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DOI
10.1088/1755-1315/290/1/012035

Publication date
2019

Document Version
Final published version

Published in
IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: A van Stijn and V H Gruis 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **290** 012035

IOP Conf. Series: Earth and Environmental Science **290** (2019) 012035 doi:10.1088/1755-1315/290/1/012035

Circular Housing Retrofit Strategies and Solutions: Towards Modular, Mass-Customised and 'Cyclable' Retrofit Products

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Abstract. The building sector consumes 40 % of resources globally, produces 40 % of global waste and 33 % of CO_2 emissions. Creating a circular built environment is therefore of paramount importance to a sustainable society. The housing stock can be made more circular through circular retrofitting. However, strategies and solutions integrating circularity within housing retrofit are lacking.

This paper focusses on developing a circular housing retrofit strategy and solution for Dutch housing constructed between 1970 and 1990. Through literature study, potential circular retrofit approaches are identified and translated into a general strategy. By developing a concrete retrofit solution, we illustrate how this general strategy can be applied in practice.

It is found that in the Dutch context 'all-in-one' sustainable retrofits are difficult to realise. By applying modular (allowing component-by-component retrofit), 'mass-customisable', and 'cyclable' retrofit products, natural maintenance moments can be employed to gradually create a circular housing stock. As an example of such a product we describe the Circular Kitchen (CIK), which was developed together with industry. The CIK applies a plug-and-play design, separating components based on lifespan. The CIK supply-chain arranges 'relooping' of the CIK in a 'return-street' and 'return-factory'. The CIK business model applies financial arrangements such as lease and 'sale-with-deposit', motivating the return and 're-looping' of the CIK after use.

In conclusion, the strategy presented in this paper has the potential to support circular housing retrofit in the Dutch context and for housing with similar characteristics. However, development of more circular retrofit products is necessary to create a fully circular housing stock over time.

1. Introduction

The building sector consumes 40 % of natural resources globally, produces 40 % of global waste and 33 % of emissions [1]. The Circular Economy (CE) proposes an alternative to the current linear economy by decoupling economic growth from resource consumption. The CE can be summarised in the following three principles [2]: (1) preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimizing resource yields by circulating products, components, and materials at their highest utility and value at all times in both technical and biological loops and (3) fostering system effectiveness by revealing and designing out negative externalities. Due to its high impacts, the transition to a circular built environment is pivotal to achieve a resource 'effective' and sustainable society.

The existing housing stock, as an important part of the built environment, can be used more circular through retrofitting. However, the natural retrofit moments can also be employed to make the stock circular at all levels: the housing stock, dwelling, components, parts and materials. Strategies and concrete solutions integrating circularity within housing retrofit are still lacking. Therefore, the aim of this paper is to develop a circular housing retrofit strategy and solution, focussing on Dutch housing constructed between 1970 and 1990. This part of the stock constitutes 24 % of Dutch housing [3,4] and will be in need of retrofitting in the coming decades [5], which makes it a logical case to focus our efforts on. This stock is characterised by (mostly) low-rise dwellings, diversified designs, fragmented ownership and mixed tenures. Most housing is in a 'decent' state of maintenance with – on average – an energy label D or C. Although the stock is not (yet) in disrepair, there is need for adaptations and improvements, and there are substantial ambitions to improve the energy efficiency of the stock. However, the diversity, fragmentation and state of the housing makes the commonly applied 'all-in-one' sustainable retrofits difficult to realise [6]. Hence, Meulendijks [6], Ubink and van der Steeg [5], and Brinksma [7] propose three requirements for retrofit solutions for the Dutch 70's and 80's housing stock. Retrofit solutions should be (1) able to spread the retrofit investment over multiple retrofit cycli; (2) should accommodate different retrofit needs and practices from professional landlords and private owners through customisation; (3) should be adaptable to accommodate future changes. We propose to extend the latter requirement so it does not only include future adaptability into the retrofit solution but requires circularity to be considered as well. Therefore, (4) the retrofit solution should be able to accommodate the loops of the circular economy (i.e., maintenance, re-use, refurbishment, and recycling [2]).

