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Towards a circular built environment

An integral design tool for circular building components

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Abstract

Purpose – The transition to a circular economy in the built environment is key to achieving a resource-effective society. The built environment can be made more circular by applying circular building components. The purpose of this paper is to present a design tool that can support industry in developing circular building components.
Design/methodology/approach – The tool was developed and tested in five steps. In Step 1, the authors analysed existing circular design frameworks to identify gaps and develop requirements for the design tool (Step 2). In Step 3, the authors derived circular design parameters and options from existing frameworks. In Step 4, the authors combined and specified these to develop the "circular building components generator" (CBC-generator). In Step 5, the CBC-generator was applied in the development of an exemplary component: the circular kitchen and tested in a student workshop.
Findings – The CBC-generator is a three-tiered design tool, consisting of a technical, industrial and business model generator. These generators are "parameter based"; they consist of a parameter-option matrix and design canvasses. Different variants for circular components can be synthesised by filling the canvasses through systematically "mixing and matching" design options.
Research limitations/implications – The developed tool does not yet support establishing causal links between "parameter-options" and identification of the most circular design variant.
Practical implications – The CBC-generator provides an important step to support the building industry in developing and implementing circular building components in the built environment.
Originality/value – Whilst existing tools and frameworks are not comprehensive, nor specifically developed for designing circular building components, the CBC-generator successfully supports the integral design of circular building components. First, it provides all the design parameters which should be considered; second, it provides extensive design options per parameter; and third, it supports systematic synthesis of design options to a cohesive and comprehensive circular design.

Keywords Circular economy, Design tool, Building components, Circular kitchen

Paper type Research paper

1. Introduction

Many authors (e.g. Bocken *et al.*, 2016; Ellen MacArthur Foundation, 2013; Ness and Xing, 2017) point out that the linear economy of "take-make-use-dispose" leads to increasing pressure on natural resources, environmental pollution, carbon emissions and waste generation.

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

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The circular economy (CE) proposes a more resource-effective model by decoupling economic growth from resource consumption. The model originates from several schools of thought, including industrial ecology (Ayres and Ayres, 2002; Graedel and Allenby, 1995), regenerative design (Lyle, 1994), the performance economy (Stahel, 2006), biomimicry (Benyus, 1997) and cradle-to-cradle (C2C) (McDonough and Braungart, 2002). The CE model can be summarised in the following three principles: "(1) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimise resource yields by circulating products, components, and materials at their highest utility at all times in both technical and biological cycles; (3) foster system effectiveness by revealing and designing out negative externalities" (Ellen MacArthur Foundation, 2013; Mendoza *et al.*, 2017).

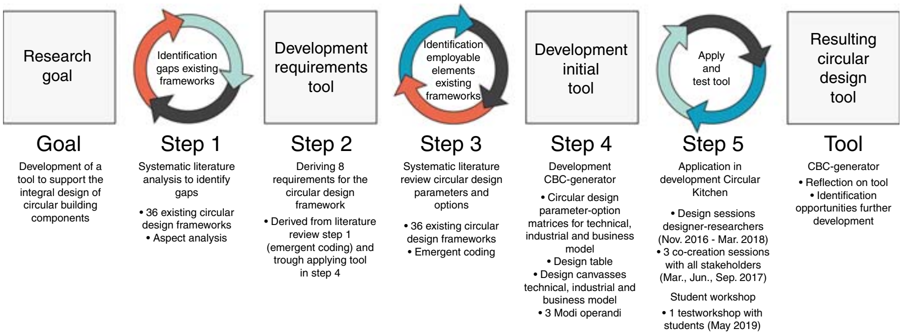
The building sector consumes 40 per cent of global natural resources, produces 40 per cent of global waste and 33 per cent of emissions (Ness and Xing, 2017). Due to its high impact, the transition to a circular built environment is key to achieve a resource-effective and sustainable society. Within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

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

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

2. Method

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



Sources: Adapted from Geissdoerfer *et al*. (2016), Bocken *et al*. (2011) and Leising *et al*. (2018)

Figure 1.
Tool development method

3. Results

3.1 Step 1: literature review of existing circular design frameworks

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

3.1.1 Literature review and analysis. De Koeijer *et al.* (2017) summarise two main types of circular design tools and models: generative and evaluative. The distinction is made on the basis of their applicability in the front-end or back-end of the product development process (Bocken *et al.*, 2014; Bovea and Pérez-Belis, 2012; de Koeijer *et al.*, 2017; Fitzgerald *et al.*, 2005; Telenko *et al.*, 2008). Generative tools offer the initial (front-end) support in synthesis of design variant(s) and, therefore, are the focus of this paper. Existing generative circular design frameworks were identified through literature review, including peer-reviewed, conference and professional sources. The frameworks were identified through Web of Science and Google Search engines using the following keywords: "circular economy" and "design" or "supply chain" or "business model" and "framework", "method" or "tool". We only included frameworks which support the design of a circular technical, industrial and/or business model and support the synthesis of a design proposal. This resulted in 36 frameworks to be included in the review. We analysed these frameworks on three aspects. First, we analysed the discipline (D) for which the framework offers design support, distinguishing the technical model (design), industrial model (supply chain management) and business model (marketing and finance). Second, we analysed the level (L) for which the framework offers design support. The CE can be designed at macro (country, region and urban area), meso (buildings, networks) and micro (company, (building) product) level (Geng *et al.*, 2012; Pomponi and Moncaster, 2017). Finally, we analysed the type of support (T) offered in the model: for example, if the framework provides step-by-step guidance and/or includes design canvasses. The results of the analysis can be found in Table I.

