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DOI
10.3390/su142315761

Publication date
2022

Document Version
Final published version

Published in
Sustainability

Citation (APA)
Jansen, B., van Stijn, A., Gruis, V. H., & 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*(23), Article 15761. https://doi.org/10.3390/su142315761

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Article

Cooking Up a Circular Kitchen: A Longitudinal Study of Stakeholder Choices in the Development of a Circular Building Component

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

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

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Citation: Wouterszoon Jansen, B.; van Stijn, A.; Gruis, V.; van Bortel, G. Cooking Up a Circular Kitchen: A Longitudinal Study of Stakeholder Choices in the Development of a Circular Building Component. *Sustainability* **2022**, *14*, 15761. https://doi.org/10.3390/su142315761

Academic Editor: Elisa Di Giuseppe

Received: 1 October 2022
Accepted: 21 November 2022
Published: 26 November 2022

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1. Introduction

The built environment is said to be responsible for a substantial part of all human-induced emissions, resource use, and waste [1]. A transition to a more sustainable built environment is therefore paramount. By increasing resource efficiency and effectiveness, and reducing resource use and waste, the circular economy (CE) could offer the means to do so.

Geissdoerfer et al. [2] (p. 759) describe a CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". In this context, slowing means using materials longer, closing means recycling at the end-of-life, and narrowing means reducing resource use or achieving resource efficiency up front [3], which can be done through value retention processes (VRPs) such as reuse, repair, refurbishing, and recycling [4,5]. To realize VRPs, components, parts, and materials should be considered from a systems perspective, focusing not only on the physical design (or technical model), but also on the supply chain (or industrial model) and business model [6].

A gradual transition to a circular built environment can be achieved by replacing building components with circular components during renovation, maintenance, or construction. Many different CE design options can be applied to a circular building component's physical design, supply chain, and business model. For example, a component can have a modular design, to be reused and updated—slowing loops in the future. However, it can also be made of biodegradable renewable resources, or be lightweight—narrowing loops now [7]. Multiple aids have been developed to support this decision-making process, distinguishing between generative and evaluative methods [8,9]. Generative methods, such as the parameter-based tool presented by van Stijn and Gruis [6], support the integration of CE options during design synthesis. Evaluative methods, on the other hand, assess the 'circular performance' of a design. Examples of such methods are the environmental assessment method of circular economy life cycle assessment (CE-LCA) [10,11] and the economic assessment of circular economy life cycle costing (CE-LCC) [5,7]. When applying these methods, these studies found that purposeful application and combinations of circular design options led to better performance.

However, to assure a successful transition to a more circular built environment, the components have to be applied in practice. The extent to which this application is achievable is defined as 'feasibility' in this study. Many authors have investigated the feasibility of applying circular economy (design) principles in the built environment [12–28]. They have identified challenges or barriers, and—to a lesser extent—drivers, enablers, or opportunities (an overview of these studies is included in Supplementary Material, Section S1). The majority of studies have researched feasibility at the construction industry level or building level. Only Azcarate-Aguerre et al. [14,15] focus on the building component level and study a façade. Some studies analyze the feasibility of a particular circular design option or limit the feasibility scope. For example, Azcarate-Aguerre et al. [14,15] focus on façade servitization models whilst Akinade et al. (2020) [13] look at design for deconstruction. Condotta and Zatta [18] take a policy and regulatory perspective and Charef et al. [17] adopt the socioeconomic and environmental perspective.

However, most authors have opted for a literature study, studied completed cases, or interviewed one or multiple stakeholders (once). These studies conclude with a list of identified barriers (see Supplementary Material, Section S1). Although these barriers are useful, designers, policymakers, and other decision-makers that influence the implementation of circular building components could benefit from knowledge of the relative importance of these barriers in the development process. Furthermore, they could benefit from in-depth analysis of when and how the barriers (re)occur in a real-world case, how they were or could be overcome, and how they influence the feasibility of a component.

Therefore, we present a longitudinal study of the development process of a circular building component: the circular kitchen (CIK). This study is limited to the kitchen as a building component, and, however important, does not include the sustainability of the activities that take place in the kitchen, such as cooking. The CIK was developed for the Dutch social housing sector in co-creation with multiple organizations, companies, and individuals that have a role in the social housing kitchen supply chain: the stakeholders. These stakeholders include, for example, housing associations (HA), a kitchen manufacturer (KM), parts and material suppliers, a kitchen appliances manufacturer (AM), and a contractor (CO)—for a full list see Table 1. In this study, we aim to identify the stakeholders' choices that led to a feasible CIK and go beyond a list of barriers by deriving lessons learned from in-depth analysis to support decision-makers in the future development of circular building components.

Table 1. List of stakeholders involved in the CIK project.

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

2. Materials and Methods

This study was conducted in several steps. In the first step, we developed a circular building component (the CIK) between 2017 and 2022. During this period, we documented the meetings in summaries. In the second step, we developed a dataset that includes an inventory of the choices made by the stakeholders in the development process based on the documented summaries. We analyzed these choices systematically and iteratively (see Section 2.2) and reflected on the development process. We then derived lessons learned by combining reflection and analysis. In the third step, we validated our findings with the stakeholders involved in the development process. The validation was then used to refine the lessons learned. In the following sections, we will elaborate on the methods applied in each step.

