches in terms of circularity. The partners indicated that the NZEB-light approach could potentially reduce the costs of NZEB renovations by 40%, increasing the financially feasibility of NZEB renovations in general. Much thought has gone into the use of materials. In many renovation projects interventions are clustered. Even if (part of) a building component could still last several years, it is combined into the larger renovation moment. In this project, stakeholders continuously considered if the replacement of the material was absolutely necessary. For example, they decided to keep the existing heating delivery system. Although replacement was found necessary, the stakeholders also investigated if it was possible to keep the existing rooftiles and to repair the floor insulation. If stakeholders considered it was necessary to (re)place materials, they considered if it could be done with less materials and if long-life, non-virgin or lower impact alternatives could be selected. Next to the physical results in the project, the stakeholders indicated that they have learned a lot on circularity and that it is now something which they consider during their decision making. The stakeholders also inventoried what did not went well in terms of circularity. The inventory has been included in Table App.D.16.

TABLE APP. D.16 Perceived circularity of proposed approach per building component

Project	Circular aspects of the renovation approach which stakeholders considered did not yet went well
Renovation project 1 Prinses Irenestraat & Wijnwaarden	Circular gap-sealing is important to improve energy-efficiency and comfort for tenants. Yet, it remains difficult as existing products glue materials together. No circular alternatives were known to stakeholders.
	The materials in the climate installations are not very circular yet. There was not enough time in the development process to really look into finding more circular installations.
	Applying more bio-based materials was not possible, partially because they were more expensive and partially because the lifespan of the materials was shorter than the desired service life extension for the project.
	Residents were not yet included into the circularity of the project. Can we provide residents with better information about sustainability and circularity so that they also understand its importance?
	The façade cavity was filled, but the material is not circular.
	The existing glazing was replaced for new glazing with a higher insulation value. The existing glazing was not broken but did not fulfil the high energy requirements. There is no circular solution available for such existing glazing.
	The integrated roof insulation panels are not yet circular.
	The circularity of the roof finishing remains a challenge: if roof tiles have to be replaced and the roof is filled with PV panels, are placing roof tiles the most circular solution? Because you place double layers of materials.
	We need more time to investigate circular options and to document our choices.
	We chose interventions based on the need to improve energy efficiency, quality and comfort of the tentant. Then, we tried to seek the most circular options to realize it. Next time should consider circularity already when choosing the intervention itself.
Renovation project 2 Koningin Emmastraat	PV panels were applied to reduce operational energy use. However, PV panels themselves are energy intensive to manufacture, require critical materials and are not easy to recycle.
	The number of transport movements during construction could be reduced. At times there were many people on the construction site. Huge savings can be made on CO_2 by driving fewer kilometers. It is better to think about this in advance, together with all the subcontractors.
	The requirements of making the dwelling NZEB as affordable as possible, and considering circularity sometimes clashed. How to weigh the different requirements was challenging.
	We should prevent trying to innovate everything at once in one project. Next time we should make choices beforehand in what we aim to achieve in this project and what we 'postpone' to a next project.
	The drilling (for the heat exchanger) made a mess on the site which needed to be repaired; it caused nuisance for tenants.
	The residents complained about drafts from the old window frames. We decided to keep the window frames and seal the gaps with sealing strips. But are old plastic frames suitable to maintain? And, did our solutions really resolve the tenants' complaints?
	No inventory has been made of the materials that were removed during renovation and could be reused. In the next project we can think about this in advance, so that there is more time to find a new use for them.
	The costs for NZEB-light were still considerable. Where can further savings be made in the follow-up process? What are the maintenance costs of the water-to-water heat pump?
	It was hard to formulate a good definition of circularity that could be shared with product and material suppliers to ask them for more circular alternatives.
	A lot of information is available to help evaluate the circularity of building products and materials. However, it remains difficult for the stakeholders to interpret this information.

During the second meeting, a format to document the choices made during the development process was proposed. In this format, the stakeholders could document the solution they proposed (e.g., building product or material); they can include reasons for (not) selecting this solution. As such, their reasoning and lessons-learned could be retained for the following renovation projects in this collaboration. The document can also help to transfer knowledge to new members of the collaboration.

The housing association also looked how they wanted to integrate circularity into their policy. They evaluated the different ambitions towards renovation projects and proposed a hierarchy of ambitions. They concluded that their main aim was to make their housing stock CO_2 neutral. Herein they saw that reducing the operational energy use was a leading consideration to determine the interventions needed. If interventions were needed, they needed to be circular (see Figure App.D.40). So, materials that come out of the renovation are (in order of preference) reused on site, reused in another project of the housing association, reused by a third party or recycled. If new materials need to be added they should be (in order of preference): non-virgin, bio-based, linear. Furthermore, the materials should be applied so they can be disassembled after use. The housing association indicated they will prioritize circular design options which can reduce environmental impacts in projects now rather than applying solutions which slow and close cycles in the future.

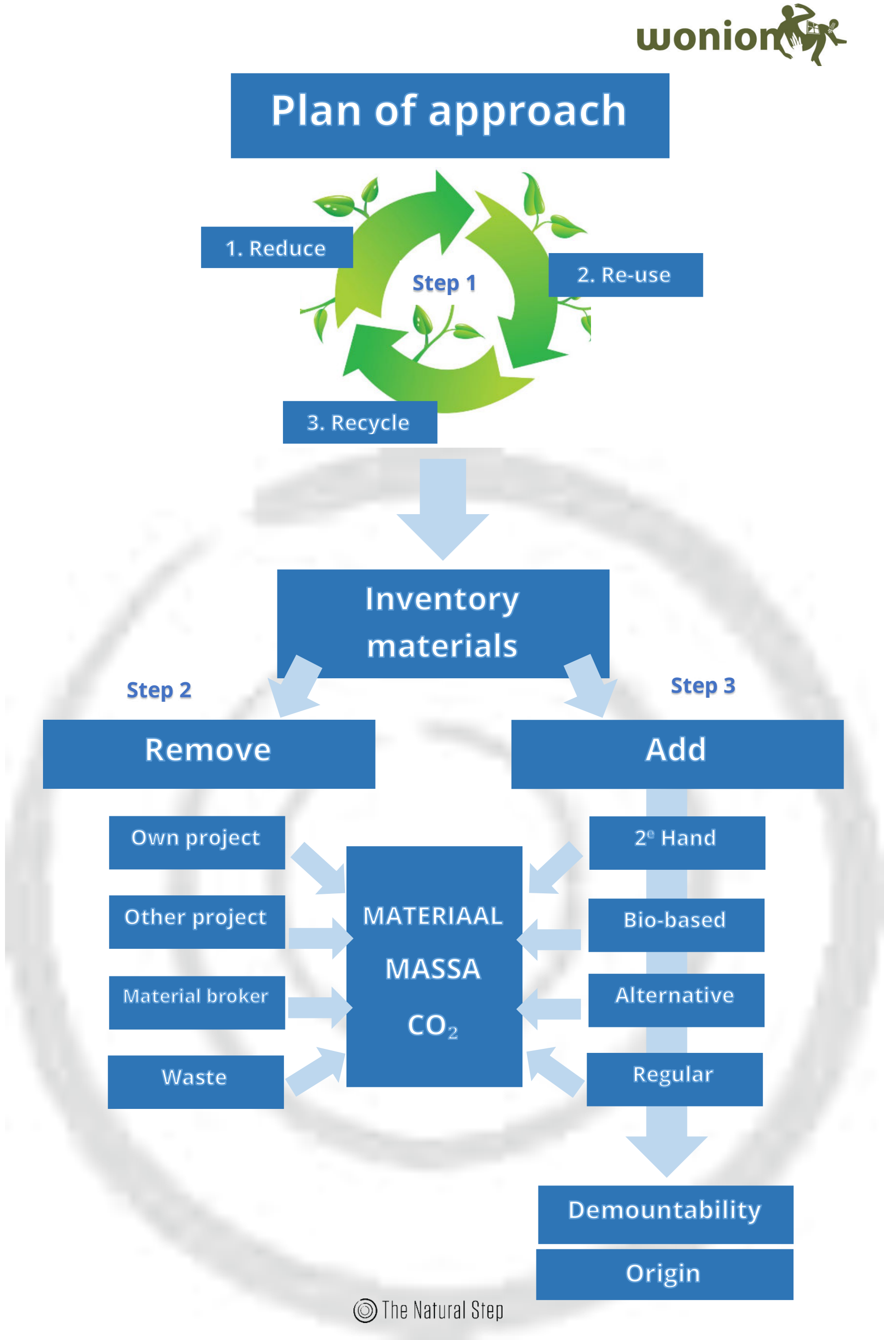


FIG. APP. D.40 Circular strategy Wonion prioritizing specific circular design options (image adapted from Wonion; The Natural Step)

APP. D.7 Summary of the development process of the circular boiler and resulting designs

In this appendix we describe the design choices and developed designs throughout the development process of the circular boiler. Although this description is elaborate, it should not be understood as exhaustive. We describe how the development took place, the type of choices we made and show the resulting designs.

APP. D.7.1 Starting with a clear objective and planning

As part of the ‘Circular components’ research project, a consortium was formed upon the initiative of researchers of the Delft University of Technology and Amsterdam Institute for Advanced Metropolitan Solutions. This consortium was interested in co-developing a design for a circular central heating boiler. The design was to include a (1) technical design, (2) design of the supply chain and (3) a business model, initially targeted at Dutch social housing associations. The project had a one-year duration and was meant to foster the innovation to the level of proof of principle. In this project the researchers drove the innovation. They scheduled meetings with individual stakeholders to learn about their practice and developed design proposals. They organized co-creation workshops during which the stakeholders were asked to reflect upon these designs.