3.1.2 Gaps in existing circular design frameworks. Several gaps were identified. First, there is a paucity of frameworks which are developed for the "meso" scale or buildings. The exceptions are the design frameworks developed by Geldermans (2016) and Leising *et al.* (2018), which address the building level. Second, most authors recognise the need for a systems, and integral approach. Yet, very few provide such frameworks. Good examples of integrated frameworks are Bakker *et al.* (2014), Bocken *et al.* (2016), Mendoza *et al.* (2017), Moreno *et al.* (2016). Third, there is a missing link between more comprehensive yet "abstract", academic frameworks (e.g. Bocken *et al.*, 2016; Leising *et al.*, 2018; Scheepens *et al.*, 2016) and frameworks which offer very concrete design options. Finally, industrial parameters are insufficiently considered in

Table I. Aspect analysis of existing circular design frameworks

		L			D			T								
		Level			Discipline			Type of support								
		L1	L2	L3	D1	D2	D3	T1	T2	T3	T4	T5	T6	T7	T8	T9
Name framework	Source	Macro level	Meso level	Micro level	Technical model	Industrial model	Business model	Guidelines or criteria	Step-by-step guide	Design canvas	Design architypes	Design strategies	Design parameters	Design options	Case examples	Summary framework
The value hill	Achterberg *et al.* (2016)			x			x		x	~		x			x	Canvas on which activities, partners and products are placed based on the lifecycle phase of a product. Designers can select from several circular design, supply chain and business model strategies to develop their design
Framework for sust. business model innovation	Antikainen and Valkokari (2016)	~	~	x			x			x			x			Business model canvas extended with the parameters “business ecosystem” and “sustainability impact”
Products that last – framework	Bakker *et al.* (2014)			x	x	~	x		x		x	x			x	Framework links circular business model archetypes and circular design strategies, offering some examples
Product req., guidelines and business for CE	Balkenende and Bakker (2015)			x	x		x	x							~	A set of circular product requirements, design guidelines and supporting business model considerations
Circular design framework	Bocken *et al.* (2016)			x	x	~	x				x	x			x	Framework links circular business model archetypes and circular design strategies, offering some examples
Circular design guide	Ellen MacArthur Foundation and IDEO (2017)			x	x	~	x		x	x		~			x	An website with a wide variety of design methods (activities or workshops), design canvasses, circular design strategies and circular case examples to aid designers in developing and realizing a circular technical and business model
ReSOLVE framework	Ellen MacArthur Foundation (2015)			x	x		x					~	x		x	Framework which translates the three principles of the CE into 6 business actions which can support development of circular technical and business models: Regenerate, Share, Optimise, Loop, Virtualise and Exchange
New framework on circular design	Ellen MacArthur Foundation (2013)		x	x		x	x		~				x		~	A concise framework introducing parameters to consider when developing a circular supply chain: the wasted resource flows, value creation potential, possible barriers and execution
Circular economy toolkit	Evans and Bocken (2014) Evans and Bocken (2013)			x	x		x					x		x	x	Website which offers circular technical and business model strategies per lifecycle phase of the product; concrete examples are provided to illustrate strategies
10 steps to create a circular business model	Fischer and Achterberg (2016)			x		~	x		x				x		x	A practical, 10 stepped, circular-business-model design framework
Design for demand	Forum for the Future and Novelis (n.d.)			x	x		x		x	x	x	~				A website which takes users in 5 steps through the design process: introduction of CE, materials, solutions (introducing 6 design strategies), strategies (proposing 3 design-business model architypes), “design brief generator”
Circular business model toolkit	Forum for the Future and Unilever (n.d.)			x	~		x				x				x	Toolkit based on “circular-” “and “enabling” business model’ architypes; the toolkit provides examples of the architypes
Circular building matrix and new-stepped strategy	Geldermans (2016)		x	x	x				x	x		~	x	~		Framework in which the building is unraveled into system elements within a “Building inventory matrix” and circular re-loop potential is mapped. The accompanying “New-stepped strategy” provides circular design strategies
Circular design checklist	Gerritsen (2015)			x	x			x				x		x		An extensive checklist, containing technical design criteria with specified design options
Design framework	Gispen (n.d.)			x	x	x		x					x	~		A framework for circular products design, containing technical and industrial model parameters and (some) design options
Speedcycle	Goldsworthy (2017)			x	x						x		x			The speedcylce supports design for different speeds within a products lifecycle, based on 4 parameters: material, production, use and recovery. Several archetypes, are introduced as examples
C3 Business model canvas	Hofmann *et al.* (2017)			x			x			x			x			Business model canvas which situates: the economic dimension (8 components of the business model canvas), within the social dimension (key stakeholders), within the ecological dimension (i.e. environmental inputs, output, impact)
Guided choices towards a circular business model	Joustra *et al.* (2013)			x	~	~	x		x			x	x	~	x	A practical guide to develop a circular business model, including 5 steps: introduction in CE, review of partners, product (re)design, service (re)design and business model calculation
Collaboration tool for CE in the building sector	Leising *et al.* (2018)		x		~	x	~	x	x		~		x		~	The tool describes 5 phases for forming a circular supply chain collaboration for the realization of a circular building project; each step specifies serval strategies and the expected outcome
Circular business model canvas	Lewandowski (2016)			x			x			x			x			Business model canvas extended with the parameters “take-back systems” and “adoption factors”
CE Business model options, patterns and design strategies	Lüdeke-Freund *et al.* (2018)			x	~	x	x				x	x		x		Circular business model design options, 6 business model architypes and supporting circular design strategies
Business cycle canvas	Mentink (2014)			x		~	x			x	x	~	x			Business model canvas adapted to fit the “Butterfly diagram” of EMF (2013), allowing the alignment of business models in the entire supply chain
Multiple loop life-cycle design frame	Mestre and Cooper (2017)			x	x					x		x		x		A multiple-loop, life-cycle framework to support circular product design. The framework links the lifecycle phases with design strategies to: slow the loop, close the loop, bio-inspired loops and bio-based loops
BECE framework	Mendoza *et al.* (2017) and Heyes *et al.* (2018)			x	x	~	x	~	x	~						The BECE framework offers a 10-step, circular guide for business innovations: it links business model planning – through back-casting and the business model canvas – with (eco)design using the ReSOLVE checklist
Circular design framework	Moreno *et al.* (2016)			x	x		x				x	x				A framework which links business model archetypes and circular design strategies (from a DfX inventory). The framework includes 5 (abstract) design guidelines
Circular business model framework	Nussholz (2017)			x			x			x			x			Business model canvas which systematically integrates lifecycle value management: the 9 building blocks of the business model canvas are offset to three circular lifecycle points (i.e. resource recovery, prolong lifespan and end-of-life)
Circular strategies embedded in the business model canvas	Nußholz (2017)			x			x			x			x			Business model canvas thought from the “applied circular strategy” of each business model parameter
Sustainability qualifying criteria for circular BM	De Pádua Pieroni *et al.* (2018)		~	x			x	x								Qualifying criteria which can serve as a checklist in the development of circular business models
Design framework	Poppelaars (2014)			x	x			x				~		x		An extensive list of guidelines for circular product design, containing various design options
Circular transition framework for business model innovation towards a CE	Scheepens *et al.* (2016)	x	x	x	x	x	x			x			x			A design canvas which considers different system levels, stakeholder networks, value capturing, effects of regulatory drivers and the four life-cycle stages of products: production, marketing, operation and end-of life
Sustainable business model canvas	Sempels (2014)			x			x			x			x		~	Business model canvas which adds the parameters: mental grasp, drivers of productivity, positive and negative externalities. The added parameters seem focused more on assessing and enabling
Design tools for a circular economy	The Great Recovery and RSA (2013)			x	x	~	~				x				~	The tool offers 4 main circular archetypes which describe the technical, industrial and business model; the tool is complemented with examples and experiences from disassembly and design workshops
Closing the loop by design: a practical guide	Toxopeus *et al.* (2018)			x	x							x				Web-based tool with coherent set of design guidelines, customised to the level of expertise of designer; strategies are supported with illustrations and examples
Circular pathfinder	van Dam *et al.* (2017)			x	x		~					x	x		x	An online guide that asks a maximum of ten product-related questions (based on design parameters), after which it recommends circular design strategies and case examples
Circular design framework	van den Berg and Bakker (2015)			x	x			x				x		x		An product design framework with extensive circular design strategies and options
Circular board	WIITHAA (n.d.)			x			x			x			x			Business model canvas game specifying the parameters to circular economy terms (e.g. natural and technical key resources). Positive and negative impacts are added as parameters

