Understanding and Managing Product Lifetimes in support of a Circular Economy

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Abstract
This special issue asks how product lifetime extension in a circular economy can best be understood and managed. Product lifetime extension through design for durability, reuse, repair, refurbishment and remanufacture, and the associated circular business models, are regarded as an important way forward to achieving a circular economy. As a research field, it has however not received much attention. The collection of 24 papers was partly drawn from the PLATE 2017 conference (Product Lifetimes and the Environment), November 2017 in Delft, the Netherlands. This special issue introductory article provides an overview of the content of the articles, divided into three topics: product design in a circular economy, circular business models, and environmental & economic impact assessment. One of the overall findings is that there is a lack of empirical validation and critical evaluation of many of the widely-held assumptions about design and business model innovation for product lifetime extension. More empirical research is needed in order to build a repertoire of validated approaches, cases, tools and methods, taking into account rebound effects.

Keywords: product life, design, business models, circular economy, built environment, assessment

1. Introduction

The circular economy (CE) has gained momentum as a promising approach towards sustainable development. The EU's circular economy action plan addresses product lifetime extension by the creation of rules on ease of repair, availability of spare parts, facilitation of end-of-life treatment, and by standards for measuring durability, reusability, repairability, recyclability and the presence of critical materials (European Commission, 2019). The action plan also recognizes the need for new circular business models and new consumption patterns that "have a significant potential to cut global greenhouse gas emissions." (ibid). This special issue focuses on the so-called 'inner loops' of the circular economy (Ellen MacArthur Foundation and McKinsey, 2013). The inner loops enable the capture of the embedded value of products over time, through design for durability, reuse, repair, refurbishment or remanufacture, thus extending their useful life and contributing to a slowdown of resource throughput in society. The issue asks how product lifetime extension in a circular economy can best be understood and managed.

We are proud to present this collection of 24 papers, partly based upon the Product Lifetimes and the Environment (PLATE) conference of November 2017 in Delft, the Netherlands. The PLATE conference brought together participants from a wide range of disciplines including design, business management, economics, sociology, anthropology and politics to discuss the effect that product longevity has on environmental, economic and social sustainability. The majority of attendees originated from the field of design, which explains the bias towards design-oriented papers in this special issue.

This introduction discusses the highlights of the 24 contributions. It aims to put these highlights into context, and to sketch the overarching research challenges as seen by the research community. The contributions were divided into three themes: Design, Business Models, and Environmental & Economic Impact Assessment. Each of these themes has an overarching research question that addresses topics of relevance for industry and policy makers: How to design for product life extension? How to create business models that enable products to cycle in the inner loops? And, to what extent is product lifetime extension beneficial for the environment and the economy?

As the majority of the papers address design, the 'Design' theme was broken down further into three sub-themes: (1) Design strategies in a circular economy, with the main question "Which design strategies enable product life extension?, (2) Consumers in a circular economy, which asks "How can users/consumers be meaningfully involved in product lifetime extension in a circular economy?" and (3) the Built Environment, focusing on: "To what extent is product lifetime extension necessary for the built environment, given that buildings usually have a long service life?" The following sections summarize the papers and highlight the most important findings.

2. Highlights: Design

Tables 1-3 provide short main-point summaries of the first theme: Design, which was broken down into three sub-themes: Design Strategies in a circular economy (paragraph 2.1), Consumers in a circular economy (paragraph 2.2), and the Built Environment (paragraph 2.3).

2.1 Design Strategies in a Circular Economy

Design strategies that enable product lifetime extension, such as modularity, adaptability, upgradability and product personalisation, have been proposed in the literature many times. To date, however, empirical research that validates their efficacy has been rare. In this special issue, Maldini, Stappers, Gimeno-Martinez and Daanen examine personalisation as a strategy for product longevity in fashion design. Product personalisation is a design strategy that claims that user involvement in design will create unique, personalised products that engender feelings of attachment and will induce consumers to delay product replacement. Maldini et al. conducted 40 wardrobe studies in order to establish whether personalized garments delay the need for new clothing. They conclude that, "contrary to expectations, the outcomes pointed out that personalised garments were not kept for a longer time, nor were they worn more frequently than standard ready-made garments." Personalised garments did also not result in decreasing clothing demand, which leads the authors to question the environmental benefits of this design strategy.