To complete the development to proof of principle, the researchers planned three steps. In the first step, the focus was on understanding the business-as-usual (BAU) in the technical design, supply-chain and business model using interviews, micro internships and factory visits. The researcher gained insight in supply-chain interests, and potential opportunities and barriers for implementing circular design options. Gaining this understanding was necessary to develop requirements for the design. In the second step, design variants for the circular central heating boiler were designed by combining different circular design options. These variants were presented to the stakeholders in a co-creation workshop. During the workshop, the stakeholders were asked to identifying the most circular and feasible variant(s). In the third step, the selected design variant(s) was developed further to a principle design and tested for feasibility. In the following workshop, a first principle design was presented and the stakeholders would identify opportunities to make the design more circular and feasible. Their remarks were used to refine the initial principle design. During the final workshop, the refined principle design was tested for feasibility by a larger group of stakeholders.

APP. D.7.2 Business-as-usual and requirements for circular boilers

The researcher visited the stakeholders, including the social housing association (Waterweg Wonen), climate-installation service provider (Feenstra) and climate-installation manufacturer (Remeha). The stakeholders completed an interactive questionnaire. Furthermore, the researcher had a mini-internship at the climate-installation service provider and manufacturer. At the climate-installation service provider, the researcher was given a tour of the logistical point. Central heating boilers are returned there after de-installation and spare parts are kept there. At the manufacturer the researcher was shown the assembly line and received a course on how to install and repair one of the business-as-usual (BAU) boilers.

These activities provided insight on the status quo in the industry and design context; from these insights the researchers derived the following requirements for the circular boiler design. First, the Netherlands is currently transitioning from gas to other sources of energy. Although several municipalities have formed gas-transition ambitions, there was no clear national policy at the time of the project. The uncertainty about the gas-transition needed to be taken into account in this research through inclusion of different scenarios: gas, hybrid and all-electric. Second, in the central-heating boiler supply chain, many Value Retention Processes (VRPs) are already present, such as maintenance, repair, reuse, refurbishment and recycling. However, these VRPs are quite transport intensive. Also, reuse and refurbishment loops are currently set-up for a limited number of boiler parts but not for boilers as whole products, which hampers a fully circular approach for the whole boiler. To keep a circular boiler cycling at its highest utility and value reuse and refurbishments of the boiler and all its parts should be facilitated, organized and incentivized.

APP. D.7.3 Circular central heating boiler design variants

The researchers developed design variants for the circular boiler using an initial version of the ‘Circular building component generator’ design tool which was later published in van Stijn and Gruis (2019). Different circular design options listed in the tool were used as the building blocks. By ‘mixing and matching’ these building blocks different variants for the circular boiler were made. 4 variants were developed (see Figure App.D.41): (1) the green boiler, (2) the plug-and-play central heating, (3) the circular central-heating (C^2) Boiler, and (4) the 3D boiler. Each design variant follows a different pathway towards the circular economy. In other words, each design is circular in ‘its own way’.

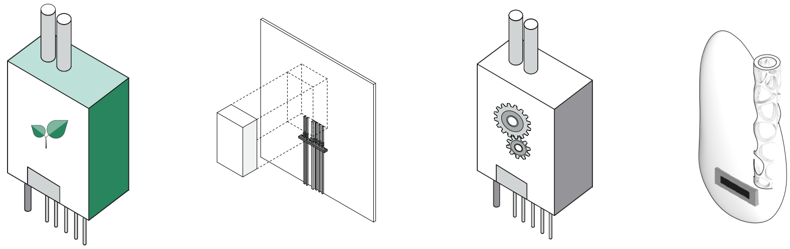


FIG. APP. D.41 Technical model for the design variants of the circular boiler

The green boiler follows the biological loop of the circular economy model. The material of the boiler is changed to a (to-be-developed) bio-based and biodegradable material. The supply-chain model remains the same as the BAU model from production to installation. At the end of use the boiler is industrially composted. By using the biological loop, the business model can remain based on product sales.

The plug-and-play central heating system proposes to separate the static climate system (i.e., plumbing and radiators) from the heating product. This model focusses on prolonging the lifespan of the climate installation itself by facilitating future adjustability of the heating product in the system. As such it accommodates different gas transition scenarios. The standardized, plug-and-play climate system could be purchased by the landlords with a take-back guarantee. The heating product could be leased separately from a provider including a maintenance contract or performance agreements. The provider could be the boiler manufacturer, climate-installation service provider or a collaboration between both parties. If the boiler is leased, the boiler could even be plugged-out to do repairs off-site.

The C^2 Boiler addresses the circularity of the heating product itself by exploring how the heating product can go through the loops of maintenance, repair, reuse, refurbishment, remanufacturing and recycling. The boiler is separated into modules and parts based on expected lifespan. Several circular design options are combined in the design of the boiler, modules and parts. The boiler has an easy and standardized design. The boiler, modules, and parts must be easy to open and close using standardized connections and tools to facilitate repair and refurbishment. The boiler is over-dimensioned to facilitate updating. The parts must be easy to separate into mono-materials to facilitate recycling. The producer becomes a key actor who – in collaboration with the climate-installation service provider – initiates the VRPs of the heating product in a return factory.

The 3D boiler makes use of the recycle loop. Using renewable energy, recyclable plastic and metals, the boiler is 3D printed as a product or in parts. 3D-printing workshops would be locally run and offer 'reprint' services to repair, refurbish and recycle boilers. A more futuristic variant as 3D-printing technology is not yet used on this scale. Additionally, plastics are not yet infinitely recyclable.

During the first workshop the 4 variants were presented. The stakeholders were asked to evaluate their feasibility. See Table App.D.17 for the results of the stakeholder evaluation.The stakeholders discussed that combining biobased materials (variant 1) and 3D-printing techniques (variant 4) could result in a very circular boiler. It would lead to non-impactful and infinite cycles, all whilst being able to adapt to newer designs. However, both variants were considered too futuristic and would require decades of development. A combination between the plug-and-play central heating system and the C^2-Boiler was identified as the most circular and feasible variant. Although the plug-and-play variant makes the climate system itself circular in its use, the heating product plugged into the system should ideally also be circular. As most of the gas transition scenarios do include the use of a central heating boiler for the perceivable future, it was concluded that the C^2 boiler should also be developed.

TABLE APP. D.17 Perceived feasibility of the design variants for the circular central heating boiler

The green boiler	+ Might be (partially) possible technically - This would take 30 years of development - A dream, not possible - Bio-based materials cannot comply to 3 regulatory requirements: (1) gas safety, (2) energy efficiency and (3) drinking-water safety - Greenwashing - No added value and additional services in the business model
Plug-and-play central heating	+ This design allows us to prepare for & adapt to the requirements of 2050 + This design allows us to adapt the dwelling to the user + This solution unburdens the client (by offering flexibility and turn-key solutions) + Creates loyalty and a long-term relationship between client, provider and manufacturer + Speed of plugging in and out means the service will be fast (residents do not need to wait at home very long) + This variant should be applied from the client's perspective as it provides an interesting value proposition + Allows for many VRPs: keeps heating system cycling at highest value ± Close to current practice (this variant does not teach us a lot) ± Might lead to less service moments on site. Also means the housing association has less opportunities to enter the dwelling and notice social/technical issues - Standardizing the docking-station is challenging: requires consensus and developments in boilers go too fast to allow for standardization - Unclear how long gas boiler will still be used
C² Boiler	+ Reliable and future-proof + A modular and easy to repair boiler is close to current design + Creates loyalty and a long-term relationship between client, provider and manufacturer ± Increases service moments on site. Also means the housing association has more opportunities to enter the dwelling and notice social/technical issues - Unclear how long a gas boiler will still be used. This prevents opportunity to invest in further development - Likely leads to a bigger boiler: will the client accept this? - More demountable joints results in higher risk of malfunctioning parts
3D Boiler	+ Easy to adapt to new requirements + Interesting to print (parts for) less common boilers + Advantage in logistics - Nice for technical conventions but too futuristic - With this technique the boiler cannot comply to 3 regulatory requirements: (1) gas safety, (2) energy efficiency and (3) drinking-water safety - Leads to high diversification of models (difficult to keep track and service)

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+' and reasoning which decreased the perceived feasibility is indicated with a '-'.

APP. D.7.4 Iterative development to a principle design

The researchers developed an initial principle design by combining and detailing the chosen variants. The stakeholders reflected on this initial design during the second workshop; their input was used to refine the principle design. For the technical, supply-chain and business model, see Figures App.D.42-45, respectively.

The technical model consists of a climate installation system where a heating product can easily and swiftly be plugged in and out. The connection between the climate installation and heating product is made in a standardized plug-and-play station with standardized plug-in-points, using standardized and easy connections and flexible joint pieces. The system accommodates the adaptation of the climate system to several gas transition scenarios: (different) gas, hybrid (using solar or heat-pumps in combination with a central heating boiler), and all-electric (solar, heat-pumps with electric post-heating, etc.).

For the heating product, principles for a circular central heating boiler (C^2 heating boiler) are proposed. A short-term and long(er)-term scenario are explored. In the short-term, BAU central heating boilers should be used in a more circular way by focusing on the lifespan of the parts instead of the boiler itself. By including live-monitoring sensors, the return loops can be executed more efficiently. On the long(er)-term, if it becomes clear that the gas transition still includes gas as an energy source, a new C^2 heating boiler needs to be developed. The C^2 heating boiler is separated – based on expected lifespan – into C^2 modules, and module parts. The C^2 heating boiler, C^2 modules and module parts need to be developed following 9 principles aimed at extending their lifespan where possible and facilitate repair, refurbishment, and re-cycling (see Figure App.D.43).

In the supply-chain model the existing loops in the supply chain are streamlined to reduce transport, and the missing loops are added. The climate-installation service provider is the key partner in the supply-chain and business model. They sell the climate installation with plug-and-play station to the housing associations, with the agreement that at the end of life they take these products back. They also offer the use of a heating product through an 'all-inclusive package'. The package deal offers heat over a period of time with a certain performance guarantee (including energy efficiency, service, or circularity KPI's). The package includes: the use of a heating product for the agreed upon time period, the maintenance and repairs, and system updates. The all-inclusive package unburdens housing associations from non-core tasks. It also incentivizes climate-installation service providers to use their boilers and parts as efficiently as possible. The reduction in their costs can benefit circular innovation in their products and/or result in a lower total cost of use.