most frameworks. For example, parameters such as mode of transport, and location of activities are omitted or only briefly mentioned, whilst these can have a significant environmental impact.

3.2 Step 2: requirements for the design tool for circular building components

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

Most frameworks (e.g. Bocken *et al.*, 2016; Scheepens *et al.*, 2016; Mendoza *et al.*, 2017; Lüdeke-Freund *et al.*, 2018) state that design for circularity requires an approach which ensures circularity is achieved within and beyond the designs' lifecycle. On the one hand, a systems approach (requirement 1) is required in which the building component is regarded from within its wider system environment. A systems approach ensures no undesirable rebound effects are caused or environmental burdens shifted from one system or system level to the next. On the other hand, an integral approach (requirement 2) is needed to ensure that the design in one discipline is in coherence with those in other disciplines. For example, a business model which is based on sales of expensive repair parts will not incentivise repair of a building component, even though it could technically be engineered for easy repair. In an integral design, the technical, business and industrial model should be developed in cohesion with each other. Our analysis of existing frameworks also indicated that a design tool has to include the relevant circular design parameters (requirement 3) and provide various practical design options to each design parameter (requirement 4). Furthermore, the design framework should be specific enough for designing in the built environment. The framework needs to relate the scale levels present in buildings (requirement 5): each material, part and component has its own lifecycle, yet interacts with the whole of the building system (Pomponi and Moncaster, 2017). Furthermore, the average lifespan of buildings and its components is long, compared to consumer products. Hence, the framework should also include approaches which are oriented towards longer lifespans (requirement 6). And the building industry has its own manufacturing techniques, materialisation, supply chain and financial arrangements. The strategies or options included in the framework should build onto these (requirement 7). Finally, a design process is characterised by an exponential information growth curve (Ullman, 2009). Hence, the framework should accommodate the different stages of a design process (requirement 8).

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

3.3 Step 3: deriving design parameters from existing circular design frameworks

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

3.4 Step 4: developing a design framework for circular building components

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

3.4.1 The parameter-option matrices. The technical model matrix includes the following parameters:

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

The industrial model matrix includes the following parameters:

1. Who are the key partners in the supply chain (or value network)?
2. What are the key activities carried out by the partners, including their "linear" activities, re-loop activities and all (re-)production processes?
3. What are the key resources needed in the supply chain? These includes the facility in which (re)activities and (re)processes take place and the system elements (e.g. (sub)components, parts, materials) which move through the supply chain. The system elements should correspond to the system elements identified in the technical model.

(4) Which transport occurs in the supply chain? The transport includes the mode of transport and the distance.

(5) What energy is needed in the make and remake phase (i.e. (re)production) of the building component?

The following parameters are included in the business model matrix:

(1) Who are the key partners in the business model? These partners should correspond to the partners identified in the industrial model.

(2) Who are the customer segments in the business model? We consider the sub-parameters owner (i.e. who is the owner?) and customer (i.e. who is the customer?)

(3) What are the supply chain relations between partners? Who is the primary partner (s) in the supply chain: who is/are the leading partner(s)? Who is the primary contact customer: is the owner contacted or the user? What is the kind of customer relationship? In other words, how is contact made between provider and customer? How is the collaboration between partners?

(4) What is the cost structure per partner?

(5) How are the revenue streams per product or service offered? We consider the type of financial arrangement (e.g. lease, sale) and income division (e.g. per company, over the supply chain).

(6) What is the value proposition? We specify the product or service proposition offered to the customer, the value creation and delivery, and value capturing per partner. Value creation and delivery clarifies how the product brings value to customers and value capturing how the business model brings value to a partner. Both are needed to align incentives within the supply chain, and it is this alignment that is crucial for the feasibility of the business model.