Design strategies such as product modularity, adaptability and upgradability have the potential to prolong a product's service life. In their systematic literature review on upgradability, Khan, Mittal, West and Wuest conclude that product lifetime extension via upgrade is challenging. It shifts a manufacturer's focus from resource throughput to asset management, which requires new business models, a new appreciation of customer relationships and the involvement of new stakeholders that provide upgradability services. They find that the concept lacks empirical validation, arguing: "even though some papers measured the attractiveness of upgradable products from the perspective of consumers, no empirical research measured the value of providers." Proske and Jaeger-Erbe also argue that empirical validation of design strategies for product life extension is much-needed. They present a critical appraisal of product modularity in one of the few consumer products where this has been tried: smartphones. Some modularity strategies may not achieve the desired product lifetime extension because of rebound effects such as over-provisioning of modules, accelerating replacement rates of modules and obsolescence through non-use. They argue for the inclusion of real-life social aspects in the design and evaluation of modular products: "Sustainable products and product services are not sustainable by design; the crucial aspect is whether the design is appropriate as intended by the user: Is a repairable device really repaired? Does the modular smartphone get upgrades?" Finally, Sauerwein, Doubrovski, Balkenende and Bakker explore the potential of additive manufacturing to prolong a product's useful life through a design analysis of 3D printed products. One of the design strategies enhanced by 3D printing, they find, is product adaptability, because additive manufacturing enables product repair or upgrading "even if these products were not originally designed for ease of repair." Additive manufacturing can however also have negative effects on product lifespan; there is for instance a lack of 3D printable materials that allow for durable use and high value reuse. All four papers present a critical view on design strategies for product lifetime extension and ask for more empirical research to create a better understanding of the way design strategies such as personalisation, modularity, adaptability and upgradability can deliver product lifetime extension as well as a lower the overall environmental impact.

The other three papers in this sub-theme aim to provide designers with empirical data and insights to help them design products that can last longer. Lilley, Bridgens, Davies and Holstov argue that designers need better information about how the materials they apply in their designs change over time, in order to create products that can age gracefully and that do not cause negative emotional responses due to perceived damage or degradation. They present a number of design resources, such as a "How will it look?" interaction table for aesthetic material change over time, and an add-on to Granta's CES Edupack materials database that contains visual information on material change over time.
Tecchio, Ardente and Mathieux provide quantitative data on frequent failures and average service lifetimes of washing machines and dishwashers. Their structured data collection helps understand which components of washing machines and dishwashers are prone to failure and which components are unlikely to be repaired. This is important data, because it "represents a discriminating factor when it comes to define when an appliance can be used again or should go to End-of-Life processes." The authors found that the electronic boards of washing machines and dishwashers tend to fail quite often and have low repair rates. As household appliances are increasingly designed with embedded electronics, the authors recommend improved design for disassembly for these parts, and availability of spare parts that could facilitate their replacement.
Novel technologies such as Internet of Things can be used by designers to create smart products that allow for data capture and analysis during and after use, according to Alcayaga, Wiener and Hansen. This will enable a better judgement of a product's condition and will allow for better informed decisions on reuse, repair and maintenance, remanufacturing and recycling. However, there is a notable

lack of best practices on the usage of product lifetime information for developing circular services. Table 1 summarizes the seven contributions.