2.1. Developing the CIK

The CIK was developed for and with Dutch HAs, as they own nearly one-third of the housing stock [29] in the Netherlands and have high ambitions of achieving circularity [30]. Their experience with long-term collaborations and a long-term investment perspective makes them favorable candidates for implementing circular principles. Furthermore, other practice stakeholders that are part of the kitchen supply chain were involved in the development process. Table 1 shows a full list of the stakeholders involved in CIK development.

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

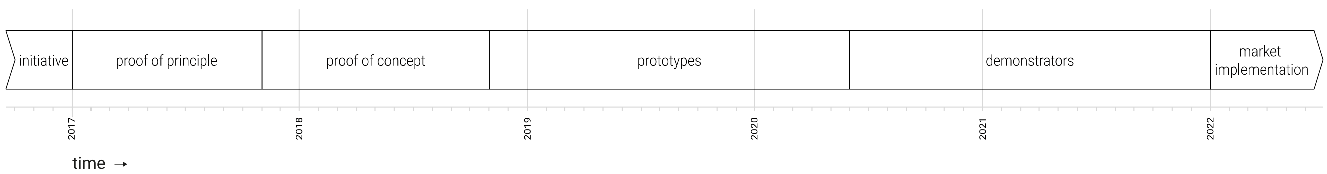


Figure 1. CIK development phases through time.

During all these phases, co-creation workshops were organized. The researchers played an active role in the process, initiating collaborations and proposing and testing design variants together with stakeholders from practice. Therefore, their expertise and background should be described: both researchers 1a (R1A) and 1b (R1B) have a background in architecture, designed parts of the CIK, and developed generative and evaluative methods for circular building components. R1A and R1B also served as project leads for periods of time. The stakeholders took the lead in the product development toward the later stages, and the researchers provided additional knowledge and reflection. Summaries of the contact moments between the stakeholders, as well as presentations, drawings, and photos were documented. An overview of these contact moments can be found in Supplementary Material, Section S2.

2.2. Stakeholder Choices

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

Figure 2 shows the parallel processes to identify which stakeholder choices influenced the feasibility of circular design options: 'zooming out', 'zooming in', and induction. Once these parallel processes were completed, the outcomes were validated. The following paragraphs describe these processes in detail.

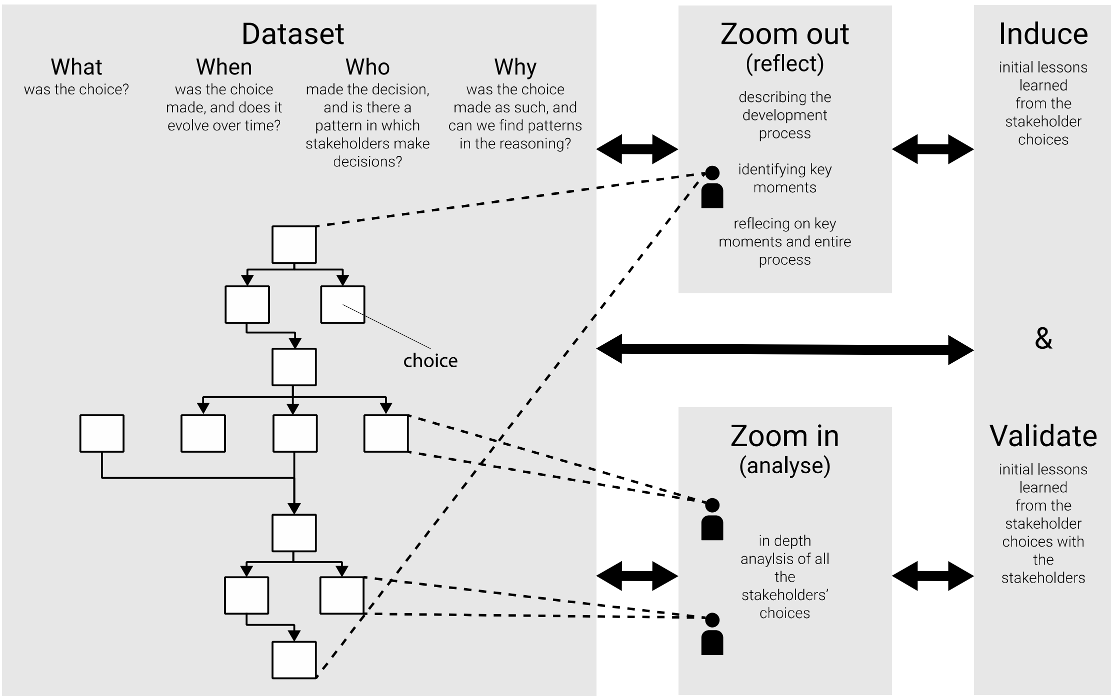


Figure 2. Approach for reflection on and analysis of stakeholder choices to induce lessons learned.