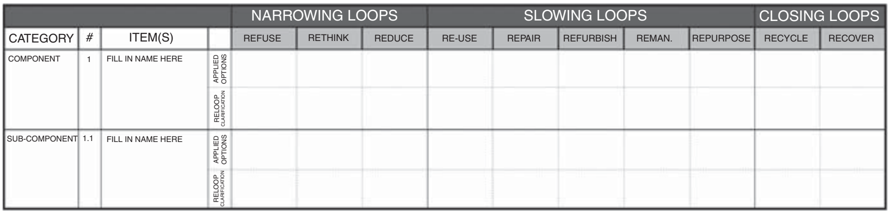
(7) What are the channels used to reach the customers?

(8) What are the take-back systems in place to ensure the return of key resources for re-looping?

(9) What are the adoption factors which determine how the business model can be implemented within the organisation of a partner, regulations and society?

3.4.2 The design table. The parameter-option matrices are complemented with a design table (see Figure 2). This table forms the frame in which options are systematically combined – applying them as building blocks – to form logical combinations for a design.

The horizontal axis of this table lists several categories in which the selected options can be organised, according to how they contribute to achieving circularity. The categories apply the taxonomy of the circular design framework developed by Bocken *et al.* (2016): “narrowing, slowing or closing resource loops”. This categorisation is further nuanced with the 9R model – (0) Refuse, (1) Rethink, (2) Reduce, (3) Re-use, (4) Repair, (5) Refurbish, (6) Remanufacture,



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

Figure 2.
Design table for the technical model generator

(7) Repurpose, (8) Recycle and (9) Recover – as developed by Potting *et al.* (2017). The vertical axis of the design table is used to list the technical, industrial or business model design from its entirety to – more and more – specified per parameters or system element.

3.4.3 Design canvasses. The design canvasses provide structure for designers to translate the design options to a circular design variant. Three design canvasses were added to the CBC-generator (see Figures 3–5); these are partly based on canvasses or frames found in the existing circular design frameworks.

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

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

The first operational pathway, ideate, supports the development of first idea(s) for a circular building component design. The design table is filled in by systematically "mixing

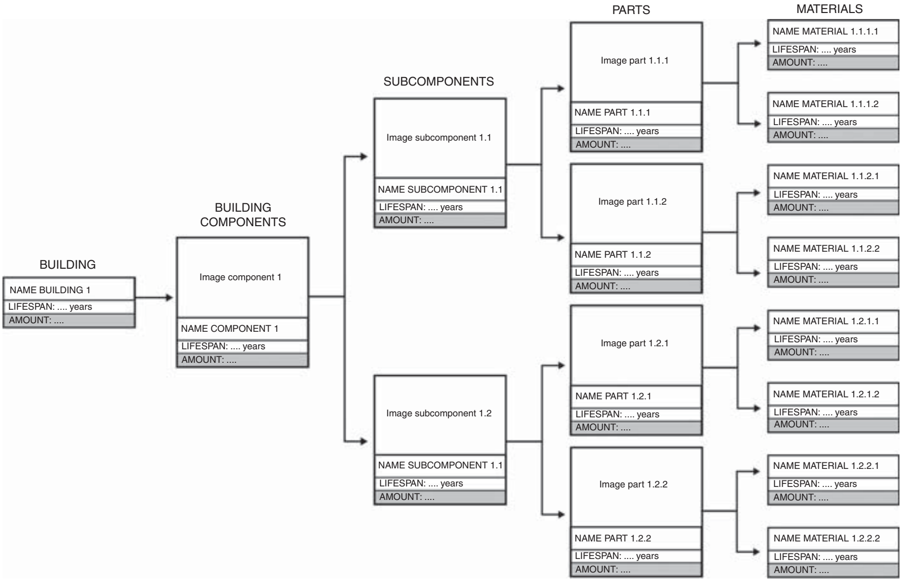
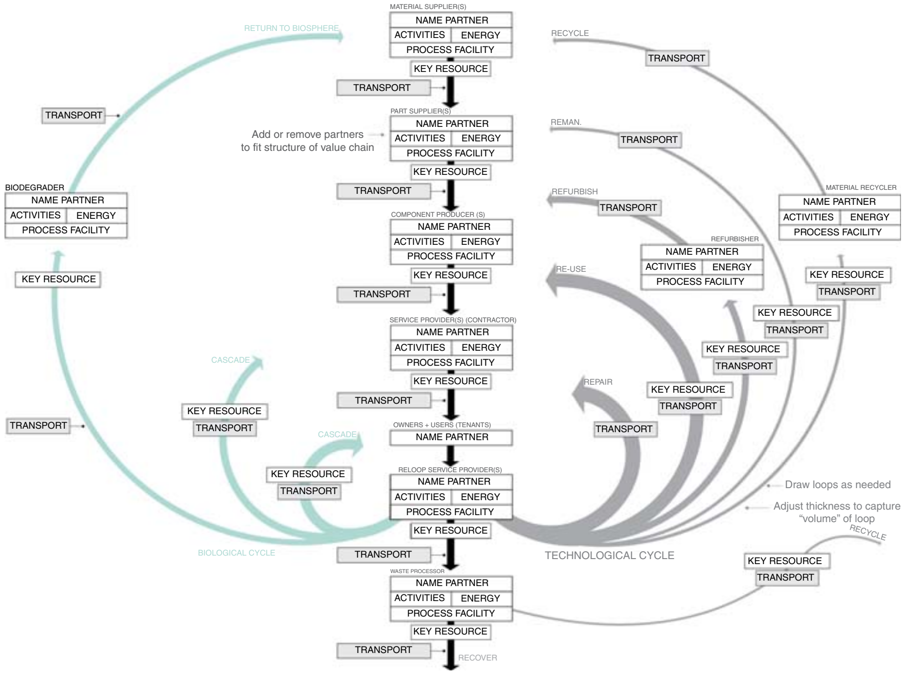