To determine key elements for a circular housing retrofit strategy and solution, we analysed existing circular building approaches (section 2). Through literature study and brainstorming we identified circular design strategies and principles. Subsequently, we identified existing building approaches which applied (some of) these circular design strategies and principles. The selected circular building approaches were analysed by identifying which of the circular design strategies and principles were applied. In doing so, the analysis identified gaps in existing approaches and elements which could be applied in the development of a circular retrofit strategy for the Dutch context (section 3). To illustrate and test if this strategy is also achievable, a concrete retrofit solution was developed to the level of a prototype: The Circular Kitchen (CIK) (see section 4). In section 5, we reflect upon the developed strategy and solution, and the conclusions are summarised in section 6.

2. Analysis of 'circular' building approaches

In this section, we elaborate on the analysis of circular building approaches. The circular design strategies and principles identified through the literature study and brainstorming are included in columns 2 and 3 of Table 1. The strategies and principles were organised into three categories: 'narrowing, slowing or closing resource loops' [9]. Strategies which 'narrow resource loops' aim to reduce resource use; strategies which 'slow resource loops' aim to slow down the flow of resources through extension or intensification of the utilization period of the (building)product; strategies which 'close resource loops', aim to facilitate recycling of materials at the end of life.

From our literature study, we selected building approaches that focus on several of the strategies and principles indicated in Table 1, including both pré-circular building approaches' and 'circular building approaches'. 'Pré-circular approaches' stem from before the circular economy model and – although, often for other motivations – share similar strategies and principles. The 'pré-circular approaches' build on the selection researched by Brinksma [3] in his work on 'future-proof' housing retrofits. Several international approaches were added to this selection. The 'circular building approaches' were identified through case study analysis. In Google search engine, various combinations of the following keywords (in English and Dutch) were entered: 'circular' and 'building', 'building system', 'house' 'retrofit' or 'renovation'. The 98 found cases were briefly reviewed; 19 cases were selected as exemplary cases for the different applied approaches. The descriptions of the pré-, and circular building approaches are included in Table 2 and 3, respectively.