The climate-installation service provider, in collaboration with the wholesaler and heating product manufacturers, initiate the return loops. Their current 'return warehouse' is extended to a 'RE-factory' from which they initiate the repair, reuse, refurbishment, remanufacturing and recycling of the climate installation, the C^2 heating boiler, C^2 modules, module parts and materials.

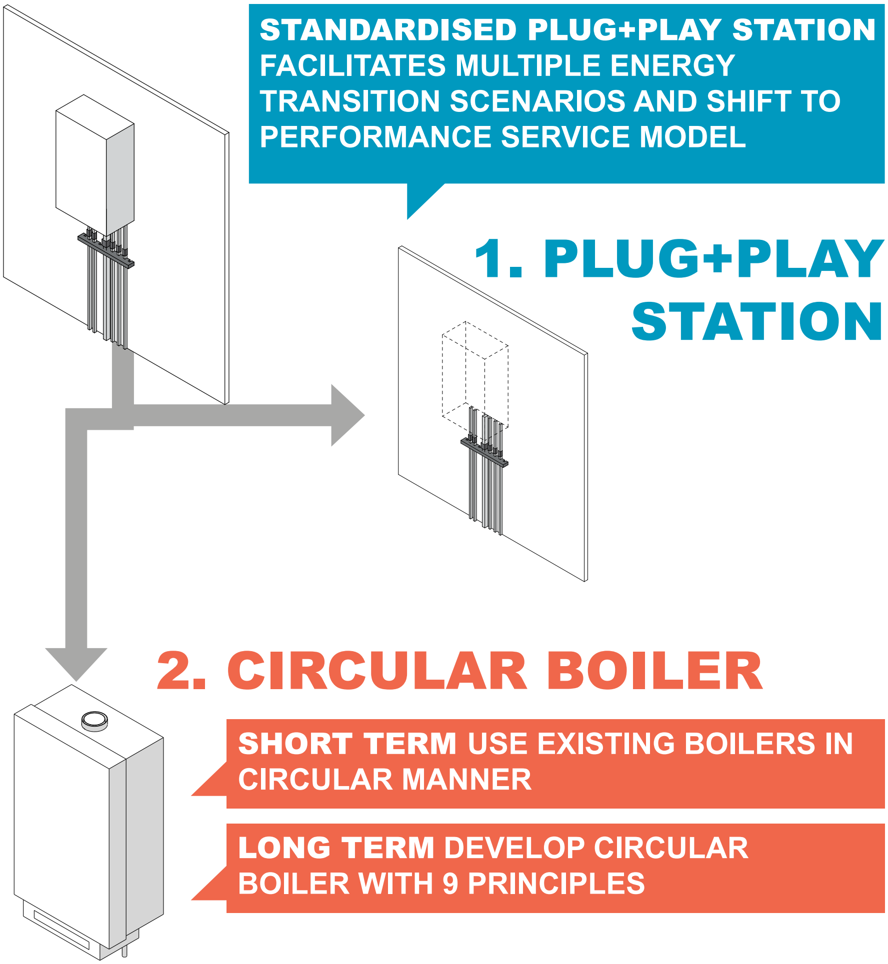


FIG. APP. D.42 Technical model circular climate system

APP. D.7.5 Testing the principle design on feasibility

In the third workshop, multiple social housing associations and circular experts were invited alongside the stakeholders involved in the development. The refined principle design was presented by the researchers. Following, in two parallel sessions, different aspects of feasibility were tested. In the session with housing associations,

TOC

the economic feasibility was tested. The housing associations were asked: is there a demand for a circular boiler? In a session with CE experts, the circularity of the principle design was evaluated. The experts were asked: is the principle design circular or how can it be improved?

The housing association representatives identified several arguments why they would purchase the developed circular building component. The ease of repair and claimed durability was seen as a major advantage. The flexibility of the building component within their housing stock and the potential convenience for asset management proved to be a motive to choose for the circular boiler. However, the housing assocation also provided conditions for the purchase of the circular boiler. Although long-term relationships within the supply chain were seen as highly desirable, the housing associations also mentioned that it was important not to be stuck to one supplier. The circular boiler needs to be scientifically assessed as a more circular and durable option. Also, it was found very important that the proof of principle allows for all possible scenarios of the gas transition. The most important condition for the developed circular boiler was an equivalent or lower total cost of ownership.

The experts suggested that in the further development of the circular boiler the following points should be reviewed. The current proposal proposes a more circular boiler which could be on the market in a few years. By looking at 'ideal' circular ideas, and then back-casting them, the short-term proposals can be improved and potential lock-ins prevented. In the further development, more attention needs to be given to circular material selection. Finally, more review is needed on tenant behavior in relation to (the use of) circular building components.

APP. D.7.6 Is there enthusiasm to develop the circular boiler further?

Following the third workshop, the researchers contacted the climate-installation service provider and manufacturer to plan a meeting to explore further development of the circular boiler. The stakeholders indicated that it was not the right moment. Although, the central heating boiler showed potential for market-uptake, the uncertainty of the gas-transition formed a significant obstacle. Later that year a decision was expected from the government on the future of gas as a heat source.

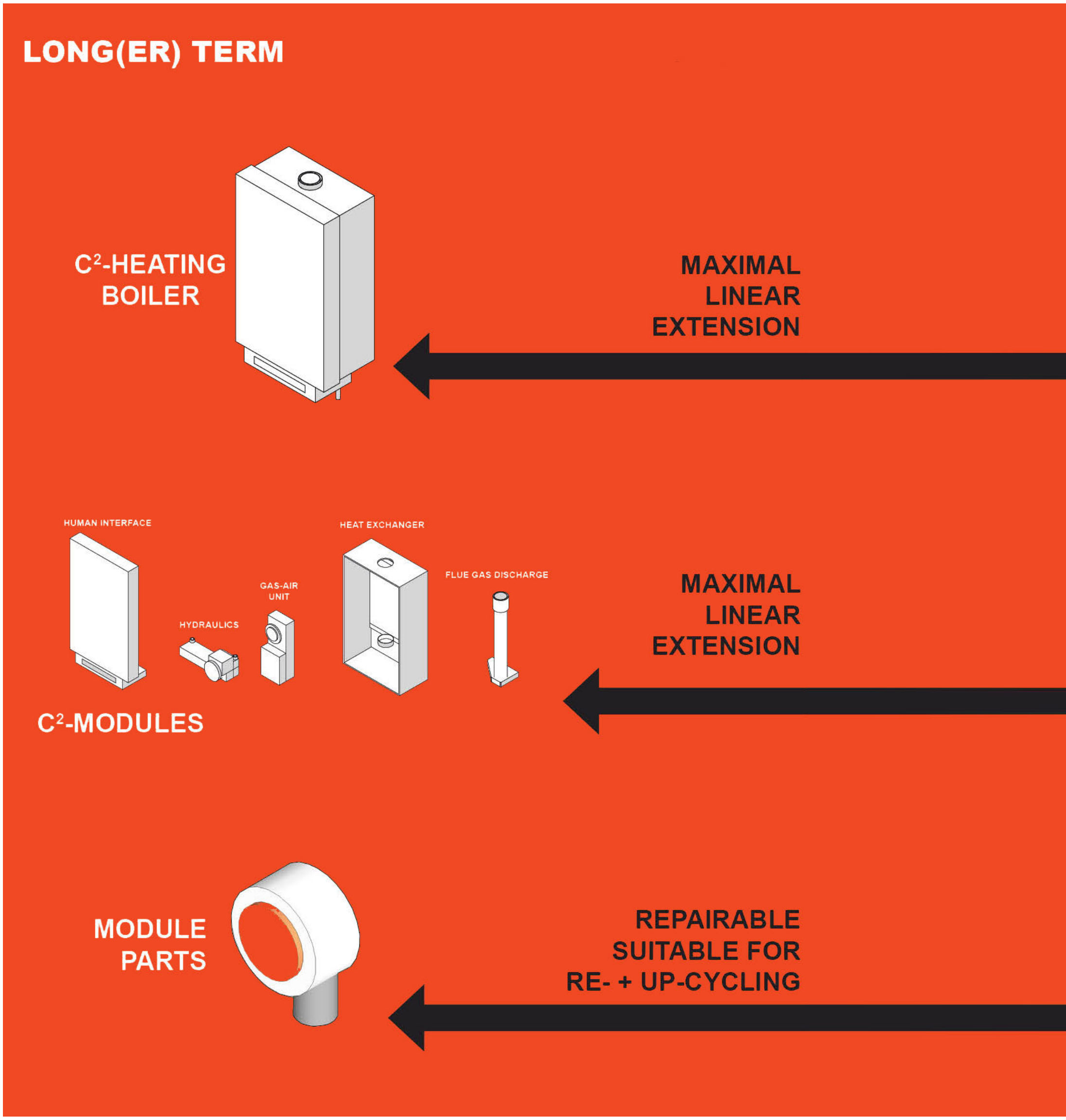
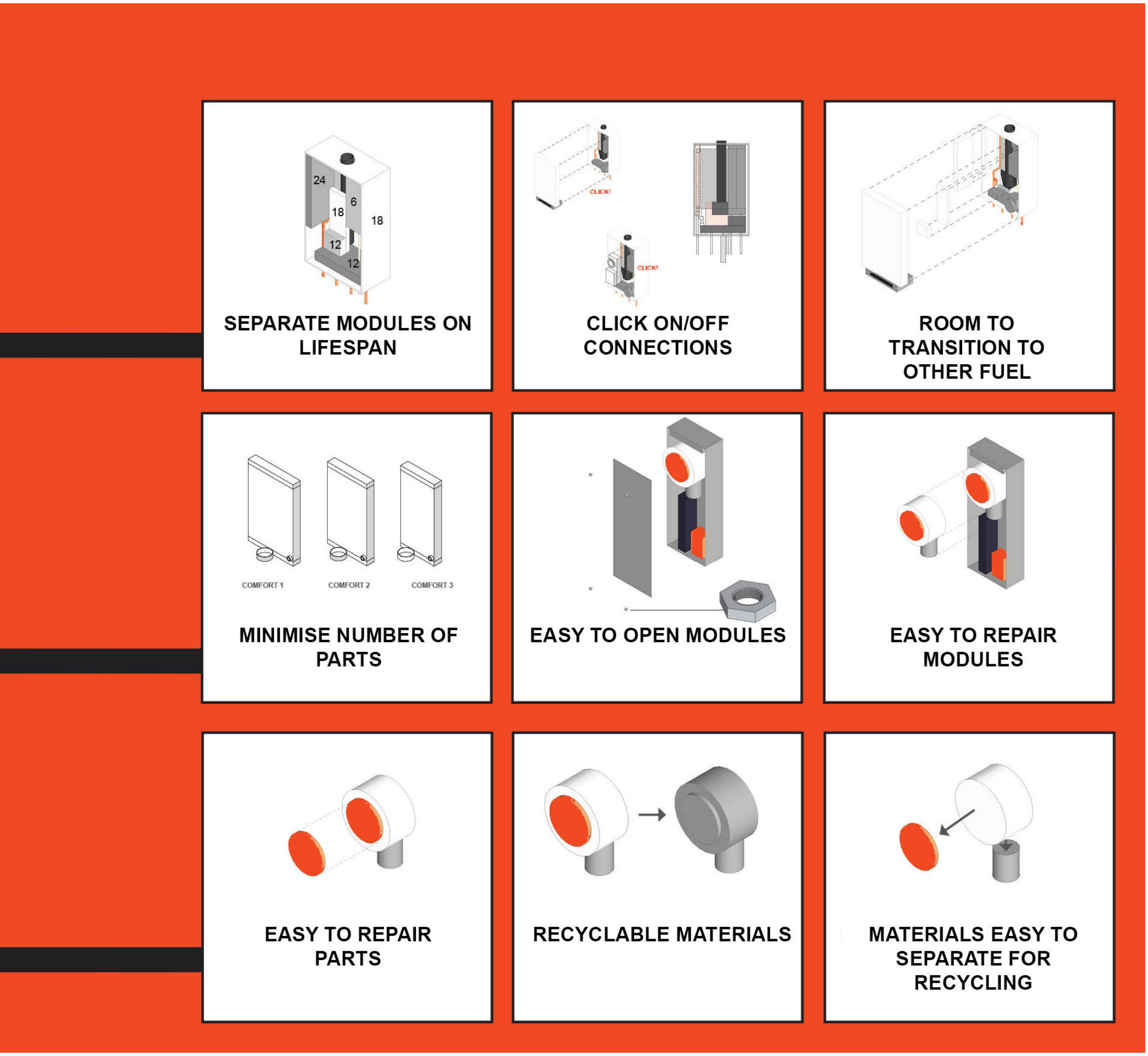