Figure 3.
The technical model design canvas

Source: Based on the circular building inventory matrix by Geldermans (2016)



Source: Based on the "butterfly model" of the Ellen MacArthur Foundation (2013)

Figure 4.
The industrial model design canvas

and matching" the design options for the different parameters listed in the matrix. A further clarification can be provided on "how the design option" can be applied in the design. The outcome can be understood as a logical combination of technical, industrial and business model options which could be applied in a design (e.g. see Section 3.5.1.1). The design team is free to start from the technical, industrial or business model generator, based on their preference. However, it is necessary to always use the generators in parallel to achieve an integral circular design. The second operational pathway, generate, supports the generation of circular building component concept designs. The combination of design options, as selected in the ideation stage, are applied as building blocks in the design canvasses and translated to a concept design. Additional design options can be selected from the matrices. The third operational pathway, refine, supports the refinement of a circular building component design. The concept design is further detailed and refined to a comprehensive circular design proposal by completing and detailing all parts of the design table and canvas. The matrices can be consulted for additional options, and alternative options for parts of the design which were considered unfeasible or undesirable.

3.5 Step 5: testing the CBC-generator: the development of the CIK

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

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

The designer-researchers used the CBC-generator to develop design proposals for the CIK. The developed designs would be discussed in the three co-creation sessions with all partners;

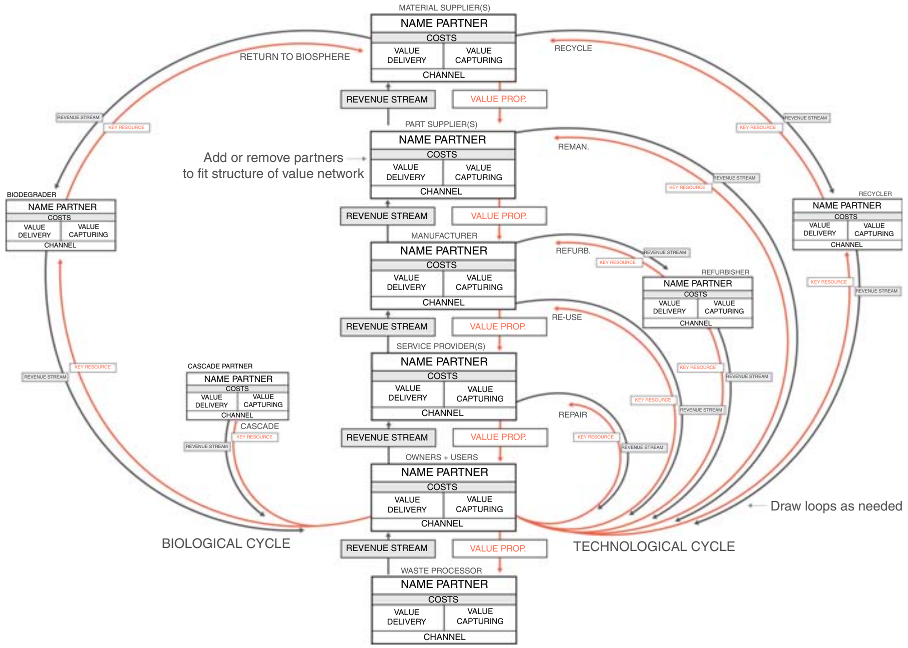


Figure 5.
The circular business model design canvas

Source: Based on the canvas of Mentink (2014)

the input from the workshops would feed further development of the design proposal. Developing the CBC-generator and the CIK was an iterative and parallel process: the CBC-generator was applied to support developing the CIK. Simultaneously, by testing the CBC-generator in the development of the CIK, the CBC-generator itself was refined.

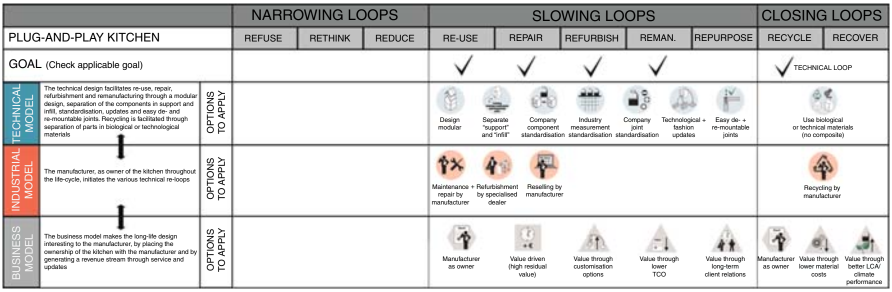
We will describe the CBC-generator in the development of the CIK following the three modi operandi "ideate" (3.5.1.1), "generate" (3.5.1.2) and "refine" (3.5.1.3).

3.5.1.1 Towards first ideas: ideating a circular building component. Applying the CBC-generator's operational pathway "ideate", we developed several ideas for CIK design variants. To illustrate how we have used the CBC-generator, we elaborate on the development of one of these ideas: "The plug-and-play kitchen".

The ideation process started by conceiving an inspirational direction (e.g. requirement, guiding theme) for the design variant. In this case, we started from the idea to make a kitchen which has a long life, can be recycled and – subsequently – saves resources. The parameter-option matrices were consulted by systematically looking at each parameter. Design options which helped to achieve the inspirational direction were selected. The technical model matrix was consulted first. Various design strategies to prolong the lifespan of the kitchen through re-use, repair, refurbishment, remanufacturing and recycling were selected. Subsequently, we turned to the accompanying business model, which needed to make the long-life design, interesting to the manufacturer. From the business model matrix, the options: "the manufacturer as owner" and "revenue stream generated through service and updates" were selected. Then, for the industrial model, options were selected for the various re-loop activities, initiated by the manufacturer. The options were organised in the design table, creating a cohesive set of technical, industrial and business model options (see Figure 6).

3.5.1.2 Generating a concept design for the CIK. The combination of options for "the plug-and-play kitchen" – as selected during ideation – were applied as building blocks in the design canvasses to generate a concept design for the CIK (see Figure 7). The completed design canvasses are shown in Figure 8(a)–(c).