Table 1. Analysis (pré-)circular building approaches

Circular design strategies				Pré-Circular Building Approaches									Circular Building Approaches							
Circular Strategy	Circular Design Strategy	Circular Design Principles		Archigram & Metabolists	Shearing layers	Lean construction	SAR + SOB	IDF construction	SlimBouwen	Conceptual building	Mass-customisation	LEGO-lisation	Circular experiment	Circular demo	Circular Renovation	Bio-based systems	Circular modules	Mass-cust., circ. Building system	Mod. Mass-cust. Cyc. Build. Syst.	Circular infill & stuff
Narrowing loops [8]	Material reduction	Reducing use material in production				x		x	x	~	x					~	x	~	~	
		Minimizing product material (i.e., light weighting, less parts, minimising product, digitalisation)		~		~			x		~						x	~	~	
		Reducing packaging material				~														
		Reduction use-phase material use (i.e. water, food)											x		x					
		Applying re-used & recycled materials & components											x	x	x		~	x	x	x
		Applying bio-based materials											x		~	x	x	x	~	x
		Non-toxic materials														x	x			
		Reduction / smart use critical material															~	x	~	
	Energy reduction	Minimized energy use in production				x			x											
		Reduce energy use in use-phase											x		~	~	x	x	x	x
		Use renewable energy											x		~		~	x	x	
Slowing loops [8]	Design for attachment [8,9]	Design for easy use															x			
		Add surplus quality	[10]					x									x	x	~	
		Designed for long emotional desirability & user trust	[10,11]																	
	Design for long-life [8,9]	Critical part dimensioned for unintended use	[10–12]	x			x	x												
		Timeless (base) design	[10]																~	
		Reduced number of moving / electric parts	[11,12]																	
		Long life materials with resistance to wear (i.e., reduce coated, plaited, painted or discolouring mater.)	[10–13]																~	
		Compatible materials & fasteners	[11,12,14,15]																	
	Design for standardisation and compatibility [8,9]	Part standardisation	[11,14]								x	x				~	x	x	x	
		(sub)component standardisation	[10,16]				~	x		x	x					x	x		x	
		Product (i.e., building) standardisation	[10,16]	~			~	x		x	x					~	x	x		
		Measurement standardisation	[16]	~			x				x	x				~	x	x	x	
		Joint standardisation	[11,16–18]	~			x	x	x	x	x	x				~	x	x	x	
		Tool standardisation									x									
		Interface standardisation	[11,14]																	
		Performance test standardisation	[10]																	
	Design for easy maintenance and repair [8,9]	Accessibility to-be maintained parts	[10,11,13–18]				x												~	
		Enclosed repair instructions	[19]																	
		Minimised number of parts	[11,13–17]																	
		Optimised sequence for repair	[10,11,14,17]				x												~	
		Designed for on-site maintenance	[11,14]																~	
		Maintenance-proof materials	[11,14]																	
		Live monitoring of performance	[10]																	
	Design for upgrades and adjustments [8,9]	Uncomplicated design	[10,11,14,20]				x									~	x		x	
		Modular design	[10,11,14–16]	x			x	x		~	x	x				x	x	x	x	
		Parts separated based on lifespan	[11,17,21]	x	x		x	x	x			x					~		x	
		Included component / part passport	[10]										x					x	~	
		Allow customisation (of infill)	[10]				x	x		x	x	x				~	x	x	x	
		Enable future changes (i.e., techn., funct. & aesth. updates)	[10,11,16]	x	x		x	x	x		x	x			~	~	~	~	x	
Slowing loops [8] / Closing loops [8]	Design for disassembly [8,9]	Easy & fast de-, & re-mountable joints	[10,11,14–17,22]	x			x	x	x			x	x		~	~	x	~	x	
		Minimised numb. of comp./parts/joints/tools	[10,11,14,15,17,18,20]																	
		No wet-joints (e.g., welded, poured concrete)	[11,14,16]					x				x	x				~		x	
		No (non-solvable) adhesive joints	[11,14]					x				x	x				~		x	
		Optimised sequence of dis-, & reassembly	[10,11,17]					x				x					~		x	
		Enclosed dis-, & reassembly instructions											x						~	
		Easy access to connections	[10,11,13–15,17]				x	x	x			x					~		x	
Closing loops [8]	Design for recycling	Biological loop-able materials	[16]										x			x	x	x	x	x
		Highly recyclable technical materials	[16]										x				~	x	x	x
		Parts separated at material boundary	[10,16]										x				~		x	
		Enclosed material passport	[19]										x						~	
		Limited number & common materials	[10,11,15,17,20,22]																	
		Recycle compatible mat. for fastener & base	[11,17]																	
		Critical & valuable & toxic materials are grouped	[10,11,15–17]																	
		No secondary (non-compliant) paint & coating	[10,11,15–17,22]																~	
		(Long) disassembly not needed																		

Legenda
x Principle is applied according to the case designs and/or according to consulted case literature.
~ Principle is applied to some extend or only in part of the cases.
(grey shading) Indicates that the circular design strategy is applied in the approach.

Table 1 shows that pré-circular building approaches 1.1–1.2 mainly facilitate future adaptability. In approaches 1.4–1.9 facilitating future adaptability is extended with standardisation and customisability.

Approach 1.3 focusses on narrowing the resource loop, in particularly in the production process. Approaches 2.1–2.3 and 2.8 focus on narrowing and closing the material loop through (local) re-use and recycling of components and materials. Alternatively, 2.4 aims to narrow and close the loop by applying bio-based materials. Approaches 2.5–2.7 integrate (some principles of) narrowing, slowing and closing loop design strategies.