Authors/title	Main points	Application area
Alcayaga, A., M. Wiener, E.G. Hansen. Towards a framework of smart-circular systems: an integrative literature review.	Through a literature review, the paper explores opportunities for smart products in a circular economy. Examples of opportunities that were identified are remote monitoring, product lifetime databases, analytics, actuating capabilities, and predictive maintenance.	Smart products
Khan, M.A., S. Mittal, S. West, T. Wuest. Review on upgradability – a product lifetime extension strategy in the context of product service systems.	This review paper shows that product upgradability has, in theory, potential to extend product lifetimes. Upgradability can facilitate the implementation of a circular economy, help scale product-service systems and enable remanufacturing. The paper notes a lack of empirical research to substantiate the theoretical benefits of product upgradability, in particular in the consumer market.	Upgradability
Lilley, D., B. Bridgens, A. Davies, A. Holstov. Ageing (dis)gracefully: Enabling designers to understand material change.	Material change is often regarded as 'damage' or 'degradation' and contributes to premature obsolescence but has potential to be used as a tool to engender emotional engagement with an object and extend product lifetimes. The authors present a framework for understanding material change as well as a number of 'material change' resources aimed at designers.	Material change
Maldini, I., P.J. Stappers, J.C. Gimeno-Martinez, H. Daanen. Assessing the impact of design strategies on clothing lifetimes, usage and volumes: The case of product personalisation.	As a result of empirical research (wardrobe studies and company interviews), no evidence is found that personalisation of garments leads to a delay of clothing obsolescence and reduction of clothing volumes. The paper calls for more empirical research to further validate this finding and for a critical approach towards other design strategies aimed at delaying clothing obsolescence.	Fast fashion
Proske, M. M. Jaeger-Erben. Decreasing obsolescence with modular smartphones? An interdisciplinary perspective on lifecycles.	The paper examines the environmental potential and risks of modularity in smartphones, taking users' functionality aspirations and practical needs into account. Comparing Fairphone with the conceptual Ara and Puzzlephone, the authors conclude that the modularity focus of the 3 phones differs, and that each approach has it benefits and drawbacks. For instance, the Ara phone's hot-swapping could lead to overprovisioning of modules which balances out benefits of longer use.	Modular phones
Sauerwein, M. E. Doubrovski, R. Balkenende, C. Bakker. Exploring the potential of additive manufacturing for product design in a circular economy	3D printing or additive manufacturing supports circular design strategies by creating opportunities to extend a product's lifespan, for instance by enabling repair or upgrades, even if these products were not originally designed for ease of repair or upgrading. However, the use of monolithic structurally complex parts that support design for recyclability may hinder high value product recovery. Also, 3D printable materials must be developed that offer durable use and reuse.	3D printing
Tecchio, P., F. Ardente, F. Mathieux. Understanding lifetimes and failure modes of defective washing machines and dishwashers.	The study provides quantitative data on frequent failures and average service lifetimes of dishwashers and washing machines, based on datasets of repair services. The work highlights critical components that fail relatively often but seem difficult to repair, such as pumps and electronics.	Repair

Table 1. Summary of papers with a focus on Design Strategies in a Circular Economy

2.2 Consumers in a circular economy

The three papers in this sub-theme of 'Design' claim that consumers are the forgotten link in product lifetime extension in a circular economy, even though consumers are the ones who can make or break a circular business model or circular design. They have to make an effort, for instance to maintain or repair a product, to sell it or give it away or to hand it in at collection points. In this respect, Zeeuw van der Laan and Aurisicchio defined four data-driven archetypical roles that consumers can play in PSSs that aim to close the loops of resource flows after the consumption of Fast-Moving Consumer Goods (FMCGs). Specifically, consumers can (1) *keep* the obsolete resources and replenish them with new consumable content; (2) *bring* the obsolete resources to designated locations where they deposit of them; (3) *consign* the obsolete resources to service providers who can retrieve value from them and; (4) *abandon* the obsolete resources in designated locations.

In a similar vein, Selvefors, Rexfelt, Renström and Strömberg underscore the importance of taking a user-centred perspective to stimulate product exchange in order to enable products to transfer in 'tight' loops from one user to another. Specifically, based on the four general design strategies of "Design for extended use", "Design for pre- and post-use", "Design for exchange", and "Design for multiple use-cycles", specific design solutions are described that can help companies and designers to address the challenges related to use-to-use opportunities.

A second finding from these papers is that no matter how well-designed and easy to maintain a product is, once a consumer starts perceiving a product as dirty, outdated or contaminated in any other way, it can become an excuse for new purchases. This is for instance the case with vacuum cleaners, as Harmer, Cooper, Fisher, Salvia and Barr explore, and it follows that designers should not only focus on the economical and physical factors regarding product lifetime extension (such as time and effort that needs to be invested) but also on the experiential and perceptual aspects of a design. In the case of vacuum cleaners, this can for instance be done by designing vacuums that are likely to retain an 'as new' aesthetic for as long as possible, by avoiding contact with dirt during maintenance tasks and by addressing ease of maintenance of ageing appliances.