When 'zooming out', we reflected on the process as a whole, based on the theories of 'reflection on action' by Schon [31] and the action research cycle by Carr and Kemmis [32]. We described the CIK development process chronologically, a summary of which can be found in Section 3, and a full description in Supplementary Material, Section S3. Summarizing allowed us to reflect upon the entirety of the process or choices in particular moments; it helped us to identify choices that were 'key' in developing feasible circular building components.

When 'zooming in', we analyzed single stakeholder choices in depth. We noted (1) what the choice was, (2) when the choice was made (according to the phases mentioned in Section 2.1), (3) who made the choice, and (4) why the choice was made as such, for which we can distinguish different categories of reasoning. These categories were added based on the studies on CE barriers in the literature review. Since most studies applied different frameworks, there was no existing framework that could include all categories. Therefore, rather than selecting a framework before the analysis, we added coding dimensions inductively, through the iterative reading of the existing frameworks provided in the literature studied (also described as emergent coding [33,34]). Table 2 shows the categories of reasoning and the applied definition to clarify the differentiation between categories in our analytical framework. For example, the difference between 'Societal and Cultural' and 'Social or Psychological' is to whom the reasoning is related. Societal and cultural reasoning is based on the fit with what is (perceived as) the cultural norm, for example: "in the Netherlands, one should build with bricks". Social or psychological reasoning is related to other stakeholders directly, for example: "we do not trust this supplier to be able to provide us with this product consistently". The difference between 'Value proposition' and 'Functional and Aesthetic' should also be clarified. In our framework, reasoning based on the value proposition is about whether something is an added value for the stakeholders, and is based on their willingness to buy, supply, produce, or take part in the development of a product. For example: "This product has an acceptable life cycle cost and allows us to offer our tenants more customization, while it has a lower environmental impact." Reasoning in the category of functional requirements is based on whether a product suffices for the intended use (aesthetics is seen as part of this but is mentioned separately since this inclusion is not straightforward). For example: "By using these connectors, the cabinet is not rigid enough, and will move if users push it".

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

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

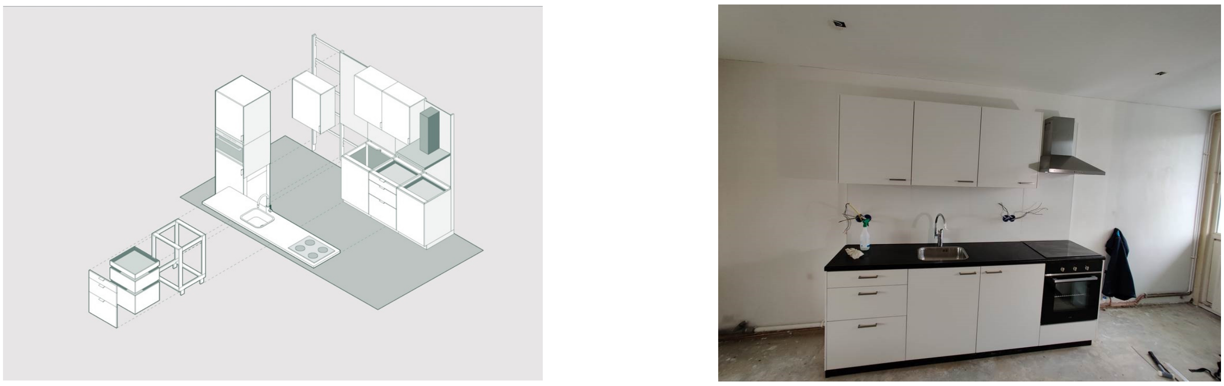
Table 2. Analytical framework.

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

3. Case Description

In social housing, the kitchen is replaced every 20 years on average. The kitchens consist of cabinets from melamine-coated chipboard panels which are glued together. These kitchens are rarely repaired or reused due to their low price. This causes unnecessary resource use, impacts, and waste generation. In the next paragraph, we will briefly describe the developed CIK and process. For a full description, see Supplementary Material, Section S3.

A modular concept design for the CIK was developed (see Figure 3a). This design combines strategies to slow and close material loops: kitchen modules can be attached to and detached from a docking station, to allow for changes in layout. The modules consist of a long-life frame, to which fronts, drawers and shelves can be connected. All of the connections in the design are made using tool-free click-on connectors, allowing for easy repair and adjustments in function and appearance. Durable plywood is used to prolong the lifespan of parts. After installing a circular kitchen, full replacement is no longer necessary, preventing future resource use, impacts, and waste. To incentivize the manufacturer to produce such a circular kitchen, a circular business model was developed: the docking station and the kitchen is sold to the HAs, and they are provided with a service subscription and a take-back guarantee. Additional kitchen modules, or alternative finishing options can be offered to tenants.



(**a**) (**b**)

Figure 3. (**a**) CIK demonstrator technical design concept; (**b**) CIK demonstrator placed in a dwelling.