The analysis shows that most of the analysed (pré)circular building approaches remain fragmented: they focus either on narrowing and closing the loop, or slowing the loop. For example, the circular approaches 2.1–2.3, narrow and close resource loops locally. Ultimately, recycling is important to achieve material circularity. However, no strategies are implemented to slow resource loops on building or component level. Hence, premature obsolesce is not prevented. Subsequently, material depletion, emissions and waste generation are not fully minimized. Similarly, focussing only on slowing the loop will still result in material depletion, emissions and waste, just at a slower pace. From all the approaches,

Table 2. Description pré-circular building approaches

Name approach	Origin	Approach description	Cases
1.1 Archigram & Metabolists – 1959	Reaction to the static, inflexible post-war mass-housing.	Avant-gardist designs of ever-evolving cities applying permanent mega-structures and interchangeable infill.	Plug-in-city, Archigram, 1961; Habitat '67, Safdie, 1967; Nakagin Capsule Tower, Kenzo Tange, 1972.
1.2 Stichting Architecten Research (SAR) & Open building – 1961	Reaction to the inability of residents to influence the post-war built environment.	Built environment is separated into layers (e.g., tissue, support, infill) to allow for user customisation and future adaptations.	Molenvliet, van der Werf, 1969-1976; Lunetten, van der Werf, 1971-1982.
1.3 Lean construction – 1993	In reaction to economic and environmental inefficiency of traditional construction.	Application of lean manufacturing principles to optimise product and process to reduce material and energy use.	
1.4 Shearing layers – [23]	Building on theories of ecologist and system theorist.	To improve adaptability and prevent premature obsolesce, the building is divided into 6 layers based on expected lifespan.	
1.5 Industrial, flexible and demountable building (IFD) – 1999	Building on SOB principles, IFD aimed to better fulfil clients demands in a construction project.	IFD unites industrialisation of the building process, flexibility (i.e., customisation), and demountability to allow future changes.	Maskerade+ concept, van der Breggen architecten, 2003; Trento® concept, Nijhuis, n.d..
1.6 Slimbouwen	In reaction to the economic and environmental inefficiency of traditional construction.	A strategy separating the building into layers – especially decoupling piping – to improve adaptability and reduce material use.	Comfort+ concept, Lichtenberg, 2008.
1.7 Conceptual building	In reaction to the inefficiency (cost & process) of traditional construction and to the supply-oriented industry unable to customise solutions.	Client-friendly construction process in which buildings are constructed with standardised, customisable building components.	Alliantie+, Bouwhulpgroep, 2017.
1.8 Mass-customisation in dwelling construction	Uniting principles of mass-production and customisation in construction.	Open & closed source concept dwellings or components which are (to an extent) standardised, customisable and mass-producible.	Boklok, IKEA, 1996; Selekthuis, Nieuwenhuis groep, 1985; B8U bathroom, ERA Contour, et al., 2016; Instant house, Sass, 2005; Wikihouse, 2011; Katerra, 2015.
1.9 LEGOlisation in construction	LEGOlisation is a reaction to the traditional and project-based construction industry.	Buildings are constructed (and renovated) with customisable, standardised, prefabricated, demountable components. The components are subdivided into sub-components, parts, etc. LEGO-lisation can improve and optimise the building process, increase adaptability and reduce material use.	Pop-up house, 2012;