Authors/title	Main points	Application area
Harmer, L., T. Cooper, T. Fisher, G. Salvia, C. Barr. Design, Dirt and Disposal: Influences on the maintenance of vacuum cleaners.	This paper explores the relationship between people's feelings about dirt, and an apparent reduction in the lifetime of vacuum cleaners. Premature disposal can occur when a product is *perceived* to be less effective, for instance when it becomes dirty and visually damaged. Design concepts were explored and tested, based on co-creation sessions.	Vacuum cleaners
Selvefors, A., O. Rexfelt, S. Renström, H. Strömberg. Use to use – A user perspective on product circularity	Putting the user-stage in the circular economy, results in an overview of challenges that circular paths may entail for people in everyday life. The paper presents four design strategies that can support the development of products and services fit for circular consumption processes: Design for Extended Use, Design for Pre- and Post-Use, Design for Exchange, and Design for Multiple Use-Cycles.	Design strategies for circular consumption
Zeeuw van der Laan, A., M. Aurisicchio. Archetypical consumer roles in closing the loops of resource flows for Fast-Moving Consumer Goods.	The paper focuses on understanding the role of consumers in the context of closed-loop Fast-Moving Consumer Goods. Consumers can *keep*, *bring*, *consign* or *abandon* obsolete components. The research concludes that revalorisation always takes place in designated locations. The roles that consumers fulfil in closed-loop PSSs involve carrying out activities to position resources in such locations. The roles always come at a cost, but PSSs can be designed to reduce it.	FMCG

Table 2 Summary of papers with a consumer or user focus in this special issue

2.3 Built environment

The papers by Casas-Arredondo, Croxford and Domenech, and Wuyts, Miatto, Sedlitzky and Tanikawa show that buildings and their fit-outs are increasingly prone to relatively rapid replacement cycles. It is an understudied field, because buildings and fit-outs (this is the process of installing interior fittings, fixtures and finishes) are usually perceived to have a relatively long service life. Wuyts et al. show that the average lifespan of a residential building in Japan is only 25 years. Housing obsolescence appears mainly triggered by non-technical, mostly economic and aesthetic, reasons. The authors argue that a people-centred, case-by-case approach is the most effective way to tackle premature obsolescence. They present a framework of obsolescence of residential buildings, which includes a number of social CE strategies. Casas-Arredondo et al. assess the short lifespan of non-domestic building fit-outs, which may be replaced no less than 30 to 40 times during the lifespan of a building. They present two different circular paths for fit-out resources: closed loop recycling (which requires well-organized reverse logistics) and reuse (which requires sharing/reuse platforms). The third paper, by Canals Casals, Barbero and Corchero has a somewhat indirect link to the built environment. It explores how obsolete electric vehicle batteries can be reused in residential smart grid applications. The availability of second-hand car EV batteries is expected to increase exponentially and finding economically viable uses for these batteries which still have up to 80% of their initial capacity when replaced is important. One of the most promising applications, according to the authors, is the reuse in residential smart grids. Table 3 summarizes the contributions.

Authors/title	Main points	Application area
Canals Casals, L., M. Barbero, C. Corchero. Reused second life batteries for aggregated demand response services.	Electric vehicle batteries are considered obsolete when they lose between 20 and 30% of their initial capacity. The paper explores whether and how these batteries can be given a second life. Reuse in residential smart grid applications seems most attractive from an economic perspective.	batteries in smart grid applications
Casas-Arredondo, M., B. Croxford, T. Domenech. Material and decision flows in non-domestic building outfits.	The authors studied fit-outs in the built environment. This is the process of installing interior fittings, fixtures and finishes. It is the area where most recurrent replacement happens, yet it is undermeasured and understudied and still largely a linear process.	building fit-outs
Wuyts, W., Miatto, A., Sedlitzky, R., Tanikawa, H. Extending or ending the life of residential buildings in Japan: A social circular economy approach to the problem of short-lived constructions.	The average lifespan of a residential building in Japan is only 25 years. The study used a qualitative approach to identify the factors and path dependencies that have led to a low average building lifespan during the second half of the 20th century. The result is a framework that can be used to decide whether the life of a residential building should be extended or ended.	residential homes

Table 3 Summary of papers with a built environment focus in this special issue

3. Highlights: Business Models

The work of Singh, Cooper, Cole, Gnanapragasam and Shapley analyses the current progress in circular business practices focused on closing and slowing resource loops. They present an analysis of 519 products that are advertised for their durability, length of guarantee, repair service availability and post-consumer product collection. Among the best practices are long-term guarantees and provisions for repair, whereas post-consumer collection is lagging behind. Similar results are reported by Ertz, Leblanc-Proulx, Sarigöllü, and Morin who find that most of the 150 companies in their sample prefer to extend the lives of products already on the market through prolonged use, maintenance, redistribution, repair and remanufacture, instead of making investments in new (long-life) product design. This leads to the central question we identified in the introduction: how to create business models that enable products to cycle in the inner loops?