FIG. APP. D.43 9 design principles for the long-term development of a circular central heating boiler



Furthermore, the researcher found that the current organization of the supply chain might have posed an additional challenge for the further development. The supply chain for boilers encompasses a service provider as well as a manufacturer. The climate-installation service provider provides necessary technical knowledge and maintenance services but also implies an extra chain between the manufacturer and the customer/user. Combined with the high competitiveness in the supply chain, it proved challenging to define a 'win-win' business case for all parties.

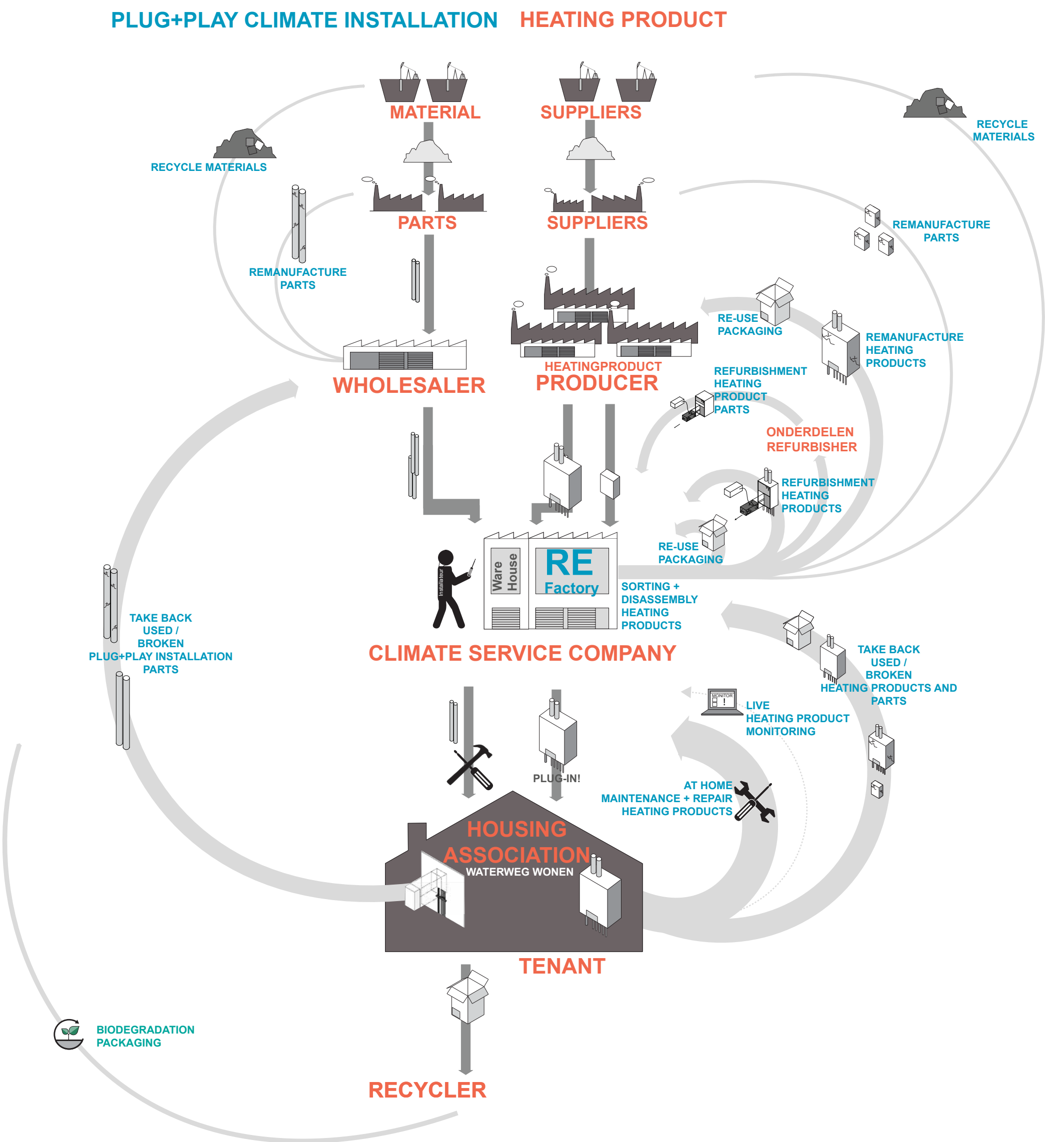


FIG. APP. D.44 Supply-chain model plug-and-play climate installation and C^2 boiler

TOC

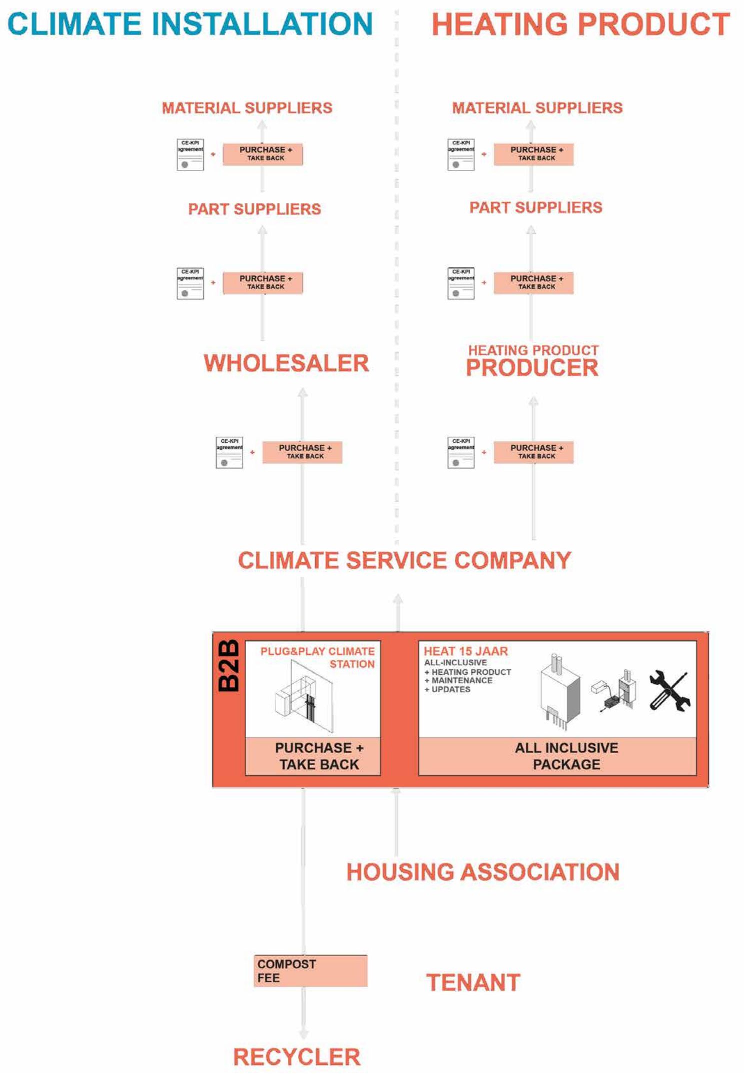


FIG. APP. D.45 Business model plug-and-play climate installation and C^2 boiler

References

van Stijn, A., & Gruis, V. (2019). Towards a circular built environment: An integral design tool for circular building components. Smart and Sustainable Built Environment. https://doi.org/10.1108/SASBE-05-2019-0063

APP. D.8

Analysis key stakeholder choices in the development of the circular kitchen

TABLE APP. D.18 Analysis key stakeholder choices in the development of the circular kitchen

#	Key choice: What?	When?						Who?									
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Research institute & funders	Housing association(s)	Real estate investor	Contractor(s)	Kitchen manufacturer	Appliance manufacturer	Worktop manufacturer	Connector manufacturer	Paint manufacturer
1.1	Repeated choice to separate construction, infill and finishing parts of kitchen using a frame-construction.		X	X	X			X	X	X		X	X	X			X
1.2	Making the construction frame in wood rather than steel		X					X	X	X		X	X				X
1.3	Applying demountable connectors		X	X	X	X	X	X	X	X		X	X	X		X	
1.4	Using a docking-station		X	X	X	X		X	X	X		X	X	X			
1.5	Applying a sustainable plywood		X	X	X	X		X	X	X		X	X	X			
1.6	Making a melamine-coated kitchen		X	X	X	X	X	X	X	X		X	X	X			
1.7	Business model based on sale with buyback rather than lease model						X						X				
1.8	Applying a sustainable chipboard						X						X				
1.9	Construct the kitchen with (thin) demountable panels rather than a frame						X						X				

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'
Stakeholde reasoning which decreased the perceived feasibility is indicated with a '-'.