The proof-of-concept of the kitchen was built to a first prototype, refined, and eight demonstrator kitchens were installed in dwellings (see Figure 3b). The kitchen manufacturer has since been redeveloping the circular kitchen to remain closer to the current production process and business model. Instead of a frame, the kitchen cabinet is constructed from demountable panels. Through this design, they aim to facilitate the repair of parts in local shops. Instead of plywood, a more circular variant of chipboard is used.

4. Results

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

4.1. Ambition

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

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

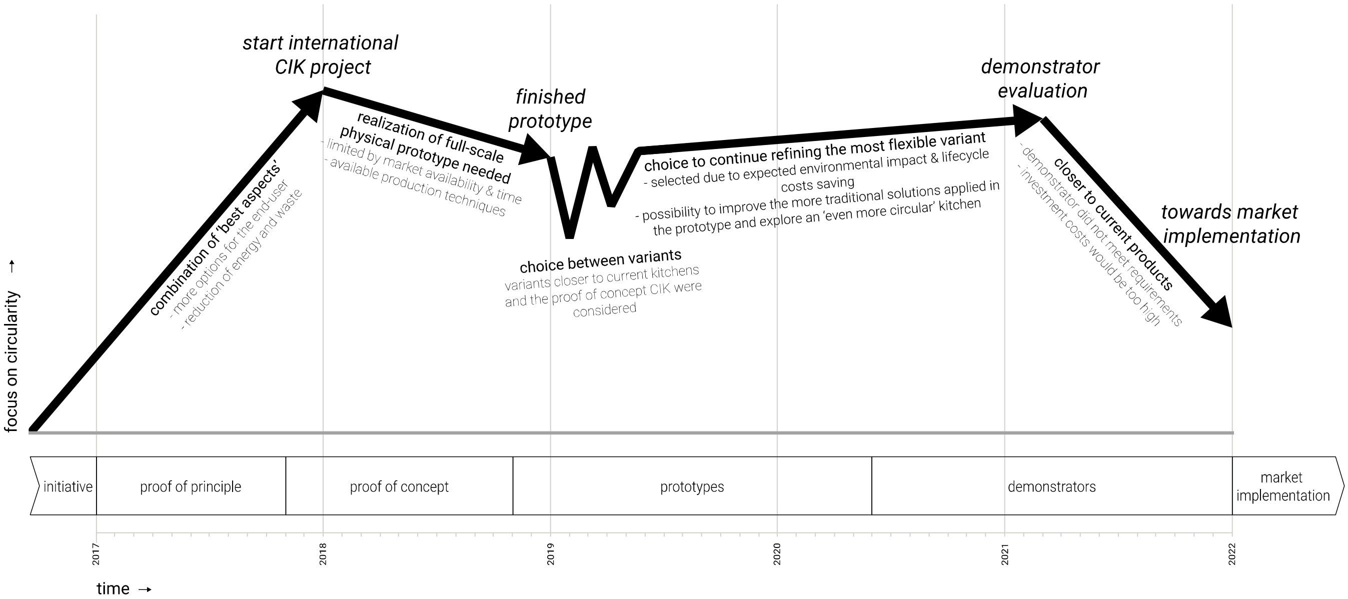


Figure 4. Level of circular focus for the CIK through time. The position on the y-axis is determined relative to previous points and is not absolute.

4.1.1. Increase in Circular Ambition

The first change in circular ambition was caused by the initiative for the CIK project. Stakeholders were asked if they could lease kitchens instead of buying them and a one-year research project was started to define such a lease kitchen. During this one-year project, a proof-of-principle was developed for the CIK. Five variants were designed (for a full description, see Supplementary Material, Section S3) and the group selected a combination of two ambitiously circular variants for the final proof-of-principle CIK: the plug-and-play kitchen, which facilitates circular loops and accommodates current and future needs by separating the kitchen into parts based on expected lifespan, and the 'all-CE kitchen', which includes appliances that reduce energy usage and waste. A business model and supply chain model to incentivize and organize all the loops for this design were developed as well (see Supplementary Material, Section S3 for a full description). Nevertheless, at this point, the radical innovative design that was selected was seen as feasible—on 'paper'.

4.1.2. First Reduction in Circular Ambition

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

4.1.3. Slight Increase in Circular Ambition after Success

After the realization of the full-scale prototype, the design of the CIK was re-evaluated. The added costs and complexity of a design that has a separated frame, infill, and style package led to the development of multiple variants that differed in the application of circular design options. To determine which variant would be further developed, preliminary CE-LCA, Material Flow Analysis (MFA), and CE-LCC results for all the variants were presented to the group (see Supplementary Material, Section S3 for a more detailed description). Subsequently, the group decided to further develop the variant that applied the most circular design options: a refined version of the prototype kitchen. Contrary to the prototype, this variant included wall-mounted cabinets that consisted of a frame, infill, and a style package—consistently applying the separation of parts based on function—and had the best 'environmental benefits to cost ratio', which was the main reason for its selection.