Table 3. Description circular building approaches

Name approach	Approach description	Cases
2.1 Circular experiments	Circular construction pilot focussing on buildings as material banks, energy neutrality and demountability. Re-used and recycled components and materials are used. Component and materials passports, and demountable joints are applied to facilitate future re-use and recycling. Infill components are separated and leased.	Circl pavilion, ABN AMBRO, et al., 2017
2.2 Circular recycling in housing demolition	Instead of full demolition, housing is disassembled (as much as possible) with the aim to re-use these components and materials locally.	Circular demolition, Woonbron, n.d..
2.3 Circular recycling in housing renewal and renovation	Focusses on local re-use and recycling of components and materials in housing renovation and renewal (i.e., housing demolition and new built). A figurative 'fence' is placed around the site: what is demolished is re-used on site. Next to cycling building material streams locally, the approach is often combined with reduction and local self-sufficiency of other material and energy streams (e.g., water, food, and energy).	Stadstuim Overtoom, Eigen Haard, 2012-2016; Superlocal, Heemwonen, 2018-2020; Heuvelstraat, Wonion, 2018.
2.4 Bio-based construction systems	Housing construction and retrofit systems which reduce environmental impact and facilitate closing the loop by applying bio-based materials. In some cases, the systems are also modular, standardised and (to some extend) adaptable to future changes.	Bio-based retrofit, Woonbron, et al. n.d.; Biological house, GXN; Bio-based building blocks
2.5 Circular module homes	Building systems which consist out of 'container-style' housing modules. These modules are built with non-toxic, bio-based and/or highly recyclable technical materials. Future adaptability mainly rests on the moving of whole modules to fulfil temporary housing needs. The modules themselves are –more or less – customisable and adaptable. Modules can be linked in different configurations. Layout and finishes are customisable and (to some extend) adaptable to future changes.	Finch modules; Woody®
2.6 Mass-customisable, 'cyclable' building systems	Standardised building systems which can be customised to fit the wishes of the client. The system applies circular materials to narrow and close the loop of the building and its materials. Modularity is applied to facilitate fast construction and not so much to increase future adaptability.	Sustainer homes
2.7 Modular, mass-customisable and 'cyclable' building systems	Highly modular building systems which integrate mass-customisation and circular design principles to narrow, slow and close the loop of the building, (sub)components and materials.	Bilt house; Circle house, GXN, 2018; Circular Retrofit Lab; Fijn Wonen Circulair; PD lab, TU/e and University of Twente & industry partners, 2017
2.8 Circular stuff & infill	Pilot projects in which circular housing infill and stuff (e.g., fridge, washing machines, furniture, decorations) are introduced in the home. Often the product is offered through a product-service-system (e.g., lease).	Circulaire huurwoning, de gemeenschap, et al., 2018; Besparen in huis, Eigen Haard, 2013

the 'modular, mass-customisable, 'cyclable' building system' (2.7) approach integrates – by far – the most strategies to narrow, slow and close the loop. However, none of the analysed approaches have yet applied all principles. The analysed approaches do provide useful elements to develop a circular retrofit strategy and solution for the Dutch context. All of the analysed cases provide concrete examples of how circular design principles can be integrated in retrofit solutions. In particular, the 'Bilt House' and the 'Circle House' – although new-built systems – provide convincing approaches. They differ from other cases in the level on which standardisation and modularity is achieved, namely on sub-component level. This seems to provide the most potential for standardisation, customisation, and adaptability.

3. Circular housing retrofit strategy: modular, mass-customisable and 'cyclable' retrofit products

By combining and specifying elements of circular building approaches in synergy to the requirements identified in the introduction, we developed a circular retrofit strategy for the Dutch context. This strategy proposes that the housing stock is retrofitted with products which are modular, mass-customisable and 'cyclable' (see Figure 1). A modular retrofit solution, as opposed to 'all-in-one' retrofit, can facilitate component-by-component retrofit. Buildings consist of many components such as installations, kitchens and facades, which could be replaced with circular retrofit products to gradually improve and create a circular housing stock. Moreover, modularity allows to spread the retrofit investment over multiple retrofit cycli. This provides an answer to the financial feasibility challenges posed by fragmented mixed-ownership and the 'minor improvements' needed in the stock. A retrofit solution suitable for 'mass-customisation' combines the advantages of mass- and industrial production with the advantages of product customisation. Mass-customisation can accommodate the different retrofit needs of professional landlords and private owners, increase affordability, and synergises with circular design principles such as: improving product quality, product and (sub)component standardisation, and offering (update) choices to users. A 'cyclable' retrofit solution is designed, applying circular design strategies and principles, to integrally narrow, slow and close the loops on building, building component, part and material level. A circular (technical) design requires an integral approach to ensure the design can be, and is (used) circular along and beyond its life cycle [9,24–27]. In an integral design a technical model, business model, and industrial model are developed in cohesion with each other [9]. This means that for the modular, mass-customisable and 'cyclable' retrofit products, a supporting business model is needed which incentivises the narrowing, slowing and closing of the loops. New contract models based on 'product service systems' [28], such as: retrofit product lease, sale-with-take-back after use, sale-with-buy-back after use, and contracts with service and updates included, can provide an interesting value proposition for all involved stakeholders. This includes a similar or lower Total Cost of Ownership (TCO) for housing owners and tenants, more customisation

