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Towards implementation of circular building components: A longitudinal study on the stakeholder choices in the development of 8 circular building components

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A R T I C L E I N F O

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A B S T R A C T

Implementing 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 throughout a development process. 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 up 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.

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 and Xing, 2017). Implementing Circular Economy (CE) principles could support minimizing pollution, 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 et al., 2017). Geissdoerfer et al. (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 et al., 2016). Value Retention Processes (VRPs), such as reduce, reuse, repair, refurbish, and recycle, are used to narrow, slow and close cycles (Wouterszoon Jansen et al., 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 et al., 2018; Malabi Eberhardt et al., 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 there are numerous circular design options (van Stijn and Gruis, 2020). Circular design options such as designing lightweight components, 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,

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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 et al., 2022; Wouterszoon Jansen et al., 2022a) 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.

2. Background

Other authors investigated the feasibility of implementing CE (design) principles in the built environment. Searching combinations of the following keywords on Scopus yielded 72 studies (in march 2022): circular economy, feasibility, barriers, enablers, trade-offs, synergies, design, building, building component, kitchen, façade, building structure, roof, floor. A further selection based on relevance yielded 16 studies; one study was added through snowballing. An overview of these studies is included in Online Supplementary Material (OSM) A.

Existing studies identified barriers (or challenges), and – to a lesser extend – drivers, enablers or opportunities. The authors categorized their findings in different ways, most commonly per VRP or circular design option (e.g., Giorgi et al., 2022; Huang et al., 2018; Torgautov et al., 2021), thematic (e.g., Akinade et al., 2020; Galle et al., 2021; Guerra and Leite, 2021) or by discipline (e.g., Charef et al., 2021; Cruz Rios et al., 2021; Ghisellini et al., 2018; Selman and Gade, 2020); categories varied between studies. We found knowledge, skills and educational barriers (33), governmental and regulatory barriers (37), and economic and financial barriers (55) were most numerous. With 110 counts, economic and financial barriers are mentioned most. The most mentioned financial barrier is the 'additional time, labor and costs to design and construct when applying circular design options'. 111 out of 362 barriers were unique to single publications. A more comprehensive overview of barriers is lacking *(knowledge gap 1)*. We provided an overview of the identified barriers in OSM B, categorized by discipline. We build upon the disciplinary categories of Charef et al. (2021) and Cruz Rios et al. (2021) – adding and specifying categories inductively through iterative reading.

The majority of studies researched feasibility on construction-industry or building level. Only Azcarate-Aguerre et al. (2022, 2018) focused on façade components. Barriers on construction-industry or building level may not always be applicable to the building-component level or to specific components. More detailed knowledge on which barriers influence the feasibility of *different* building components (*knowledge gap 2*) may support the development of circular building 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 Disassembly. None of the reviewed authors compared the feasibility of multiple circular design options. Various 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. However, to develop and realize circular building components a comprehensive understanding of feasibility is needed, comparing multiple circular design options (*knowledge gap 3*).

Nearly all authors did a literature review, interviewed stakeholders (once) or studied completed cases. They collected data at one point in time, often long after decisions were made. Barriers are listed but authors do not study their relative importance throughout the development process. Akinade et al. (2020) and Charef et al. (2021) called for more empirical and longitudinal studies on stakeholder decisions in circular building projects. Knowledge on which barriers may be overcome and which barriers are the true bottle necks – at different stages of the development process – can aid stakeholders to better navigate development processes; such knowledge can help prioritize the circular research agenda. For this we need more detailed insight in what specific choices throughout the development process influence how stakeholders perceive the feasibility of circular design options; who makes them; for what reason are these choices made as such *(knowledge gap 4)*.

Recently, Wouterszoon Jansen et al. (2022b) 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 stakeholders' 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 the research of Wouterszoon Jansen et al. (2022b).

3. Goal and method

We 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.

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 3.1-3.3 of this article, we elaborate on the methods applied per step. In section 4, we describe the developed circular building components. In section 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 6, we discuss our findings. In section 7, we conclude this article.