4.1.4. Decline in Circular Ambition toward Market Implementation

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

4.2. Aesthetics

To maximize the impact of the CIK, it was initially intended for the social housing sector, which makes up for 28% of the housing sector in the Netherlands [29], and can structurally apply circular solutions as a part of a transition to a more sustainable housing portfolio. However, to realize this impact, the kitchen has to be applied and accepted by users. In this section, we describe one of the factors that played a key role in the acceptance: aesthetics. Discussion on the aesthetics of the CIK was detected in the dataset by choices made regarding the style package, materials, and other elements that determine the look of the kitchen.

4.2.1. Functional Requirements

Currently, housing associations provide their tenants with—mostly white—kitchens that consist of three base cabinets and three wall cabinets without appliances. In the proof-of-concept phase, the researchers, KM, and HAs met to determine the functional requirements for a kitchen for HAs. The researchers and KM wanted to go beyond statements such as 'it has to be white' and wanted to take the underlying reason as a starting point for the refinement of the proof-of-concept design. Table 3 shows the requirements that were mentioned in this meeting that could influence the aesthetics of the kitchen, whether these are stated for the sake of aesthetics, or are a result of the kitchen's functioning.

The first two reasons in Table 3 can be explained by the role of housing associations: they provide housing for a varied group of tenants, with different backgrounds and tastes. Although the users might favor exclusivity and authenticity [27], the HA has to provide a single solution that is acceptable for all tenants. The latter three requirements have a significant influence on the aesthetics but were stated for functional reasons.

Table 3. Requirements for kitchens mentioned by HAs that influence the aesthetic of the kitchen directly.

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

4.2.2. Acceptance of the Prototype

In the refinement of the proof-of-concept design, the list of functional requirements was one of the three pillars by which the CIK was assessed (together with environmental impact and life cycle costs). All the functional requirements, including those influencing the aesthetics of the CIK, were implemented in the design. Drawers were used instead of doors as much as possible in the base cabinets due to their better ergonomics and their expected longer functional and technical lifespan. Their use also eliminates the need for interior panels inside the cabinet that would need to have a finishing layer. Because the inside of the cabinet does not become fully visible, the appearance of the kitchen could be traditional, while the design was unconventional. The drawers were made out of a material with a layer that is easy to clean, and the design, therefore, met the requirements. Figure 5a shows the base cabinet with drawers of prototype 1, and Figure 5b shows the frame structure behind the drawers.

(**a**)

(**b**)

Figure 5. (**a**) CIK prototype 1; (**b**) CIK prototype 1 with a drawer opened to show the interior of the cabinet.

4.2.3. Rejection of the Demonstrator

After the prototype, the demonstrator was designed with a higher circular ambition (see Section 4.1). This included making the wall cabinets out of a frame with a separate infill and style package. The infill was designed so that the interior side panels did not need a finishing layer, while the horizontal panels did—since belongings would be stored on these panels. Figure 6 shows the interior of the wall cabinets of the demonstrator kitchens.

Figure 6. Interior of the demonstrator wall cabinets.

After the placement of demonstrator kitchens in homes, one of the HAs was not completely satisfied with the kitchen. Among other reasons (see Supplementary Material, Section S3), the HA noted that users were expected to reject the unfinished panels on the inside of the cabinets.

4.3. Design Scale

To lower the environmental impact of the CIK compared to conventional kitchens, while aiming for a similar lifecycle cost, the aim was to make the materials last as long as possible. By applying materials with a long technical lifespan (the maximum period during which it can physically function [35]) where possible, some parts could be reused multiple times after the end of the functional lifespan (the period in which the object meets the functional demands of the user [36]), therefore lowering the environmental impact and costs over time (see [5,37]). Therefore, the properties of the materials, and how they would be connected and disconnected, were of utmost importance. The first since the material should not only last as long as possible, but it also has to last without changes such as deformation and discoloration, and it must be available in the longer term. The latter is of importance since reuse can only occur if the parts can be connected and disconnected from each other multiple times, without loss of strength or stability.

4.3.1. Materials

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

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

4.3.2. Connecting Materials

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

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

4.4. Participants

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

4.4.1. Consequences of Change in Participation

The replacement of participants from the KM is a striking example, especially since the KM plays a crucial role in the development, being the only organization that has specific knowledge of the technical design and parts of the supply chain. Figure 7 shows the involvement of three employees of the KM throughout the process, the effect their involvement had, and their influence, technical knowledge, and focus on the CIK project. KM1 (KM chief executive officer) was involved in the initiative and proof-of-principle phases. Since KM1 has the most influence within the KM, a support base within the organization was created, and decisions could be made quickly. However, KM1 lacked technical knowledge, and could not support the project team with specific knowledge. In the proof-of-concept phase, the manager of product and process development (KM 2) joined the CIK project. KM 2 had relatively high influence within the organization combined with ample technical knowledge, enabling fast decision-making for the technical side of the project—which was needed in this phase. However, in a later stage, KM 2 was assigned new tasks within the organization, and the focus on the CIK was reduced. Consequently, a product manager (KM 3) joined the CIK project team. KM 3 had limited influence in the organization and limited technical knowledge. The period in which KM 3 was the main participant for the KM in the CIK project was therefore characterized by low decisiveness and initiative from the KM's side. Toward the demonstrator phase, the KM appointed a dedicated 'business developer, circular kitchen' (KM 4). Although KM 4 lacked some of the technical knowledge of KM 2, the fact that KM 4 was dedicated to the CIK project, combined with more influence in the organization, caused the initiative and decisiveness of the KM to increase.