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	Uses less materials over time, reducing environmental impacts; makes partial repair and adjustments of the cabinet possible; offers customisation opportunities for tenants; costs more initially but saves costs over the lifecycle. Requires large investment of kitchen manufacturer to built new production line. Risky because it deviates from kitchen regime.	+	-	+	-	+	-			-	+	-	
	Steel has a higher environmental impact than wood; a steel frame deviates more significantly from the kitchen manufacturer's production processes.	+			+							+	
	Crucial to make VRPs possible which reduces resource use, environmental impacts and life-cycle costs; connectors are difficult to apply in manufacturing process, not readily available and expensive.	+	-	+	-					-		-	
	Makes kitchen adjustable over time. Less demolition work needed as tiles do not need to be replaced; hard to fit into existing dwellings (e.g., spaceplan and plumbing); behind the stove a melamine-coated board is not as heat resistant as tiles; increases costs.	+	+/-			+				-	+/-		
	The material is affordable and available for mass production in short- and long-term; the material is more expensive than chipboard; the material is more durable than chipboard, making parts last longer; the material may be less circular than more innovative materials.	+/-	-	+	+								
	Makes the kitchen easy to clean; neutral and modern appearance; makes the circular kitchen have a similar appearance to 'normal' kitchens to increase client and user acceptance.				+	+	+	+			+		
	There is too much resistance in the market for lease. Lease is considered unfavourable for housing associations: they have a lower interest rate than market parties, negative influence on the book value, 'being stuck to one manufacturer' or having to sell contracts on.		+		+	+							
	The material is affordable and available for mass production in short- and long-term; the material is less expensive than plywood; the material may be less circular than more innovative materials.	-	+		+								
	Makes partial repair of the cabinet possible; more stable construction. Less risky and easier to produce than a frame construction within current production processes.	+	+	+	+	+	+			+	+	+	

APP. D.9

Analysis key stakeholder choices in the development of the circular skin

TABLE APP. D.19 Analysis key stakeholder choices in the development of the circular skin

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
2.1	Repeated choice for development of NZEB-level second skin (exterior roof and facade insulation components)	x	x	x				x	x	x	x	x	x	x
2.2	Repeated choice for off-site manufacturing of circular skin (prefabricated)	x	x	x				x	x	x	x			
2.3	Choice for a modular skin variant based on standard-sized blocks which can be adjusted and reused		x					x	x	x				
2.4	Combine the modular skin variant with using bio-based and reclaimed materials		x					x	x	x				
2.5	Using timber-frame construction for façade modules rather than EPS-foam modules			x				x		x				
2.6	More focus on using reclaimed materials in circular skin			x				x		x	x	x	x	x

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Directly renovating to energy-performance requirements of 2050, prevents premature replacements when energy-performance requirements increase over time. – Saves operational energy (and impacts) optimally. – Requires more renovation measures: more resource use and embodied impacts now – Requires high initial investment now. – Big and costly components in total renovation: risky to make circular. – 'NZEB-but-then-circular' did not match client's demand (does not solve client's problem).	+/-	-		-	-			+		+		
	– More construction materials required then in on-site construction. – Prefabricated component can be deinstalled and reused: higher end-value. – Faster and cleaner installation causes less nuisance for residents and requires less builders on site.	+/-		+		+							
	– Design enables repair, adjustments and reuse of skin modules in the future. – No reduction of (non-circular) material use and embodied impacts now. – Business model offers most opportunities such as long-term connection to client. – Gaps between modules could hinder realising insulation value and water-proofness. – Gaps between modules might decrease aesthetics of façade.	+/-		+		+				-	-		
	– Design reduces virgin and non-renewable material use and embodied impacts now. – Design reduces impacts and material use in the future by enabling future repair, adjustments and reuse of skin modules and recycling of materials.	+				+							
	– Easier to redesign with circular design principles and materials. – More material use to reach same insulation value. – Results in thicker and heavier façade: reduces light incidence (risky for housing associations as it decreases tenant approval) and additional foundation is required (increasing costs).	+/-	-		-	-				-	-		
	– Reduces virgin material use and embodied impacts now. – The market for reuse of materials should be started now.	+											

>>>

TABLE APP. D.19 Analysis key stakeholder choices in the development of the circular skin

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
2.7	Shift from modular design with 'standard blocks' that can be reconfigured to larger façade panels facilitating likely adjustments on site only			x				x		x	x	x	x	x
2.8	Separation of façade finishing and insulation panels			x				x		x	x	x	x	x
2.9	Timber-frame construction with reused materials resulted in thick façade which led to choice for thinner panel with reused floor beams and insulation of new cavity (between old and new façade)			x				x		x	x	x	x	x
2.10	Standard-sized brick strip panels as façade finishing			x				x		x	x	x	x	x
2.11	Focus on developing circular roof					x		x	x	x				
2.12	Timber-frame roof consisting of standard-sized timber-frame modules which allow adaptations in the roof					x				x	x	x		
2.13	Developing 'skin of the future': step-by-step approach for circular energy renovation					x		x		x				

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'
Stakeholde reasoning which decreased the perceived feasibility is indicated with a '-'.

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Standard-sized (smaller) modules require more material now whilst the end-value is questionable; large panels have lower costs. – Standard-sizes do not match random sizes in existing housing. – Easier to manufacture and less costly that standard-sized blocks. – Wall-to-wall and floor-to-floor size panels fit current product process and bring more value-for-money. – No belief that small façade modules will be reused in other projects in the future (this is not done). – Accommodating likely future adjustments is considered added value and worth investing in.	+	+	+	+	+	+	+		+	+		
	– Design enables repair, adjustments and reuse of façade panels without having to replace the entire façade component.	+		+		+					+		
	– Design reduces virgin material use and embodied impacts now. – Cavity thickness is adjustable allowing to adjust insulation to project specifications and increasing energy-performance requirements in the future. – Thinner and lighter façade component: – Results in thinner and lighter façade: increases light incidence and no additional foundation is required (decreasing costs). – Reclaimed floor beams are readily available. – Reclaimed floor beams difficult in manufacturing process (tolerances too high for machine park).	+	+		+	+			+	+/-	+		
	– More circular than glued brick strips because panels have reuse value. – Relatively high production/recycling impacts: more circular materials are available. – Brick finishing is required to sell the skin: brick is a client wish and part of national culture. – Brick finishing is (often) required to receive a permit for the renovation. – Difficult to get the joints between panels to look 'nice' in terms of visual quality.	+/-		+		+	+		+	-	-		
	– The contractor needs a total renovation concept (only a façade is not enough as value proposition. – Roof module (in combination with cavity wall insulation and new windows) will likely be applied more often: a external façade is too expensive.		+			+							
	– Design enables adjustments and reuse of roof modules in the future, providing future flexibility and preventing premature disposal and costs.	+		+		+					+		
	– Step-by-step approach ensures components are not replaced until necessary. – Flexibility of renovation approach to (future) demands of clients and changing requirements. – Enables spreading of initial costs over multiple investment cycles. – 'Circularity as a means of speeding up the energy transition' matches client demand.	+	+	+	+	+			+		+		

APP. D.10 Analysis key stakeholder choices in the development of the circular dwelling extension

TABLE APP. D.20 Analysis key stakeholder choices in the development of the circular dwelling extension

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
3.1	Combine modular extension variants applying standard-sized modules and easy-to-disassemble joints with using bio-based and reclaimed materials		x					x	x	x				
3.2	(Repeat) choice to place a higher quality extension than the one that is removed		x	x				x	x	x				
3.3	Modular and easy to disassemble concept design for the circular dwelling extension							x						
3.4	Investigation of reusable materials from project and preliminary design applying these materials (wood from the old pergola, double glazing, old door)			x								x		
3.5	Choice to make extension modules which are slightly insulated (not up to new-build standard)			x				x	x	x		x		

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Standard modules allow configuration of different extensions and future adjustments. – Scalable design has value to client: potential to reduce costs and risks. – Design reduces virgin and non-renewable material use and embodied impacts now. – Design enables future repair, adjustments and reuse of extension modules and recycling of materials.	+	+	+	+	+					+		
	– Making high-quality extension adds value for tenants; it reduces risk that they do not agree to the renovation. – Making insulated space reduces operational energy use. – Making insulated modules allows them to be (re)used in more types of extensions (higher end-value). – Requires more materials and costs more.	+/-	-	+	+	+					+		
	– Standard and scalable modules allow configuration of different extensions: potential to replicate in other projects and offer as choice module to tenants. – Design enables future repair, adjustments and reuse of extension modules and recycling of materials. – Potential to include non-virgin materials.	+		+		+					+		
	– Reduction of (non-circular) material use and embodied impacts now. – Does not enable future repair, adjustments and reuse of extension modules and recycling of materials.	+/-											
	– The extension in the project did not require new-built insulation levels. – Reduction of material use and initial costs now. – Limits reuse value of modules (modules need to be doubled in extensions with new-built insulation requirements).	+/-	+	-					+		+		

>>>

TOC

TABLE APP. D.20 Analysis key stakeholder choices in the development of the circular dwelling extension

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
3.6	Definitive design and detailed design combining standard-sized modules, easy to disassemble joints and using reclaimed materials from the site (wood from the old pergola, double glazing, old door, reclaimed hardwood frames) and recycled materials (recycled cotton insulation)			x	x	x		x	x	x	x	x		
3.7	Separation of façade finishing and façade insulation modules			x				x	x	x	x	x		
3.8	Standard-sized modules on 60-cm grid			x	x	x		x	x	x	x	x		
3.9	Applying new materials (new pine wood was used in the modules)				x	x		x	x	x	x	x		
3.10	Applying reclaimed hardwood to increase the technical lifespan of the floor module				x	x			x	x	x	x		
3.11	Brushing the reclaimed wood before reuse in the façade finishing				x	x		x	x	x	x	x		

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'
Stakeholde reasoning which decreased the perceived feasibility is indicated with a '-'.