3.1. Methods in the development of circular building components

The circular building components were developed between 2017 and 2022 (see Table 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 favorable context for implementing circular design options.

The components were developed in co-creation workshops 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 development process and choices made. This documentation formed our dataset. More detailed

Table 1
Developed components per case and stakeholders involved.

Case name	Developed components	Stakeholders	When
1. **Circular kitchen** *Wouterszoon Jansen* et al. *(2022b)*	Circular kitchen component including cabinetry and appliances	Researchers: TU Delft[a] Knowledge institute: AMS-institute[a] Kitchen manufacturer 1: Bribus Keukens[a] Appliance manufacturer 1: ATAG[a] Worktop manufacturer 1: Topline Maatwerkbladen BV Contractor 1: Dirkzwager Groep[a] Housing association 1.1: Waterweg Wonen[a] Housing association 1.2: Eigen Haard[a] Housing association 1.3: Ymere[a] Housing association 1.4: Stichting Woonbedrijf SWS[a] Housing association 1.5: Woonstad Rotterdam Housing association 1.6: Portaal[a]	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[a] Knowledge institute: AMS-institute[a] Contractor 2: Dura Vermeer[a] Housing association 2: Ymere[a] 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[a] Knowledge institute: AMS-institute[a] Housing association 3: Eigen Haard[a] Contractor 3: ERA Contour[a] Architect 3: DOOR architecten Carpenter 3: Van den Oudenrijn	Mar 2018-Aug 2021 87 co-creation sessions and contact moments
4 **Circular NZEB-light**[b]	Net-Zero-Energy-Building (NZEB)[b] renovation concept including climate installation, renovation roof and -façade components, optimized on circularity	Researchers: TU Delft[a] Knowledge institute: AMS-institute[a] Housing association 4: Wonion[a] 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[a] Knowledge institute: AMS-institute[a] Climate systems manufacturer 5: Remeha[a] Climate systems installer 5: Feenstra[a] Housing association 5: Waterweg Wonen[a]	Jan 2017-Sep 2017 9 sessions and contact moments

[a] Stakeholders who were committed partners in the research projects Circular Components, CIK and/or REHAB.
[b] 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.

information on the set-up of the development processes, the co-creation workshops and methods applied for documentation are included in OSM C.

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 Fig. 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.