Whalen describes three archetypical business models that play a role in extending product value, with the aim to assess their resource efficiency. She distinguishes between facilitators, redistributors and doers. All three models derive value from obsolete products, but in different ways. Facilitators provide mediation services and capture value without directly interacting with obsolete products and Redistributors have minimal interaction with obsolete products (e.g. inspection and repackaging). Doers, however, capture value with the resale of remediated products and have a high level of product interaction. Doers appear the most likely to achieve resource efficient outcomes. Nußholz finds that, in a circular economy, it is necessary to create novel value architectures for each subsequent product use cycle. She presents a tool for the design of new business models for multiple product lifecycles, that offers deeper insight than the much-used business model canvas. Wells and Nieuwenhuis also extend a well-known method: Rogers' model of innovation diffusion. They argue that the model doesn't do justice to flourishing niche markets of presumed obsolete products. Understanding the 'downswing' of the innovation diffusion model better, including the characteristics of consumers such as 'reluctant disposers' and 'determined retainers', could lead to the development of more enduring products. Hofmann finally presents a critical perspective of circular business models. He argues that the majority of studies do not incorporate systemic rebound effects, and that conceptions of circular business models fail to address the roots of the persistent sustainability problems they aim to solve: "Researchers primarily pursue an ecological modernist position that technical solutions can create an efficiency revolution to decouple economic expansion from ecological burdens." Table 4 summarizes the contributions.

Authors/title	Main points	Application area
Nußholz, J. A circular business model mapping tool for creating value from prolonged product lifetime and closed material loops.	The paper presents a visualization tool to help companies map their circular business model. The objective of the tool is to create and capture value from prolonging the useful life of products and parts and the closing of material loops. The tool, which was tested with Fairphone, focuses on the value creation architectures that may need to be designed for each subsequent cycle.	Smart phones
Wells, P., P. Nieuwenhuis. Over the hill? Exploring the other side of the Roger's innovation diffusion model from a consumer and business model perspective.	The paper argues that the persistence of old technologies and their capacity to become core to new business models is overlooked in Rogers model of innovation diffusion. The authors present a case study of classic cars, and show how keeping old technologies alive can provide value for consumers and entrepreneurs. Understanding the potential of 'over the hill' products can lead to development and promotion of more durable products.	classic cars
Whalen, K.A. Three circular business models that extend product value and their contribution to resource efficiency	The paper aims to explore the characteristics of 'extending product value' business models and their associated environmental consequences. It finds three Extending Product Value business model archetypes: Facilitators, Redistributors, and Doers. The analysis suggests that the higher the firm-product interaction, the greater the resource efficiency potential of the business model.	Circular business models
Singh, J., T. Cooper, C. Cole, A. Gnanapragasam. Evaluating approaches to resource management in consumer product sectors – an overview of global practices.	The study evaluated 519 consumer products and identified 145 examples of best practice. The focus was on the resource management approaches to enhancing product life-spans and recovery and recycling processes. The study identified a huge gap in current business models that do not focus on value recovery from post-consumer discards.	consumer products

Ertz, M., Leblanc-Proulx, S., Sarigöllü, E., Morin, V. Made to break? A taxonomy of business models on product lifetime extension.	The study develops a framework of product lifetime extension business models (PLEBM), and offers a taxonomy of PLEBM, consisting of seven categories: Relational product-as-a-service, Brick & digital product nurturers, Quality product designers, Secondhand vendors, Marketer-managed access systems, and P2P access brokers. Most of these models are focused on extending the life of products already on the market, rather than designing circular products from scratch.	Circular business models
Hofmann, F. Circular Business Models: Business approach as driver or obstructer of sustainability transitions?	The paper critically reviews the inherent normative settings and operational change approaches that underpin circular business models (CBM). For instance, the proposed main objective of CBMs to "decouple economic growth from natural resource consumption" may not be compatible with the modes of value creation and offerings to slow resource loops. Also, CBMs need to explicitly include aspects of social justice in order to label them as sustainable.	Circular business models

Table 4 Summary of papers with a Business Model focus in this special issue

4. Highlights: Assessment

To what extent is product lifetime extension beneficial for the environment and sustainable development? The five papers in this sub-theme try to find answers to this question, and are summarised in Table 5. Nakamoto, Nishijima, and Kagawa analyzed the impacts that changing the passenger vehicle lifetimes of 15 countries worldwide would have on vehicle stock and flow in those countries by using a vehicle lifetime distribution model. The results showed that extending vehicle lifetime has a very limited effect in reducing the carbon footprint in countries where vehicle lifetimes are longer, such as Australia and Finland, but is expected to greatly reduce emissions in countries where vehicle lifetimes are shorter, such as Germany and Japan. The work shows that increasing the average age of vehicles to the global average of 15.8 years would reduce overall CO2 emissions.