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Standard and scalable modules allow configuration of different extensions: potential to replicate in other projects and offer as choice module to tenants. – Design enables future repair, adjustments and reuse of extension modules and recycling of materials. – Reduction of non-virgin material use and embodied impacts now. – Application reclaimed materials saves cost of new materials (e.g., new windows and wood). – Reclaimed materials increased labour and costs in manufacturing; reclaiming materials required a different type of laborers for harvesting, cleaning, reworking. – Reclaimed materials increased complexity of building process, increasing labour and costs of contractor: requires more preparation, resident communication, safety and on-site capacity. – Recycled materials had longer delivery time.	+	+/-	+	-	+				-	+	-	-
	– Design enables repair and adjustments of façade finishing without having to replace the entire façade module. – Easy to use reclaimed material for façade finishing.	+		+		+					+		
	– Increases standardisation of modules: increases potential for repair, adjustments and reuse value of extension modules. – Resulted in larger extension compared to existing extension, requiring a new foundation (increasing impactful material use and costs).	+/-	-	+		+					+		
	– Does not reduce virgin material use, but is a renewable material with relatively low impact. – Available and increased feasibility in manufacturing process. – No alternative materials available.	±			+					+			
	– Using softwood in the floor module would lead to rot and premature disposal; using hardwood increases the end value of the module. – Reclaimed hardwood reduces the share of virgin material and embodied impacts now. – Differentiating the floor modules from the roof and façade modules decreases ease of reuse.	+/-								+			
	– Made the façade look 'like new'. This increased aesthetic appeal of the circular extension. – Important for the approval of the tenants and the visual quality of the neighbourhood.					+					+		

APP. D.11 # Analysis key stakeholder choices in the development of the NZEB-light

TABLE APP. D.21 Analysis key stakeholder choices in the development of the NZEB-light

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
4.1	Development of circular building components not feasible		x							x				
4.2	Make NZEB renovation approach as circular as possible using existing products and materials		x					x	x	x				
4.3	Circular NZEB renovation approach not feasible			x				x	x	x				
4.4	Reduce the energy ambition in the renovation project (lower than NZEB level)			x					x	x				
4.5	Make NZEB renovation concept without exterior skin renovation and apply water-to-water heat pump			x					x	x				

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'
Stakeholde reasoning which decreased the perceived feasibility is indicated with a '-'.

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Not considered as the role of the contractors to develop at component level.						-					-	-
	– Fits with the role of the contractors involved in development. – Dependent on existing materials which are (often) not circular. – Component-level design is key to slow and close future cycles optimally. Not designing on component level results in focus on narrowing loops and applying more circular materials in project now.	-					+					+	+
	– The initial costs of the NZEB renovation alone (without circular measures) was already too high in that particular project. This was due in part to the large surface and complexity of the building skin in the project.		-							-			
	– Less high ambitions for energy reduction means less renovation measures, means less use of resources and embodied impacts now. – Does not reduce impacts from operational energy use optimally, does not comply to require-ments client. – Savings on initial costs creates opportunities to apply circular materials.	+/-	+				-						
	– Less renovation measures: saves on material use and embodied impacts now. – Reduces the impacts from operational energy use optimally and fits client requirements. – Less renovation measures: saves on initial costs which allows more homes to be renovated.	+	+				+						

APP. D.12 Analysis key stakeholder choices in the development of the circular boiler

TABLE APP. D.22 Analysis key stakeholder choices in the development of the circular boiler

#	Key choice: What?	When?						Who?						
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker
5.1	Combination of a modular central heating installation which is easy to repair, update and reuse in the future with a modular central heating boiler which is easy to repair, update, reuse and recycle in the future		x					x	x	x	x			
5.2	Sketch design of circular central heating system in which a standard-sized and over-dimensioned dockingstation is placed to which different heating products can be clicked in - and replaced easily in the future		x					x	x	x	x			
5.3	Sketch design in which the lifespan of modules are leading over the lifespan of the boiler itself through monitoring system and part guarantees			x				x	x	x	x			
5.4	A sketch design of a modular boiler in which the layout of parts and joints, measurements of parts and connections are standardised. The boiler is easy to open and joints between parts are easy to dis- and reassemble			x				x	x	x	x			
5.5	Making circular boiler modules recyclable by using parts from high-value recyclable mono-materials (i.e., no composite materials and coatings)			x				x	x	x	x			

TOC

	Main reasoning for this choice: Why?	Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– It is unclear if gas boilers will be utilised much longer and this allows clients to prepare for different scenario's in the energy transition (e.g., hybrid or all-electric scenarios). – Design enables future repair, adjustments, reuse and refurbishment of boiler parts and the boiler.	+				+			+		+		
	– It is unclear if gas boilers will be utilised much longer and this allows clients to prepare for different scenario's in the energy transition (e.g., hybrid or all-electric scenarios). – Developments on heating systems are going too fast to make a standard dockingstation.	+			+/-	+			+	-	+		
	– Prevents premature disposal of boilers in which most parts are still functioning and increases incentive to reuse the boiler and/or parts. – Increases end value of boiler. – Possible to implement in short term (does not require product redesign).	+		+	+								
	– Design enables future repair, adjustments, reuse and refurbishment of boiler parts and the boiler. – Allows clients/manufacturer the flexibility to adjust their heating product to different scenario's in the energy transition (e.g., hybrid or all-electric scenarios). – Increases size of boiler (not in line with client demand). – Increases initial costs but saves costs over the lifecycle. – Long-term relationship between clients and suppliers. – In line with business-as-usual design. – Developments in boilers are going too fast to make standard components. – Requires redesign of the product which is high-risk (as it is not sure gas boilers will be used in the future).	+	-	+	+/-	+/-			+	+	+		
	– Safety and energy performance of boilers are primary requirements (and regulated). These require high-performance materials which are often not high-value recyclable mono-materials.	+							-	-	-		

>>>

TOC

TABLE APP. D.22 Analysis key stakeholder choices in the development of the circular boiler

#	Key choice: What?	When?						Who?							
		Initiative	Proof of principle	Proof of concept	Prototype	Demonstrator	Market implementation	Researchers	Housing association(s)	Contractor(s)	Component manufacturer	Architect	Climate install. specialist	Reclaimed mater. broker	
5.6	Principle design in which a circular central heating system is installed now with a linear boiler which is used more circular. A more circular heating product can be developed in the long term if it becomes clear that gas will be used in the future as a heat source			x				x	x	x	x				

Stakeholder reasoning which increased the perceived feasibility is indicated with a '+'
Stakeholde reasoning which decreased the perceived feasibility is indicated with a '-'.

	Main reasoning for this choice: Why?												
		Environmental	Initial costs / profit	Life cycle costs	Risk	Value proposition	Societal & cultural	Behavioural	Governmental & regulatory	Technical	Functional & aesthetic	Supply chain	Information, skills & education
	– Design enables future repair, adjustments, reuse and refurbishment of heating system, boiler parts and the boiler. – Allows clients/manufacturer the flexibility to adjust their heating system to different scenarios in the energy transition (e.g., hybrid or all-electric scenarios). – Limits risk of development circular heating system through short- and long-term scenarios (awaiting developments on the energy transition). – Long-term relationship between client and supplier was seen as desirable, but also a risk as clients did not want to be 'stuck' with one supplier. – Misalignment of costs of development and revenue of circular building component due to the service provider as intermediary between client and manufacturer. – Competitive supply chain pressured for low initial costs of the boiler hinders circular innovation.	+	-	+	+/-	+/-			+		+	-	-

APP. D.13 Feasibility synergies and trade-offs when combining circular design options

We found that combining circular design options causes additional feasibility trade-offs and synergies between them (see Tables App.D.23-24).

Some circular design options can undermine the environmental benefits of other options. Multiple trade-offs were found between *reducing material use* and other circular design options. Stakeholders initially estimated that *modular design* and *applying de- and remountable joints* would require more materials with a higher environmental impact. In the circular skin case, the concept design proposed smaller timber-frame modules for the façade. This increased the number of structural timber required. Due to the high wood percentage, the building physics consultant calculated that more insulation materials were needed to reach the same insulation value. When the small modules were abandoned in favor of larger modules with adjustable timber frames, the material use did not increase. Likewise, modularity in the circular extension only resulted in one additional vertical timber-frame per wall and roof panel. *Applying biobased-* and *non-virgin materials* was also perceived to increase *material use.* In some cases, more materials were needed to fulfil the functional and technical requirements specified for technical and virgin materials. This held true for the insulation materials (cases 2, 3 and 4), but not for board-materials used in the kitchen case.