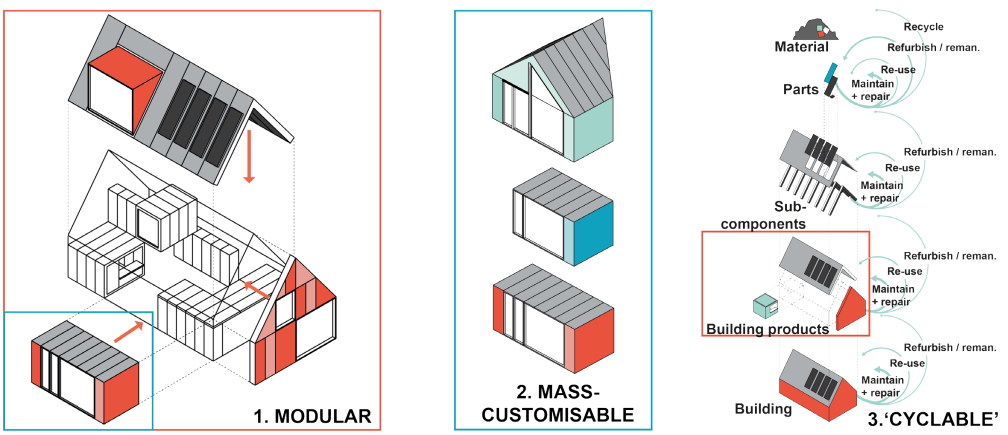

Figure 1. Three principles of the circular retrofit strategy for the Dutch context: (1) Modular, (2) mass-customisable, and (3) 'cyclable' retrofit products.

options and future adaptability for users, a steadier revenue stream for manufacturers and (service)providers of retrofit products, long-term partnerships with clients, and a more sustainable product. Similarly, a supporting supply chain model is needed which organises the narrowing, slowing and closing loop activities. By (re)forming partnerships the needed (loop)activities – and the facility in which these takes place – can be determined.

4. A circular housing retrofit solution: The Circular Kitchen

To illustrate and test if the proposed strategy is achievable, an exemplary modular, 'mass-customisable', and 'cyclable' retrofit product – the Circular Kitchen (CIK) – was developed in co-creation with the TU Delft, AMS-institute, housing associations (as initial target group) and industry partners. The CIK was developed 'integrally' including not only the technical model (design), but also the supply chain and business model.

The CIK applies a modular design which facilitates various circular loops by separating parts based on lifespan (see Figure 2). The kitchen consists of a docking station in which kitchen modules can be easily plugged in and out, allowing for customisation and 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 closet interiors) and 'style packages' (e.g., front, countertop, handles) can be easily attached using click-on connections. To narrow the loop, the CIK minimises material through separating the constructive 'frame' and the 'style package'. As the panels of the style package are optional and thinner (non-constructive), material use is reduced. Furthermore, the choice of materials for the kitchen – a low-impact, formaldehyde-free plywood with separable HPL coating – reduces the environmental impact and facilitates refurbishment and recycling.