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

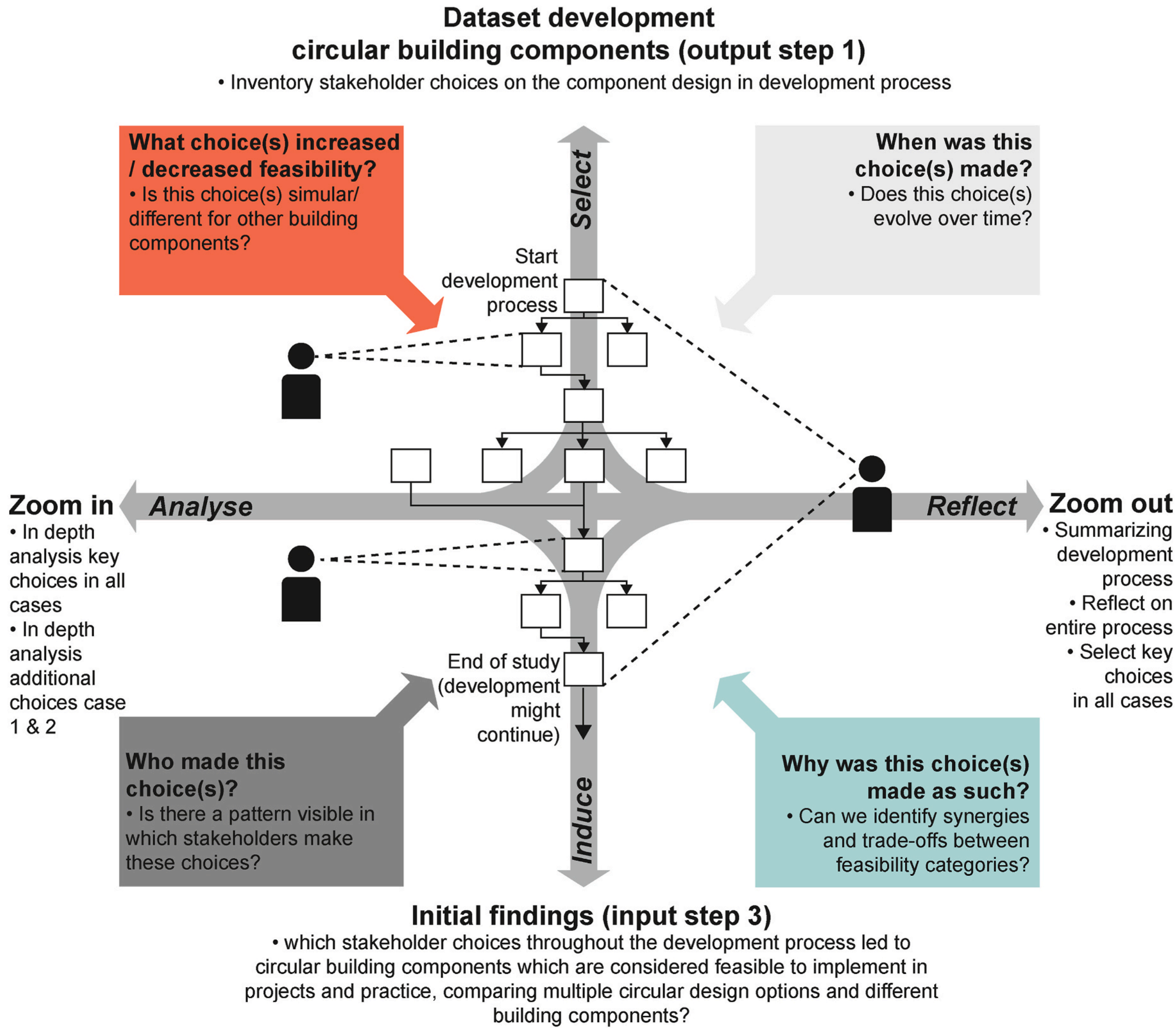


Fig. 1. Approach for reflection and analysis of stakeholder choices to induce findings.

such? From the stakeholder's reasoning we identified why they perceive a choice is or is not feasible to implement. We categorized their reasoning using the feasibility categories found in our literature review (applied definitions are included in Table 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.

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. (2022b). As case 5 was finalized in 2017, no validation with stakeholders occurred.

4. Description of the developed circular building components

Table 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 the OSM D-H.

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 the OSM I-M.

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 circular 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 4 we summarized the main

Table 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.

circular design options applied per design variant and the main reasoning of stakeholders on their feasibility (see the OSM D-H 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 components, parts and materials 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 client demands and project-specific requirements. In cases 1–4, modularity was combined with using reclaimed or bio-based materials to reduce environmental impacts now. This also made the component's circularity outwardly visible to stakeholders. This was considered conditional to ensure the acceptance of the design's circularity with clients and the market. Notably, the exception lay 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 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.

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.

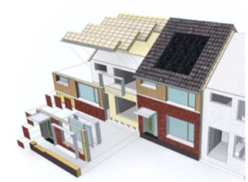
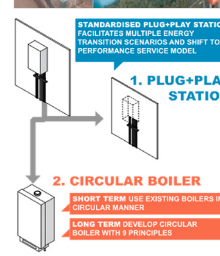
5.2.1. *Feasibility synergies and trade-offs*

Analyzing detailed choices, we found that all circular design options have trade-offs on at least one feasibility category (see Table 5a). 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*.

Circular design options also have synergies on feasibility categories (see Table 5b). 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 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 potential *initial profits*. In some applications, circular design options became feasible by smartly combining them (see the last example in Table 5b).

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

Table 3
Overview of developed circular building components.