Another noteworthy trade-off was between *applying non-virgin materials* and *modularity and standardization*. The former requires to deformalize the design and realization process. After the design is finalized, reclaimed materials are sourced and need to be fitted into the design. This requires flexibility in (e.g.,) acceptable dimensions, technical specifications and aesthetics. The more flexibility, the higher number of reclaimed products and materials are available. On the other hand, designing modules which facilitate future repair, adjustments and reuse requires high levels of standardization and formalization. Everything needs to be considered early in the design and should be documented to facilitate and guarantee future VRPs. These circular design options require two different mindsets which can compete with each other in the design and realization process – but can be applied side by side successfully as well. In the case of the circular dwelling extension, flexibility was built into the standard-sized design; in the circular skin, design parameters for reclaimed materials were specified early on in the design process.

TABLE APP. D.23 Trade-offs between combinations of circular design options

Trade-offs circular design options		Case	Examples from cases
Reducing material use	Modular design	Case 2	Separating the façade finishing from the façade insulation layer required to glue the brick strips on a separate panel. So, an additional panel was used compared to a non-modular design.
		Case 3	Making the wall and roof panels modular will increase the number of timber beams in the timber-frame panel design.
		Case 3	To make the modules of the dwelling extension reusable in a living room extension, they should have a higher insulation value than required for the dwelling extension in the current project. This would require using additional materials now. Using just enough insulation would limit their reusability.
	De- and remountable joints	Case 2	Using aluminum frames to make the façade finishing panels demountable adds a lot of high-impact material.
	Long life materials	Case 2-4	Long-life materials (e.g., ceramics, bricks, hardwood, metals) are often quite heavy and/or manufacturing them causes high impacts.
	Applying bio-based materials	Case 2,4	Bio-based insulation materials have a lower thermal performance than technical insulation materials. It means more bio-based materials are needed to reach the same insulation value.
		Case 2,4	Currently available, façade and roof products made from technical materials (e.g., EPS) are lighter because they do not require structural materials (like a timber-frame).
	Applying non-virgin materials	Case 2	Using reclaimed insulation materials requires more materials to reach the same insulation value: for directly reused materials a forfeit insulation value needs to be applied in the calculation. This value is lower than the value for new insulation materials. Reused 'hard' insulation boards often do not have the desired insulation value. So double boards need to be applied (surpassing the desired insultation value) and using more materials. Recycled insulation materials also require thicker layers to reach the same insulation value than virgin foam insulation.
	Standardization & modular design	Case 2	Making the façade modular through making smaller, standard-sized blocks increased the number of timber beams in the timber-frame panel significantly. More insulation materials are needed to reach the same insulation value if there is a higher wood percentage in the timber-frame façade.
Standardization & modular design	Applying non-virgin materials	Case 2	To be able to incorporate reclaimed materials during realization, flexibility needs to be kept in the design. If everything is specified up front, not a lot of reclaimed materials will fit. However, to design standard-sized modules which can be repaired, adjusted and reused in the future requires specifying and guaranteeing as much as possible up-front. These are two fundamentally different mind-sets.
Modular design	Design for attachment	Case 1,2	By facilitating adjustments in the building component, you invoke that those adjustments will be made rather than cherishing the component and keeping it as long as possible.

TABLE APP. D.24 Synergies between combinations of circular design options

Synergies circular design options		Case	Examples from cases
Reducing material use	Modular design	Case 2	Making larger-sized modules with adjustable timber beams did not increase the number of timber beams in the timber-frame panel.
		Case 3	Making the wall panels of the dwelling extension modular did not require a lot of extra material: one extra vertical timber beam per timber-frame panel was needed.
		Case 3	Making dwelling extension modules with a lower insulation value than required for new built reduces the amount of material used in the extension now. When reused elsewhere, the modules can be doubled so the required insulation value is reached (only when needed).
	De- and remountable joints	Case 2	Using timber furring to make façade finishing panels de- and re-mountable adds some material but the impact of the material is not so high.
	Applying bio-based materials	Case 1	Using (more) bio-based alternatives did not increase the amount of material used in the kitchen.
Modular design	Applying non-virgin materials	Case 2	Early specification of the design parameters for reclaimed materials allowed just-in-time sourcing during realization.
		Case 3	The front panel of the dwelling extension was treated as a custom piece which did not need to respect the standard-sizes so reclaimed windows and doors with different measurements could be used.
		Case 3	Using reclaimed materials was used as a starting point in the design by making an inventory of materials which could be reused from the project. During procurement, products and materials were actively sourced from other projects and recycled material providers. This allowed reclaimed materials to be successfully integrated into the modular design, including in the façade finishing, the timber-frame modules, the doors, windows, roof felt, insulation, rainwater pipes.
	Applying non-virgin and bio-based materials	Case 2-4	A flow chart on material procurement helps to integrate circular materials into a modular design. For each project materials are first reused from the project or other local projects, then bought from reused or recycled material providers, then bio-based and low-impact virgin materials are used. Only if this is not possible, 'regular' virgin materials are applied.
	Applying bio-based materials	Case 2; Case 4	On the market, timber-frame façade and roof components are easier to make modular than the façade and roof components made from technical materials (such as EPS). The latter are highly integrated products which cannot be redesigned easily.

Curriculum Vitae

Anne van Stijn

Who am I?

I am an engaged researcher, designer and manager committed to developing integral solutions to improve the quality, affordability and sustainability of housing in the Netherlands and abroad. I organize the processes needed to activate stakeholders to realize these changes. I work from the level of **strategy and tools** towards proof-of-concepts, **prototypes, pilot projects and scale-up** aiming for a **high societal impact**; I have **published in authoritative international journals and developed practice publications and tools**.

I thrive in **national and international collaborations** with academia, research institutes, universities of applied sciences, practice partners and government. I have a **large network** in Dutch housing associations and their supply-chain partners. I have studied and worked in and with top international universities including **Tsinghua University, Yale University, Aalborg University, Chalmers University of Technology, and Delft University of Technology**. I am experienced in applying an **Action Research and Research-through-Design (RtD) approach** and contribute to methodological development; I have experience with both qualitative and quantitative research methods, including Material Flow Analysis (MFA) and Life Cycle Assessment (LCA).Being a strong planner with a "getting-it-done" attitude, I excel in **setting-up and managing projects, directing processes and organizing education**; I have **successfully applied for grants and acquisitioned funding in industry**.Last, but not least, I am a **frequent speaker on circular housing renovation in practice** and **an enthusiastic tutor and lecturer** in BSc and MSc courses; I have experience **supervising MSc graduation** students.

Academic appointments and professional experience

Mar 2022 – Now	**Sector developer sustainability | Aedes, national association of Dutch social housing associations** At Aedes I support the Dutch housing association sector to realise their sustainability ambitions including the energy transition, circularity and climate adaptation
Mar 2018 – Mar 2022	**PhD-researcher | Management in the Built Environment Delft University of Technology** – PhD Dissertation: 'Developing circular building components: between ideal and feasible – Development of grant proposals and industry funding acquistioning – Collaboration with housing assocations and industry partners – Project management of research projects with large national and international industry consortia – Lecturer, tutor, supervisor and (co)developer in BSc and MSc courses and graduation projects **Chalmers University of Technology |** 4-year research collaboration on the development of circular kitchens and circular design tools **Aalborg University |** 3-year research collaboration on development of multi-cycle LCA approaches
Jan 2017 – Jan 2018	**Research fellow & researcher (dual position) Amsterdam Institute for Advanced Metropolitan Solutions & Management in the Built Environment | Delft University of Technology** Development and testing of a circular kitchen and circular boiler in co-creation with housing associations and industry partners.
May 2013 – Jul 2016	**Student assistant MSc 1&2 | Urbanism, Delft University of Technology**
Mar 2015 – Aug 2015	**Internship | Urbanus | Architecture and urban design firm, Beijing**

TOC

Sep 2012 – Jan 2013	**Internship | Veldacademie | Research & design on architecture and urbanism, Rotterdam**
Jul 2011 – Aug 2011	**Internship | Broekbakema | Architecture and urban design firm, Rotterdam**

Education

Sep 2015– Nov 2016 Sep 2013 – Jul 2014	**MSc in Architecture, Urbanism and Building sciences Delft University of Technology** Graduation thesis: Development of an integral rehabilitation process and redesign of the early high-rise housing of Beijing (Grade: 10.0/10.0) Average grade: 9.0/10.0 (Annotation: Cum laude) **TU Delft | MSc honours program |** Additional 20 ECTS
Sep 2014 – Jan 2015	**MSc Exchange | Tsinghua University, School of Architecture, Beijing** Additional 30 ECTS; Average grade: 9.0/10.0 **Yale University |** Joint design studio and student exchange with Yale University
Sep 2010 – Jun 2013	**BSc in Architecture, Urbanism and Building sciences Delft University of Technology** Average grade: 8.2/10.0 (Annotation: Cum laude) **TU Delft | Bsc honours program |** Additional 28 ECTS
Sep 2004 – Jun 2010	**Gymnasium** Pre-university education at Trevianum scholengroep, Sittard

Training

Jun 2021 – Aug 2021	**Innovation and creativity management | RTW Aachen**
Mar 2021 – Apr 2021	**University Teaching Qualification | Supervise Module | TU Delft**

Feb 2021 – Mar 2021 **Real Estate Finance | Spryg real estate academy**

Sep 2020 – Oct 2020 **Housing portfolio and asset management | PAO-TM**

Funding

Aug 2020 – Mar 2022 **CIRcular COLlaboration (CirCol): Delivering circular renovation at scale through multi-cycle, multi-scalar and multi-level collaboration Research project | NWO**
Lead partner, 5-year project, funding awarded to project: ± €1.400.000
– Development of proposal and consortium in collaboration with prof.dr. Paul Chan, prof.dr.ir. Vincent Gruis and dr. Tuuli Jylhä;

Oct 2017 – Aug 2018 **Developing circular REnovation solutions for HABitats (REHAB) | Research project | AMS-institute and industry funding**
Lead partner, 4-year project, funding awarded to project: ± €250.000
– Lead in development of proposal and consortium

Sep 2017 – Jan 2018 **Circular Kitchen (CIK) | Demonstrator | EIT-Climate KIC**
Lead partner, 4-year research project, funding awarded to project: ± €1.000.000
– Development of proposal and consortium in collaboration with prof.dr.ir. Vincent Gruis

Awards

2018	**Nomination for the Archiprix Netherlands 2018** My MSc graduation project "Rehabilitating China's Crumbling High-rises" has been nominated for the Dutch Archiprix award (total of 26 nominees). Since 1980 the Dutch Archiprix foundation annually awards a prize for the best graduation projects in the fields of architecture, urban design and landscape architecture.
2018	**Nomination for the Young talents Architecture Award (YTAA) 2018** My MSc graduation project "Rehabilitating China's Crumbling High-rises" has been nominated for the YTAA. The YTAA aims to support the talent of recently graduated Architects, Urban Planners and Landscape Architects, who will be responsible for transforming our environment in the future. YTAA, is part of the European Union Prize for Contemporary Architecture – Mies van der Rohe Award.