The benefits of extending the lifetime of products was also noted by Glöser-Chahoud Pfaff, Walz and Schultmann. They use smartphones as a case, and note that one of the main barriers for reuse is the prolonged storage ('hibernation') of unused but functioning phones. Their dynamic stock and flow models show there is a significant proportion of unused but functioning electronic devices in society, which leads them to propose a cascade use system that avoids storage. Cascading smartphones could significantly reduce new product demand and associated resource consumption. And Civancik-Uslu, Puig, Ferrer, and Fullana-i-Palmer calculate that the replacement of eucalyptus wood by plastic sheets in a sheet application is more durable as well as environmentally preferable.

For air conditioners and LED lamps the story is more complicated. Old air conditioners should be replaced with more energy efficient models to achieve a reduction in overall greenhouse gas emissions. However, Nishijima, Kagawa, Nansai, and Oguchi calculate that such a replacement program is not necessarily economically effective. It should be considered to what extent the energy efficiency of products will improve and the increases in product replacements that can be expected through the replacement program. Richter, Tähkämö and Dalhammar present important factors to consider when trading off longer lifetimes for products versus replacing them with products based on more modern, energy-efficient technology. Using LED lamps as a case, they show that improved efficiency over time, improved material design and ongoing decarbonisation of the energy supply all influence whether longer lifetimes result in lower environmental impacts for LEDs.

Authors/title	Main points	Application area
Civancik-Uslu D., R. Puig, L. Ferrer, P. Fullana-i-Palmer. Influence of end-of-life allocation, credits and other methodological issues in LCA of compounds: An in-company circular economy case study on packaging.	The study presents a comparative LCA of eucalyptus wood vs plastic compound in sheet application. The sheets are used to separate loaded pallets to prevent damaging each other during storage. The results show that, for this case study, plastic compound sheets are the environmentally better alternative than eucalyptus wood sheets for most of the environmental impact categories evaluated because of their higher number of uses, lower weight, use of recycled PP, and longer lifetime.	packaging
Nakamoto, Y., D. Nishijima, S. Kagawa. The role of vehicle lifetime extensions of countries on global CO2 emissions.	Comparing vehicle lifetimes in 15 countries, it is concluded that increasing the age of the average vehicle lifetime in 10 out of 15 countries to the global average of 15.8 years, a reduction of 17 Mt-CO2-eq. could be achieved.	cars
Glöser-Chahoud, M. Pfaff, R. Walz, F. Schultmann. Simulating the service lifetimes and storage phases of consumer electronics in Europe with a cascade stock and flow model.	Storage of unused consumer electronics (‘hibernation’) counteracts efforts towards increasing the service lifetime of devices. The authors present a dynamic cascade stock and flow model to simulate use and storage phases of devices. The results show that for smartphones, the implementation of a cascade use system avoiding storage would significantly reduce product demand and associated resource use.	phones
Richter, J.L., L. Tähkämö, C. Dalhammar. Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts.	This research demonstrates some of the important factors to consider in whether longer lifetimes for products with improving technology are beneficial from an overall environmental perspective. The scenario-based approach indicated that considering improved efficiency, improved material design and decarbonisation of electricity supply can all influence whether longer lifetimes result in lower environmental impacts for LED products.	LED lamps
Nishijima, D., Kagawa, S., Nansai, K., Oguchi, M. Effects of product replacement programs on climate change.	This study examines the effects of the Japanese Home Appliance Eco-Point Program on the timing of household air conditioner replacements and the resulting GHG emission reduction effects and assesses the program's cost-effectiveness. Whilst GHG emission reductions were achieved, the program was not cost-effective.	appliances