Case name	Circular design options	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	

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.* 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

Table 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 + Reclaimed material 'feels' circular to stakeholders +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 + Bio-based material 'feels' circular to stakeholders +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 + Bio-based material 'feels' circular to stakeholders +Fits market trend -Without more maintenance the visual quality of the neighbourhood may decline -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.
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 - Recycling does not 'feel' circular	**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**
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 remountable 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 challenges (air-tightness, 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 maintenance - Developments too fast for standardiz. - 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-related material flows through smart design of building component and including additional 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**
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 '-'.

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 –

Table 5a
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.

(continued on next page)

Table 5a (*continued*)

Trade-offs			Case	Examples from cases
	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.
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 behaviour; 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

(*continued on next page*)

Table 5a (*continued*)

Trade-offs			Case	Examples from cases
				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.
		Initial cost; 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	Material; impact	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, 3, 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.
Modular design	Technical	Initial costs; 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.
		Initial 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, 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, 3	Long-life materials (e.g., aluminium frames, ceramic tiles, plywood) are more expensive than materials with shorter lifespans.

Table 5b
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 proposition;	Case 3	After cleaning the reclaimed wood used for the façade finishing, it had the visual quality desired by the client.
	Risk (availability)	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 proposition; governmental & 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 proposition	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 proposition	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 stakeholders 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

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Table 5b (*continued*)

Synergies			Case	Examples from cases
				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 proposition	Case 2	By making a modular NZEB-renovation concept, the initial 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.
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 component facilitates future reuse of the building 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).

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 OSM N.

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 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 6 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 demonstrators 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 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., 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 on the continuation of gas use for domestic heating was expected by the government. 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 clients 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 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.

Table 6
Reasoning for shift in circular component designs.

	Case 1 Circular kitchen	Case 2 Circular skin	Case 3 Circular dwelling extension	Case 4 Circular NZEB-light	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 connections	Modular boiler facilitating repair and updates
Circular design options towards realization	Kitchen constructed with demountable 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- performance; 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 manufacturable on current machine park 2. Repairability is more important to the client than (future) adjustability	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 realize energy transition	N/A	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	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

Notably, there is one case in which no shift occurred. In the circular dwelling extension, 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 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.

5.4. Feasibility of circular design options varies per component

We found similarities and differences between 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 components and their development context.

We found that characteristics of some building components are more akin to products whilst others are more akin to buildings. Fig. 2 shows the characteristics we associate with both types.

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.

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.

Building components can also share characteristics with both types (e.g., climate installations are highly complex products). Fig. 2 shows how 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, 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.

6. Discussion

This research yielded five scientific contributions. First, we provided a more comprehensive overview of barriers for circular (design)