Teaching

Mar 2020 – Mar 2022	**MSc graduation theses | Supervisor | Delft University of Technology**
Apr 2021 – Jul 2021 Apr 2018 – Jul 2018	**BK6AC3 Academic skills on Design reflection | Tutor | Delft University of Technology | BSc Architecture, Urbanism and Building Sciences**
Feb 2019 – Jun 2020	**AR0054 Energy-Friendly Renovation Processes | Lecturer and tutor | Delft University of Technology | MSc Architecture, Urbanism and Building Sciences**
Nov 2018 – Sep 2020	**AR1R035 Housing policy, management and sustainability | Lecturer | Delft University of Technology | MSc Architecture, Urbanism and Building Sciences**
Feb 2019 – Jun 2019	**Circular kitchen appliances project | Lectures and workshops | HAN University of Applied Science | BSc course (Interdisciplinary)**

Feb 2017 – Jun 2017 **4413INTPGY Interdisciplinary project group | Circular kitchen | Tutor and course development| Leiden University & Delft University of Technology | MSc Industrial Ecology**

Conferences, guest lectures, workshops and talks in practice

1 Oct 2021 **University of Applied Sciences Utrecht | Master of Urban and Area Development**
Interactive guest lecture: "Circular housing renovation: how?!?".

25 Mar 2021 **C-creators, Ministry of Interior Affairs and North-Holland Province | Circular renovation cycle for housing renovation**
Presentation handbook on circular renovation for housing associations.

19 Feb 2021 **CHARM practice day | Developing circular building components**
Presentation on how to develop circular building components.

2-4 Nov 2020 **World Sustainable Built Environment (WSBE) 2020 conference | Beyond 2020 | Goteborg, Sweden**
Paper presentation: "Environmental design guidelines for circular building components: the case of the circular kitchen".

21 Oct 2020 **Buyers groups | Circular renovation, what is it?**
Presentation on circular renovation guidelines, the circular skin, and circular purchasing.

17 Apr 2020 **Delft University of Technology | REM bootcamp on research methods**
Interactive guest lecture: "Research through design: Value for you, or not?"

TOC

Jan 2020 **Delft University of Technology | ProfEd | Circular Building Products for a Sustainable Built Environment**
Video guest lecture: “circular assessment and lifecycle assessment”.

11 Dec 2019 **Groene Huisvesters**
Presentation and workshop on the Circular Skin.

1 Nov 2019 **C-creators | Expert session on circular renovation**
Presentation on circular renovation and the Circular Skin.

11 Oct 2019 **Rotterdam University of Applied Science | BSc Built Environment | Prototype course**
Guest lecture: “Circular renovation skin”.

3 Sep 2019 **Symposium | Circulair opdrachtgeverschap**
Presentation on the Circular Skin and circular business models for the built environment.

2-4 Jul 2019 **SBE19 | Central Europe towards Sustainable Building (CESB) 2019 conference | Prague, Czech Republic**
Paper presentation: **“**Circular housing retrofit strategies and solutions: Towards modular, mass customised and ‘cyclable’ retrofit products”.

13 Jun 2019 **Renda | Dag van de circulariteit**
Presentation and workshop on the circular extension for dwellings | presented together with ERA Contour.

7 May 2019 **Pakhuis de Zwijger | AMS Science for the city**
Interactive presentation on the Circular Kitchen.

28 Mar 2019 **CorporatieNL | Vastgoed Event**
Presentation on the Circular Kitchen | presented together with Bribus Keukens.

21 Feb 2019 **University of Applied Science Utrecht | BSc Built Environment | Innovation lab circular housing management, maintenance & renovation**
Guest lecture: “Towards a circular built environment through circular components”.

4-7 Dec 2018	**Smart and Sustainable Built Environment (SASBE) 2018 conference | Sydney, Australia** Paper presentation: "Towards a circular economy in the built environment, development of a design framework for circular building components".
5-7 Nov 2018	**SBE19 | Retrofit Europe Conference | Eindhoven, The Netherlands** Presentation extended abstract: "Solutions for the coming retrofit challenge: Towards modular, mass customized and circular retrofit products".

Committees and memberships

Sep 2017-Mar 2022	**Circular Built Environment (CBE) Hub** Platform for researchers with the aim to promote the development of knowledge towards a circular built environment that enables the design of future buildings, cities and infrastructures.
Sep 2012 – Sep 2013	**Commissioner at the faculty student council**
Sep 2011– Jan 2013	**Commissioner study tour committee of Stylos | Architecture student association**
Sep 2007 – Jun 2010	**Member student council Trevianum**

TOC

List of publications

Journal publications (peer reviewed)

- (Under review) van Stijn, A., Wouterszoon Jansen, B., Gruis, V, & van Bortel, G. A. (2022). 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.*
- 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, Bas, 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
- van Stijn, A., Malabi Eberhardt, L. C., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation and Recycling*, 174(105683), 1–34. https://doi.org/ https://doi.org/10.1016/j.resconrec.2021.105683
- Malabi Eberhardt, L.C., van Stijn, A., Kristensen Stranddorf, L., Birkved, M., & Birgisdottir, H. (2021) Environmental design guidelines for circular building components: The case of the circular building structure. *Sustainability*, *13, 5621.* https://doi.org/10.3390/su13105621
- Malabi Eberhardt, L. C., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustainability, 12(22),* 9579. https://doi.org/10.3390/su12229579
- Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling, 161,* 104857. https://doi.org/10.1016/j.resconrec.2020.104857

– van Stijn, Anne, & Gruis, V. (2019). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment, 9, 4.* https://doi.org/10.1108/SASBE-05-2019-0063

Conference publications (peer reviewed)

– van Stijn, A, Malabi Eberhardt, L. C., Wouterszoon Jansen, B., & Meijer, A. (2020). Design guidelines for circular building components based on LCA and MFA: The case of the Circular Kitchen. *Beyond2020, World Sustainable Built Environment Conference*. Goteborg, Sweden: *IOP Conference Series: Earth and Environmental Science, 588, 042045.* https://doi:10.1088/1755-1315/588/4/042045
– Dokter, G., van Stijn, A., Thuvander, L., & Rahe, U. (2020). Cards for circularity: Towards circular design in practice. *Beyond2020, World Sustainable Built Environment Conference*. Goteborg, Sweden: *IOP Conference Series: Earth and Environmental Science, 588, 042043.* https://doi.org/10.1088/1755-1315/588/4/042043
– Malabi Eberhardt, L. C., van Stijn, A., Nygaard, F., Brikved, M., & Birgisdottir, H. (2020). Towards circular life cycle assessment for the built environment : A comparison of allocation approaches. *Beyond2020, World Sustainable Built Environment Conference.* Goteborg, Sweden: *IOP Conference Series: Earth and Environmental Science, 588, 032026.* https://doi.org/https://doi.org/10.1088/1755-1315/588/3/032026
– van Stijn, A., & Gruis, V. H. (2019) Circular housing retrofit strategies and solutions: Towards modular, mass-customised and 'cyclable' retrofit products *CESB19 Conference*, Prague: *IOP Conference Series: Earth and Environmental Science, 290, 012035.* https://doi:10.1088/1755-1315/290/1/012035
– van Stijn, A., & Gruis, V. H. (2018). Towards a circular economy in the built environment: An integral design framework for circular building components. *In R. Roggema and A. Roggema. Smart and Sustainable Cities and Buildings*. Springer, Cham. https://doi.org/10.1007/978-3-030-37635-2_39

Book chapters (peer reviewed)

– (In press) van Stijn, A., & Lousberg, L. H. M. J. (2023). Approaching research-through-design in the field of Architecture and the Built Environment. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods: A critical guide on research to engineer change*. Taylor & Francis.
– (In press) van Stijn, A. (2023). Guidance in the application of research through design: the example of developing circular building components. In L. H. M. J.

Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods: A critical guide on research to engineer change*. Taylor & Francis.

- (In press) Lousberg, L. H. M. J. & van Stijn, A. (2023). Positioning interventionist research methods. In L. H. M. J. Lousberg, P. Chan, & J. Heintz (Eds.), *Interventionist Research Methods*: *A critical guide on research to engineer change*. Taylor & Francis.

Professional publications (non-peer reviewed)

- Stolker, M. & van Stijn, A. (2021). *Handboek circulair renoveren voor woningcorporaties*. Amsterdam, The Netherlands: C-Creators, AMS-Institute and Delft University of Technology. Available on https://www.ams-institute.org/documents/49/Handboek_Circulair_Renoveren_voor_Woningcorporaties.pdf

TOC

List of Tables

Appendices

List of Figures

Appendices

23#05

Developing circular building components

Between ideal and feasible

Anne van Stijn

A building consists of building components, such as a kitchen, façade and roof. By replacing building components with more circular ones during new construction, maintenance and renovation, we can gradually create a circular built environment. In this dissertation, we develop and test 8 circular building components for housing renovation together with Dutch social housing associations and industry partners. Combining 'Action Research' and 'Research through Design' approaches, we generate knowledge on the development of feasible, circular building components. We present a design tool, assessment model, environmental design guidelines and identify key stakeholder choices. This research makes scientific contributions to circular design theories, management models for the built environment, and research methodology. We recommend 4 changes in practice to implement more circular building components.

A+BE | Architecture and the Built Environment | TU Delft BK