Table 5 Summary of papers with an Assessment focus in this special issue

5. Discussion: Old wine in new bottles?

The concept of the circular economy is an amalgamation of many familiar sustainability and industrial ecology principles (Ellen MacArthur Foundation and McKinsey, 2013) and can be said to encompass concepts and guidelines that were already introduced in the 1990s through various ‘Design for X’ approaches. In fact, Korhonen et al. (2018) argue that CE’s underlying principle of modelling material and energy flows on natural ecosystems, has been referred to by many scholars “time and time again... in the course of centuries” (p.45). The question can therefore be asked: what is new here? Why should we research design strategies and business models for a circular economy, when most of these strategies and business models are well-known in the fields of design for sustainability, sustainable business models and product-service-systems, and have been written about for many years? We would like to argue here that the contributions in this special issue are very important, for a number of reasons:

- New social and technological paradigms create new contexts for Design for Sustainability. An increased general awareness about the need for climate change mitigation, and the complex challenges this poses for production and consumption, makes that the likelihood of successful introduction of Design for Sustainability guidelines in industry is increasing. New technologies like the Internet of Things and additive manufacturing, as well as the increasing integrated nature of new 'smart' products, necessitate the constant reappraisal of well-known design strategies (such as modularity, repair, etc.). As such, design strategies and guidelines formulated decades ago need constant validation to make sure that they keep pace with the significant technological and social changes taking place. What used to be valid two decades ago is not necessarily valid today. We may need to reinvent the wheel over and over again because the vehicle we will outfit them with, is continuously changing.

- Circular economy research furthermore puts certain aspects of consumer and user engagement into much sharper focus than previous concepts such as Cradle-to-Cradle did. Earlier approaches and design guidelines addressed mostly the question of what industry could contribute, taking consumer behaviour and practices as a given. Circular economy research increasingly asks questions about, for instance, the level of responsibility we can and should expect from consumers when it comes to taking care of and maintaining products that are acquired through products-as-a-service business models. Also, we need to understand better how and when to stimulate self-repair, and how to ensure that consumers take responsibility for a proper end-of-life treatment of their products. Such questions have not been asked for a long time, and need to be re-examined if we want to successfully implement a circular economy.
- This special issue also shows that engaging with a circular economy forces new business development to take a long-term perspective. As Nußholz in this special issue remarks, existing tools for business model design "do not incorporate the idea of value management and valorisation opportunities along the product lifecycle, and thus do not adequately support designing circular business models for multiple cycles". While taking such a long-term, multiple life-cycle perspective is not new in sustainable design, it is certainly new in sustainable and circular business model development.
- And finally, the research on circular economy presented in this special issue contributes to a reinvigoration of sustainability and industrial ecology research, making it relevant for a new generation of researchers and designers.

6. Conclusions

In this special issue we set out to address three overarching research questions: How to design for product life extension? How to create business models that enable products to cycle in the inner loops? And, to what extent is product life extension beneficial for the environment?

Regarding product design one of the lessons is that taken-for-granted design strategies such as personalisation or modularity, may not always work in the messy dynamics of people's everyday lives. A second lesson that follows from this, is that in order to truly prolong product lifetimes, understanding consumers or users is crucial, for example through involving them in the (re)design process. And thirdly, empirical validation of circular design strategies is necessary, both because of potential negative rebound effects as well as potential co-benefits and spill-over effects of implementing a design strategy in real life. Regarding circular business models, the papers in this special issue show that academics have carefully developed and mapped business models that enable products to cycle longer in the inner loops, but that uptake of these business models in practice is still slow, with most companies (understandably) focusing on the low-hanging fruits. Related to this is the need to extend and build upon existing tools and methods for circular business innovation, because many of the current tools and methods were developed from a linear perspective.

Regarding assessment, the papers show the importance of assessing the environmental and economic benefits of extending product lifetimes. Scenario studies show that improved energy efficiency over time, improved material design and ongoing decarbonisation of the energy supply all may influence the optimal lifetime of a product and that one should be careful with general claims that longer lifetimes or circularity always contribute to lower environmental impacts in the longer term.

Overall, what stands out is the current lack of empirical validation and critical evaluation of many of the widely-held assumptions about design and business model innovation for product lifetime extension. More empirical research is needed in order to build a repertoire of validated approaches, cases, tools and methods, taking into account rebound effects. This is important because designers and business developers need reliable and tried-and-tested guidelines, or at least they need to be (made) aware of the potential pitfalls and benefits of their interventions towards a circular economy.

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