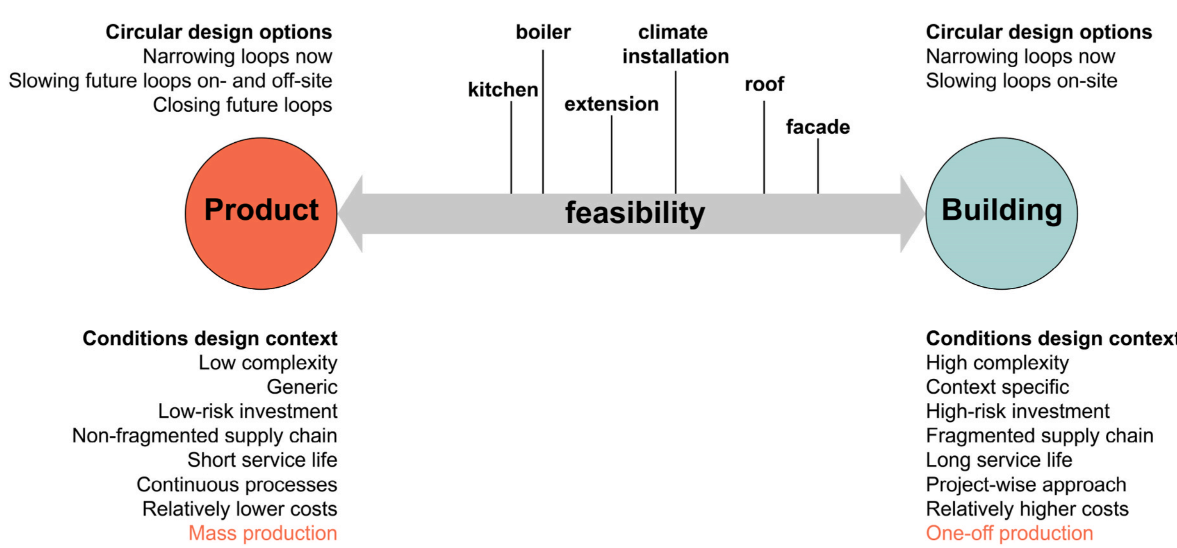

Fig. 2. Feasible circular design options per building-component type.

principles in the built environment. Second, existing studies on feasibility of circular (design) principles in the built environment focused on building and construction-industry level. In OSM B, we compared the barriers found in literature to those encountered in our study; we found similar barriers. Although our barriers may not be novel, we strengthen their validity by finding them empirically, on building-component level, and in a different context. However, we did not encounter as many governmental and regulatory barriers as previous authors. Most participating individuals did not require circular norms as incentive nor did existing regulation prevented them (yet) from applying circular design options. Furthermore, we provided detailed insights on which barriers are applicable to *different* building components.

Third, we found that different combinations of circular design options were perceived as more feasible for different circular building components. We induce the hypothesis that *for components with product-like characteristics, it is more feasible to focus on narrowing loops now and slowing and closing likely future cycles. Whereas for building-like components, it is more feasible to prioritize narrowing loops now and slowing likely*

Table 7
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 reason influencing feasibility in circular building components	Key reason was also found by	Related barriers found in literature (see also OSM B)	Possible directions to help overcome barriers
- Circular design options to slow and close future loops. Especially loops requiring new activities and taking place in long-term or off-site - Options such as modular design, standardizing sizes and applying demountable joints to facilitate reuse, adjustments, and recycling - All building components, but building-like components in particular	- Fit is needed between circular technical model, supply-chain and business models - Fits includes 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	Adams et al. (2017) Azcarate-Aguerre et al. (2018, 2022),Guerra and Leite (2021), Selman and Gade (2020)	- 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	- 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 VRPs to optimize all loops - Involve stakeholders needed to realize all cycles and collaborate in value network
- All circular design options - All building components	- Development process has many design parameters and requirements - Stakeholders need to consider circularity as a priority throughout the development process	Kanters (2020)	- Lack of awareness, consideration or concern of CE amongst stakeholders - Lack of CE knowledge	- Increase feeling of urgency - Develop common goals - Knowledge on how to integrally weigh circularity to other requirements
- All circular design options - All building components	- Building components consist of many parts and materials; During its lifecycle many stakeholders are involved during production, construction, use and VRPs - High complexity makes it difficult to optimize all loops - Time and capacity constraint for innovation	Charef et al. (2021),Cruz Rios et al. (2021)Galle et al. (2021)	- Complexity of buildings	- Simplify the circular technical, supply-chain and business model so optimizing all the loops is easier - Reduce the number of parts and materials - Source building components, parts and materials locally - Focus on circular design options which narrow loops and slow loops in the near future - Limit the scope of innovation to fit the available resources and timeline.
- All circular design options - All building components	- (Previous) experience of stakeholders influences what is perceived as feasible - Stakeholders avoid risks of the unknown	Cruz Rios et al. (2021)Charef et al. (2021)Galle et al. (2021) Guerra & Leite (2021) Hjaltadóttir and Hild (2021)	- Lack of CE knowledge - Lack of CE experience and skills by stakeholders - Risk, doubts on safety and quality when applying circular design options - Lack of examples in practice - Unclear benefits of circular design options whilst investment is needed now	- Increase circular (design) experience through strategic pilots; sharing lessons-learned - Increase circular (design) knowledge and skills including: systems-, lifecycle and integral-design thinking - Increase knowledge and skills on environmental performance assessment

future loops on-site. This hypothesis is novel to literature; it may support practice in developing circular building components. We stress that particular applications and context can influence the perceived feasibility. So, we invite scholars to test the validity of our hypothesis.