The design of the CIK facilitates various re-loops by separating parts based on lifespan. The kitchen consists of a docking station in which modules can be easily plugged in and out, allowing for future changes in lay-out. The kitchen modules themselves are also divided in a long-life frame to which "module infill" (e.g. appliances) and "style packages" (e.g. front, countertop, handles) can be easily attached using click-on connections. The high level of modularity and customisability of this design allowed for additional opportunities in the business model, such as diversification of revenue streams and enlargement of the targeted customer segments. The business model parameter-option matrix was reviewed and additional options were selected and applied in the design. In the business model, the kitchen manufacturer sells the docking station and base modules directly to the housing associations, with a take-back guarantee, maintenance subscription and circular KPIs. This financial arrangement offers a clear incentive for the manufacturer to realise a kitchen which is easy to repair and to give a second life, or more. The extra modules and style packages are made available to users through financial arrangements such as lease and sale-with-deposit, which



<table>
<tr><th colspan="3"></th><th colspan="3">NARROWING LOOPS</th><th colspan="5">SLOWING LOOPS</th><th colspan="2">CLOSING LOOPS</th></tr>
<tr><td colspan="3">PLUG-AND-PLAY KITCHEN</td><td>REFUSE</td><td>RETHINK</td><td>REDUCE</td><td>RE-USE</td><td>REPAIR</td><td>REFURBISH</td><td>REMAN.</td><td>REPURPOSE</td><td>RECYCLE</td><td>RECOVER</td></tr>
<tr><td colspan="3">GOAL (Check applicable goal)</td><td></td><td></td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td><td colspan="2">✓ TECHNICAL LOOP</td></tr>
<tr><td>TECHNICAL MODEL</td><td>The technical design facilitates re-use, repair, refurbishment and remanufacturing through a modular design, separation of the components in support and infill, standardisation, updates and easy de- and re-mountable joints. Recycling is facilitated through separation of parts in biological or technological materials</td><td>OPTIONS TO APPLY</td><td colspan="3"></td><td colspan="5">Design modular
Separate "support" and "infill"
Company component standardisation
Industry measurement standardisation
Company joint standardisation
Technological + fashion updates
Easy de- + re-mountable joints</td><td colspan="2">Use biological or technical materials (no composite)</td></tr>
<tr><td>INDUSTRIAL MODEL</td><td>The manufacturer, as owner of the kitchen throughout the life-cycle, initiates the various technical re-loops</td><td>OPTIONS TO APPLY</td><td colspan="3"></td><td colspan="5">Maintenance + repair by manufacturer
Refurbishment by specialised dealer
Reselling by manufacturer</td><td colspan="2">Recycling by manufacturer</td></tr>
<tr><td>BUSINESS MODEL</td><td>The business model makes the long-life design interesting to the manufacturer, by placing the ownership of the kitchen with the manufacturer and by generating a revenue stream through service and updates</td><td>OPTIONS TO APPLY</td><td colspan="3"></td><td colspan="5">Manufacturer as owner
Value driven (high residual value)
Value through customisation options
Value through lower TCO
Value through long-term client relations</td><td colspan="2">Manufacturer as owner
Value through lower material costs
Value through better LCA/ climate performance</td></tr>
</table>