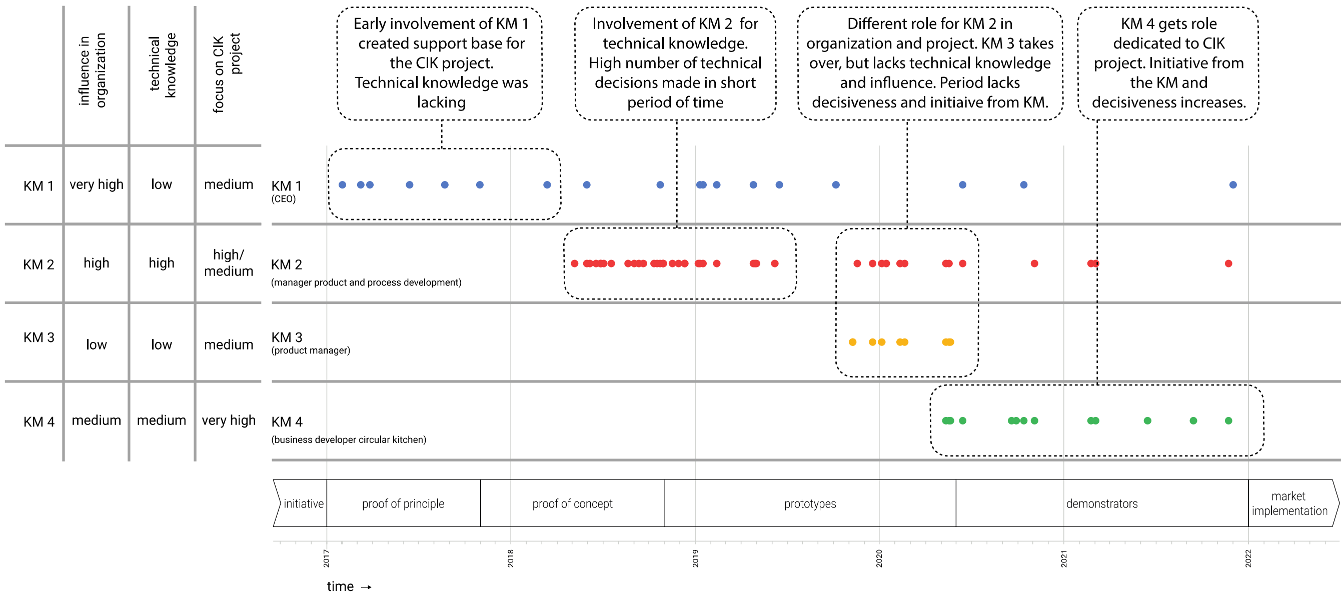


Figure 7. Participation of the four different individuals from the KM involved over time, including their level of influence, technical knowledge, and focus on the CIK project.

4.4.2. Is the Future Supply Chain Fully Represented?

Table 4 shows the 16 organizations that participated in the CIK project. The inclusion of both the manufacturer and the client has led to better alignment of the value proposition; this improved the coordination among the stakeholders about what was possible and what was needed. For example, a synergy was found between modularity as a way to reduce environmental impact and material use, and a way to offer tenants customization of their kitchen. Notably, we did not include the end users (the tenants) in the list of organizations. However, a focus group was organized with tenants in the proof-of-principle phase.

Furthermore, Table 4 shows the lack of involvement of stakeholders that are involved in the raw materials stage, and end-of-life stage (such as material manufacturers and recyclers respectively). The inclusion of experimental, new materials, or new recycling techniques was, therefore, not explored to their full extent in the scope of the CIK project. Furthermore, the development of the supply chain and business models concept focused on the life cycle stages that were represented by the involved stakeholders.

4.5. Focus

Successful circular innovation often requires a change in three elements: (1) the physical design, (2) the supply chain, and (3) the business model of a building component [37]. The CIK project started with the suggestion of shifting toward a new business model: leasing kitchens instead of buying them. Although all three elements were further developed, the effort that was put into these elements was not equal in some stages of the development. The next paragraph describes the development of the business model, supply chain, and physical design.

Table 4. List of organizations participating, and organizations defined in the supply chain, in which X signals (current) full involvement in the product lifecycle stages, and / signals a partial involvement in the lifecycle stage.

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

Development of the Business Model, Supply Chain, and Design

Figure 8 shows the meetings in which the design, business model, and supply chain were mentioned internally. Events are excluded, as they were used to present the ideas to a broader audience, and not to decide on potential changes. Furthermore, workshops and meetings that were linked to the project, but did not concern the kitchen itself were excluded as well (such as workshops discussing the development of kitchen appliances, outcomes of research, or meetings to plan for an event or website).