Fourth, 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. We showed that what is perceived as feasible changed throughout the development process. Amongst all, we found that the feasibility of circular design options in the technical design needs to fit the supply-chain and business models. We induce the following hypothesis: *if the current supply-chain and business model are not part of the development scope, it is more feasible to focus on applying circular design options which narrow loops now and slow loops occurring in the near future and on-site*. Supporting our hypothesis, Selman and Gade (2020) found that stakeholders [in today's industry] preferred narrowing loops to slowing and closing. Adams et al. (2017); Azcarate-Aguerre et al. (2022), Cruz Rios et al. (2021), Giorgi et al. (2022), and Selman and Gade (2020) found that today's fragmented supply chain hinders realization of circular design options to slow and close loops.

Finally, our research showed that many circular design options are already feasible to implement. So, many of the barriers listed in literature can already be overcome. Yet, we also showed that not all circular design options are yet feasible to implement. So, which barriers were the real bottle necks? In Table 7, we identified 4 key reasons that influenced the feasibility of circular design options in our study. We identified related barriers; we proposed suggestions on how these barriers might be overcome. Few of the reviewed authors identified key barriers; none of their lists were identical nor matched ours. Yet, there is some overlap (see Table 7). We consider that similarity in findings strengthen the validity of these being key barriers. However, we stress that this list is not meant as exhaustive. Other recurrent key barriers found in literature - but not this study - were 'lack of CE regulation' and 'lack of CE tools'. Still, this short-list of key barriers can help prioritize the research agenda and support the development and implementation of more circular building components and, as such, speed up the transition to a circular built environment.

Our study also has several limitations. The development processes underlying this research went from initiative *up to* market implementation. Stakeholders raised feasibility concerns which might occur if circular building components reach market implementation. For example, there are not enough reclaimed and bio-based materials to meet demand. However, these concerns remain expectations. The feasibility of market implementation of circular building components warrants its own empirical study.

Even though our findings are based on multiple cases, we are careful to claim their generalizability. The building components were all developed in the Dutch social housing context and with particular stakeholders and individuals. Some stakeholders had no or limited involvement, such as tenants, material suppliers, part manufacturers, maintenance companies and recyclers. 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. Our findings remain based on situational knowledge and might not be true for all, for always, everywhere.

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. Our study investigated what choices in the *design* of circular building components influenced their feasibility. We already explained that choices on how to arrange the *development process* can also influence what is perceived as feasible.

Finally, we introduced the CE as a means to remedy growing resource use, environmental impacts and waste generation in the built environment. Some critical reflection on the efficacy of this premise may be appropriate. Van Stijn et al. (2022) found that not all circular design options increase the environmental performance of building components in the long-term. Best-performing designs combining circular design options purposefully, did not nullify resource use, environmental impacts and waste generation. Nor do these designs necessarily reduce CO_2-emissions on the short-term. In this research, we found that not all circular design options are yet perceived as feasible. So, more circular building components can be developed and implemented in projects and practice today. However not every circular design option is desirable and not every option which is desirable is yet feasible. With resource use expected to double by 2050 (United Nations Environment Programme, 2021), *additional* sufficiency-oriented strategies may be needed to find a timely solution to the increasing resource use, environmental impacts and waste generation in the built environment.

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) principles 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 up to market implementation and documented the choices made by stakeholders. Through iterative process reflection and analysis, we identified which choices 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. 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. 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 4 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. The short-list of related key barriers can help prioritize the circular built environment research agenda and support the development and implementation of more circular building components and, as such, speed up the transition to a circular built environment.

CRediT authorship contribution statement

A. van Stijn: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft. **B. Wouterszoon Jansen:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – review & editing. **V. Gruis:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. **G.A. van Bortel:** Conceptualization, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data underpinning this study has been summarised and provided in a separate file (online supplementary material).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138287.

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