Figure 6.
Design table as filled in during operational pathway ideate

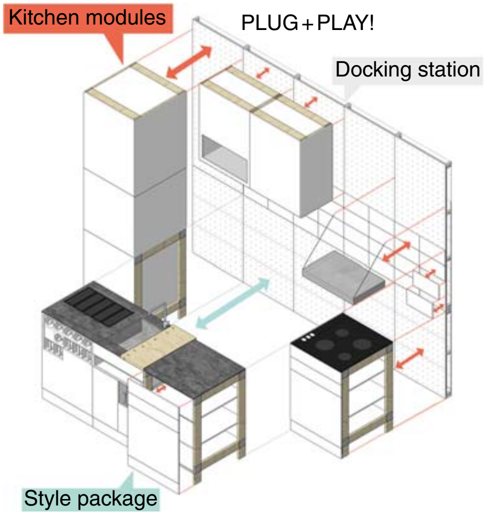


Figure 7.
Concept design for the circular kitchen

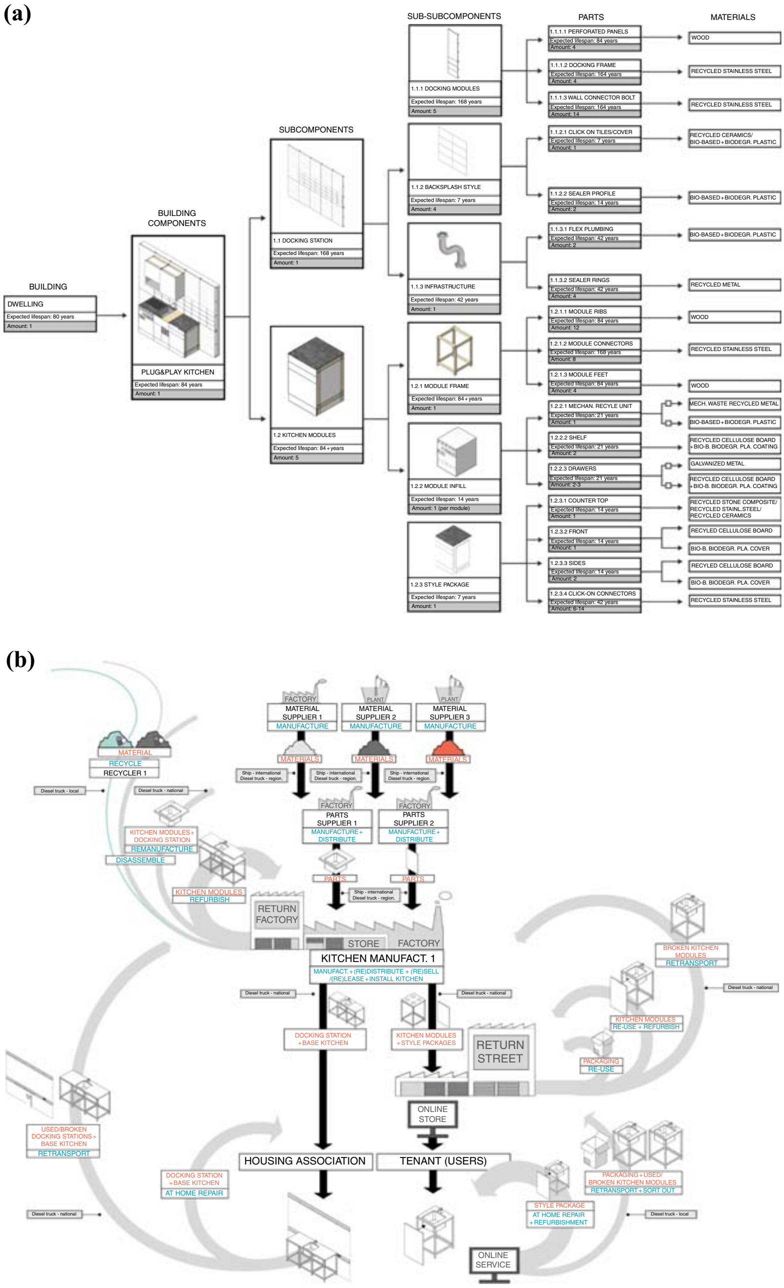


Figure 8.
(a–c) Design canvasses for the circular kitchen's technical, industrial and business model as filled in during the "generate" and "refine" operational pathways

(*Continued*)

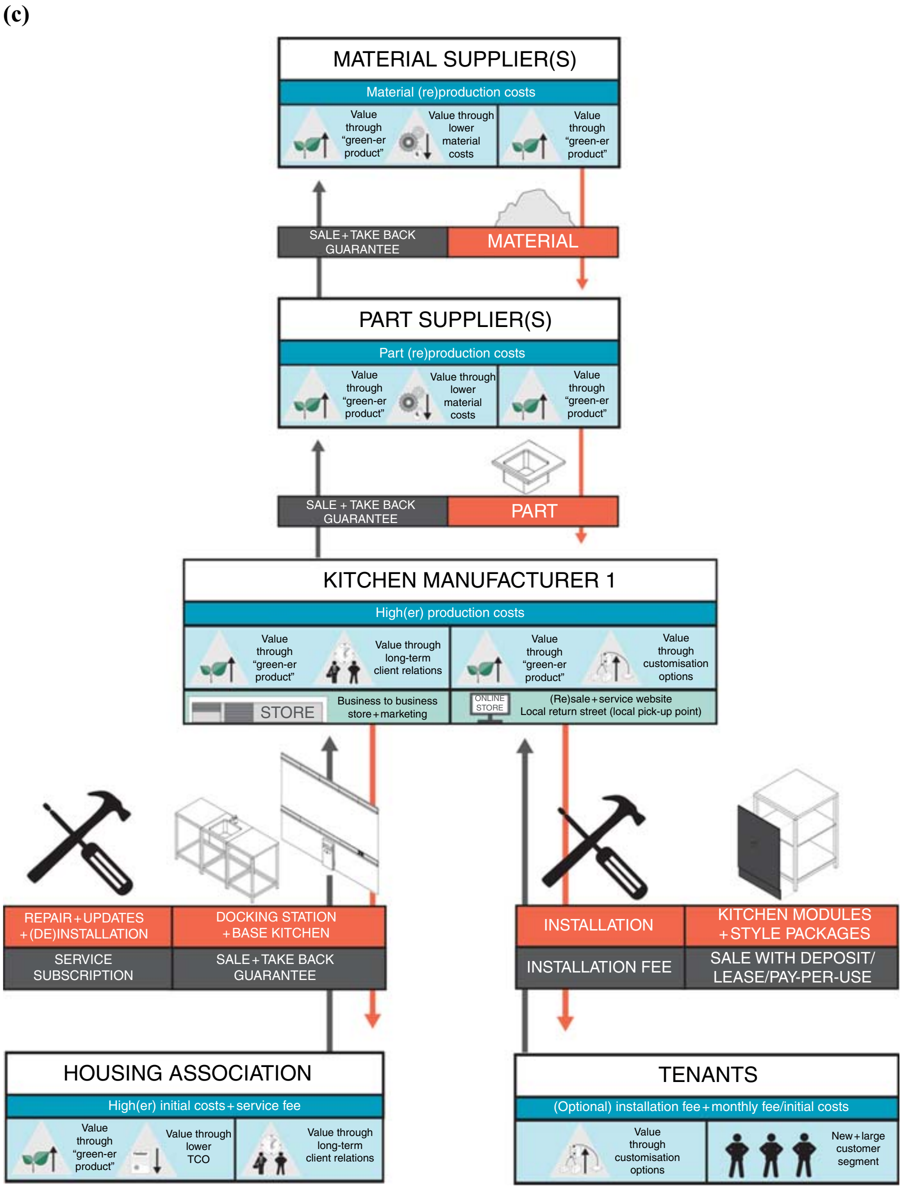

(c)
MATERIAL SUPPLIER(S)
Material (re)production costs
Value through "green-er product"
Value through lower material costs
Value through "green-er product"
SALE + TAKE BACK GUARANTEE
MATERIAL
PART SUPPLIER(S)
Part (re)production costs
Value through "green-er product"
Value through lower material costs
Value through "green-er product"
SALE + TAKE BACK GUARANTEE
PART
KITCHEN MANUFACTURER 1
High(er) production costs
Value through "green-er product"
Value through long-term client relations
Value through "green-er product"
Value through customisation options
STORE
Business to business store + marketing
ONLINE STORE
(Re)sale + service website
Local return street (local pick-up point)
REPAIR + UPDATES + (DE)INSTALLATION
DOCKING STATION + BASE KITCHEN
SERVICE SUBSCRIPTION
SALE + TAKE BACK GUARANTEE
INSTALLATION
KITCHEN MODULES + STYLE PACKAGES
INSTALLATION FEE
SALE WITH DEPOSIT/ LEASE/PAY-PER-USE
HOUSING ASSOCIATION
High(er) initial costs + service fee
Value through "green-er product"
Value through lower TCO
Value through long-term client relations
TENANTS
(Optional) installation fee + monthly fee/initial costs
Value through customisation options
New + large customer segment