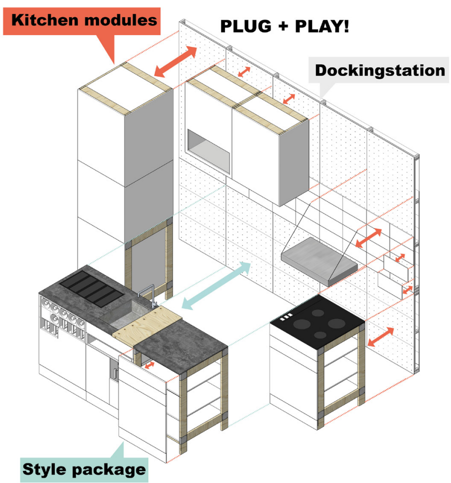

Figure 2. Design of the CIK

Figure 3. The prototype of the CIK. Developed as part of the PhD research of B. Jansen

The supporting business model of the CIK is separated in a business-to-business (B2B) and business-to-consumer (B2C) side. The kitchen producer sells the docking station and modules directly to housing companies with a take back guarantee and maintenance subscription. This arrangement offers a clear incentive for the manufacturer to make products which are easy to repair and to give a second life, or more. A dealer offers extra kitchen modules and style packages to tenants through a variety of financial arrangements that motivate returning the product after use, such as: lease and sale-with-deposit. After use, products are collected in a local 'Return-Street' and are sorted to be traded, resold, lightly refurbished or sent back to the kitchen producer. Products that come back to the producer are sorted in their 'Return-Factory' to be refurbished, remanufactured or recycled. The design of the CIK was validated with a preliminary LCA (Life Cycle Analysis), material consumption analysis, and TCO (Total

Cost of Ownership) analysis. The TCO analysis showed that the CIK could have a slightly lower TCO as the regular kitchen, due to the design based on lifespan. The material consumption analysis showed that, compared to the regular kitchen, the CIK could reduce material input with 25 % or more. The LCA showed that the CIK reduces the CO_{2eq} emissions with 75 % and eco-costs with 50 %. The CIK was tested for economic viability with housing associations, industry, and users. A prototype has been developed for further testing and refinement (see Figure 3).

5. Discussion

The developed CIK provides a concrete example of a modular, mass-customisable, 'cyclable' retrofit product. Through its preliminary validation, the proposed circular retrofit strategy presented in this paper has showed its potential to support circular housing retrofit in practice, both in the Dutch context and for housing elsewhere with similar characteristics. However, several limitations should be noted. First, the selection of (pré-)circular building approaches which we analysed, although extensive, was not complete. Other (pré-)circular approaches could provide valuable insights. Furthermore, a similar analysis can be made for the supporting industrial and business models. Also, future research is needed to refine and validate the developed strategy and solution. More retrofit products would need to be developed and tested (through implementation in demonstration projects) to validate the proposed strategy. To support the refinement of the CIK and to support industry in developing other circular retrofit products, a circular assessment method is needed. The assessment method should help select the most circular design variant in terms of design value, environmental impact, material consumption, and Total Costs of Ownership/Use [29,30]. Further research can contribute to develop such assessment tool(s).

6. Conclusion

The goal in this paper was to develop a circular housing retrofit strategy and solution, focusing on Dutch housing constructed between 1970 and 1990. It was found that in this context 'all-in-one' sustainable retrofits are difficult to realise due to the fragmented ownership, the state of the housing stock and diversified dwelling designs. An alternative circular retrofit strategy was developed which applies modular (allowing component-by-component retrofit), 'mass-customisable', and 'cyclable' retrofit products, allowing natural maintenance moments to be employed to gradually create a circular housing stock. As an example and test, the Circular Kitchen (CIK) was described. The strategy presented in this paper has the potential to support circular housing retrofit in practice, both in the Dutch context and for housing elsewhere with similar characteristics. However, development and testing of (more) circular retrofit products is necessary to create a fully circular housing stock over time.

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