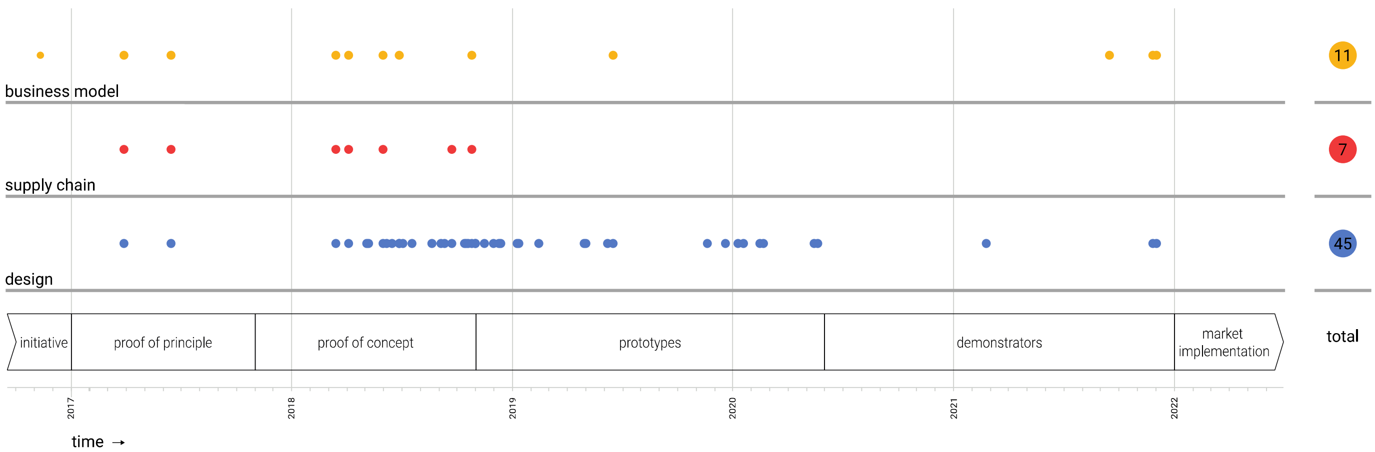


Figure 8. Meetings in which the business model, supply chain, and design were discussed over time.

In Figure 8, we can see that the number of meetings in which the design of the CIK was discussed is by far the highest with 45 meetings. The business model and supply chain were only discussed in 11 and 7 meetings, respectively. Furthermore, we can see periods in which the focus on the design of the CIK was intensified, generally before a phase in which a new physical deliverable was needed (the prototype and demonstrator phases). During these periods, many decisions on the physical design of the kitchen were made to realize a full-scale version.

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

5. Lessons Learned

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

5.1. Lesson 1: Ambition

From Section 4.1, we can derive the first lesson learned from the analysis of the CIK project. We have seen a high circular focus at the start of the project, in which the best parts of all the proposed variants were selected and combined. However, throughout the process, we can identify two moments in which the circular focus decreases. Both of these decreases were mostly caused by the need to realize a fully functional component: the prototype was limited by the market availability of materials and the production techniques that were available. The changes from the demonstrator toward a market-ready CIK were limited by requirements set by the clients and possible investment costs for unconventional production methods.

In the CIK case, both decreases in circular ambition were caused by conditions that were known beforehand but were not seen as insurmountable. Although the ambitious variants chosen might have been seen as more circular, if they are not applied in practice due to lack of feasibility, the building practice does not become more circular at all, as sticking to the business-as-usual model is rarely the most circular option [7]. However, we do recognize that what is feasible might change over time, and more ambitious designs might become more feasible later. Considering that lock-ins (see for example [38]) of non-circular or non-sustainable practices should be avoided at all times, we derive the following lesson: *prioritize implementing feasible circular options now, and improve to the most circular options over time.*

5.2. Lesson 2: Aesthetics

As can be seen in Section 4.2, not all requirements that led to a conventional aesthetic of the CIK were for the sake of aesthetics. We can distinguish two lines of reasoning when it comes to the required aesthetic for an HA's kitchen: (1) aesthetic to increase the expected acceptance among users, and (2) aesthetic as a result of functionality. However, both lines of reasoning ultimately have the same goal: user satisfaction, which is a crucial factor in the adoption of circular products—if the users are not satisfied, a transition to these products will not take place [39]. Although the 'most circular' design solution—on paper—might not be developed by trying to please as many users as possible, a design that is less circular but accepted by more users is more likely to be adopted. In turn, large-scale adoption of a product can make standardization more effective and reuse more likely. The lesson we can therefore derive is: *adjust the aesthetics to satisfy as many clients/users as possible.*