Figure 8.

motivate returning the product at the end of their use cycle. The industrial model was aligned with the technical and business model. As the repair, re-use, refurbishment and remanufacturing possibilities increased, the mode of transport and/or location of these re-loop activities became increasingly important to define. As the selected transport option relies on fossil fuels, options were selected from the matrix which reduce the distance between the user and the facility where frequent re-loop activities take place. A local “return-street” is introduced in which collected products are sorted to be traded, resold, lightly refurbished or sent back to the kitchen manufacturer. Products that come back to the manufacturer are sorted in their national “return-factory” to be refurbished, remanufactured or recycled.

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

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

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

The design workshop itself was split in two parts. In the first part, the students made technical design variants for a circular extraction hood, electric cooking hub and oven. The students were divided into four groups and were given 20 min per appliance. Afterwards, each group would present their design variants. In the second part of the workshop, the students developed a circular business model for the appliances. The students were, again, divided into four groups. Each group was provided with a financial arrangement (e.g. lease, pay-per-use, rent, ownership) as a starting point. After 1 h, each group would present their business model. After the workshop, the students were asked if they had used the CBC-generator, and why or why not?

We found that for the first workshop the students had developed their own playing cards. Rather than using the options from the parameter-option matrix, they had translated circular design options to “what it would mean” for their appliance. The students indicated that the design options of the CBC-generator remained far too abstract and needed more explanation and specification to their design context. For example, what does “separate the design based on lifespan” mean in a CIK appliance? A group who had worked with the design table – to “mix and match” design options – concluded it provided structure during the design process. For the second part of the workshop, the students had developed their own design canvas to provide structure in ideating the business model. Note that the earlier version of the CBC-generator did not yet provide the design canvasses. Furthermore, the students limited the ideation to several parameters, such as key partners, financial arrangement and value proposition. See Plate 1 for pictures of the tools used during the workshops.

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

4. Conclusion and discussion

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

Yet, some limitations should be noted as well. First, the framework analysis focused on frameworks explicitly related to the CE. CE-precedent design frameworks – such as eco-design, C2C, design-for-X, biomimicry and sustainable business model design tools – are not explicitly part of the scope of the analysis. Although these precedents are often at the base of circular design frameworks, further review could provide additional insights and design options. Second, user acceptence is key for the success of circular building components. Preferably, the user(perspective) should be included throughout the co-creation of circular building components. Further research could focus on the user perspective on, and user acceptance of, circular building components. Third, being a generative design tool, the CBC-generator only provides support in the synthesis and not in the assessment of the most circular design. For example, if it is more "circular" to upgrade or recycle a building component, does not become evident in the framework. An appropriate choice for a circular assessment method – and the indicators considered – is vital to ensure circularity of the design: the assessment method determines on which metrics design variants are selected and optimised. Scheepens *et al.* (2016) propose that the environmental assessment of circularity should include quantitative assessment of material consumption, environmental impact and the value of the designed artefact. Bradley *et al.* (2018) suggest that the financial assessment of circularity could consist of an analysis of the "total cost of ownership". Future research could focus on how to integrate *ex ante* evaluation methods in the CBC-generator.

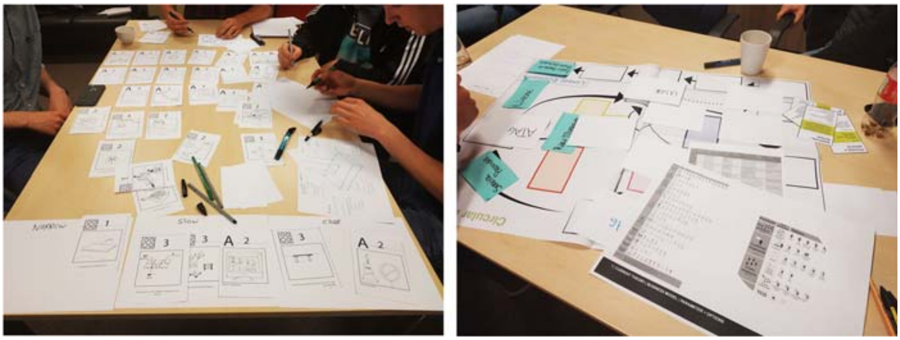


Plate 1.
The playing cards translating the design options to the technical model and the design canvas aiding circular business model ideation

Finally, the CBC-generator does not show any causal link yet between different options nor between the technical, industrial and business models. For example, if for the parameter transport energy, the option fossil fuel is selected, then the parameter distance should not offer any long(er) distance options such as global, continental and national. The long transport with fossil fuels would likely have such a negative impact on the environmental performance that the process had better be performed locally, or not at all. The lack of advice on what makes "logical combinations" of design options makes it difficult to guarantee the circularity of the design. Comprehensive, integral and systemic circularity of the outcome could be ensured in several ways. First, designers should design the technical, industrial and business model in parallel, using the design canvasses and (ultimately) considering all design parameters. Second, the design should be made in co-creation with all key partners: their knowledge and interests is needed to achieve a circular design. Third, a CE-expert who joins design sessions can indicate potentially (ill)logical combinations of design options. Fourth, circularity can be guaranteed by evaluating design variants with the above-mentioned circular assessment method throughout the design process. Finally, assessment results of "what are logical design combinations" could be integrated into a (web-)programmed version of the CBC-generator to ease the use of the tool by non-skilled circular designers.

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Appendix. Technical, industrial and business model parameter-option matrices

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