5.3. Lesson 3: Design Scale

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

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

5.4. Lesson 4: Participation

The example of the KM's participants in Section 4.4.1 shows that who is involved has a significant influence on the effectiveness of the process. This is especially true for the stakeholders that have a crucial role in the development, such as primary manufacturers. Furthermore, the example in Section 4.4.2 shows the importance of the participation of all the stakeholders that will have a role in the envisioned supply chain. These stakeholders each bring specific knowledge to the project and allow for better alignment of the value proposition between the stakeholders, making the component and its business model and supply chain more feasible, and possibly more circular. The lesson learned from these findings is, therefore: *involve people with the optimal amount of influence, technical knowledge, and focus on the project, and make sure all the relevant stakeholders are represented.*

5.5. Lesson 5: Focus

During the CIK development, a substantial focus on the physical design of the CIK can be seen. There are several factors that might have caused this focus. First, the requirements for the funding of the research project were to deliver a prototype in 2018 and to place demonstrators in real-world homes in a later phase. Second, the two main researchers involved in the development have a background in architecture, which could have led to a focus on the physical design. The involvement of certain stakeholders such as the kitchen manufacturer and a contractor, and the exclusion of others, such as a recycler (see also Section 4.4.2) could have affected the focus as well. Finally, the physical design of the product was the 'most urgent' problem to solve, since a fully functional product was needed now, while the changes in the supply chain accommodating CE loops would most likely be needed in more than 5 years. However, a system for tracking parts would have to be implemented from the sale of the first product. Furthermore, the business model should be defined when the product becomes available on the market since agreements regarding finances and liability should be agreed on before the sale.

In the CIK process, we have seen an attitude of "product first, and then we will figure out how to sell and reuse it". Although many authors state that the physical design, supply chain model, and business model should be developed integrally [40,41], fully developing all three did not fit within the time and resources available for the CIK project, and eventually, the CIK's physical design was adapted to fit within the current supply chain and business model as much as possible. Since the environmental and economic performance of some designs can rely heavily on future cycles [7], these future cycles should be guaranteed in the design, business model, and supply chain model, from which we derive the following lesson: *plan for sufficient time and resources if the physical design, supply chain model, and business model are to be completely redeveloped integrally.*

6. Discussion

Our lessons learned can be used when developing circular building components in the future. However, there are several limitations to this study, and the lessons should not be applied without taking note of these limitations. First, some of the barriers found in the current literature can be recognized in the CIK development process (for an extensive list, see Supplementary Material, Section S1). For example, the second most mentioned barrier—"additional time, labor and cost to design and construct circular design options" [13,17,19,22,23,26,28]—and other barriers that were mentioned often—"circular design options and materials require higher initial investment" [17,20,21,23,28], and "risk or unwillingness to pay for long term financial benefits of CE that may not occur whilst up-front investment is needed" [13,17,20,27]—align with the reasoning for the lesson about ambition. However, some barriers that are frequently cited in the literature are not represented in the CIK development. For example, the most commonly mentioned barrier—"lack of or ambiguous legislation and regulation for CE and circular design options" [13,18,19,21,22,24,26,27]—is not reflected in our lessons. This could be caused by an absence of this barrier but also by regulations being considered implicitly by the stakeholders. Furthermore, barriers related to the use of non-virgin materials are not reflected directly in any of the lessons. Moreover, we do not claim that our lessons are the only lessons to be learned from our dataset; analyzing our dataset from other points of view may yield other results.

Second, since the five lessons were derived from the experiences of one case, we cannot claim that the lessons apply to all building components. The development of a circular structure [40] can differ significantly from the development of a circular kitchen [41]. Furthermore, the particular application of a lesson and the context in which it is applied influences its usefulness significantly. Since the CIK was developed in just one context—that of social housing in the Netherlands, with specific people from specific stakeholders, who did not comprehensively represent the supply chain—this could limit the generalizability of the research. Future research, involving more cases, in various contexts, should be done to further validate our findings.

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

Fourth, our lesson on participation (lesson 4), indicated a lack of participation from some stakeholders that were relevant to the CIK process. We would however also like to state the positive side, as many relevant stakeholders were involved in the process, and their active involvement contributed to gathering more realistic and relevant knowledge regarding the development of circular building components. Therefore, lesson 4 should not only be seen from the perspective of possible improvement for the CIK, but also from the perspective of how the CIK was already relevant to current practice while achieving a significantly better environmental and economic performance than the business-as-usual approach [7].

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

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

7. Conclusions

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

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

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

Supplementary Materials: The Supplementary Materials can be downloaded at: https://www.mdpi.com/article/10.3390/su142315761/s1.

Author Contributions: Conceptualization, B.W.J. and A.v.S.; Methodology, B.W.J. and A.v.S.; Validation, B.W.J. and A.v.S.; Formal analysis, B.W.J.; Investigation, B.W.J.; Data curation, B.W.J. and A.v.S.; Writing—original draft, B.W.J.; Writing—review & editing, B.W.J., A.v.S., V.G. and G.v.B.; Visualization, B.W.J.; Project administration, V.G.; Funding acquisition, A.v.S. and V.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by EIT Climate-KIC, grant number 210060, and Amsterdam Institute for Advanced Metropolitan Solutions (AMS), grant number CIR17018.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available in the Supplementary Material.

Conflicts of Interest: The authors declare no conflict of interest.

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