CHALMERS
UNIVERSITY OF TECHNOLOGY

Circular products and business models and environmental impact reductions: current knowledge and knowledge gaps

Downloaded from: https://research.chalmers.se, 2025-05-22 20:48 UTC

Citation for the original published paper (version of record):
van Loon, P., Diener, D., Harris, S. (2021). Circular products and business models and environmental impact reductions: current knowledge
and knowledge gaps. Journal of Cleaner Production, 288.
http://dx.doi.org/10.1016/j.jclepro.2020.125627

N.B. When citing this work, cite the original published paper.

research.chalmers.se offers the possibility of retrieving research publications produced at Chalmers University of Technology. It covers all kind of research output: articles, dissertations, conference papers, reports etc. since 2004. research.chalmers.se is administrated and maintained by Chalmers Library

(article starts on next page)

Journal of Cleaner Production 288 (2021) 125627

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Circular products and business models and environmental impact reductions: Current knowledge and knowledge gaps

Patricia van Loon [a, b, 1, *], Derek Diener [c], Steve Harris [d]

[a] Chalmers University of Technology, 412 96, Göteborg, Sweden
[b] Chalmers Industriteknik, Sven Hultins Plats 1, 41258, Göteborg, Sweden
[c] RISE Research Institutes of Sweden, Lindholmspiren 3A, 41756, Göteborg, Sweden
[d] IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 41133, Göteborg, Sweden

ARTICLE INFO

Article history:
Received 20 January 2020
Received in revised form
17 November 2020
Accepted 21 December 2020
Available online 24 December 2020

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Circular economy
Environmental impact
Life-cycle assessment
Sustainability
Rebound effects
Renewable energy

ABSTRACT

The circular economy is billed as a solution to increase economic growth while reducing environmental impact. It is argued that retaining the value of products, components and materials by fostering the "inner loops", such as reuse, refurbishment and remanufacturing, increases the resource-efficiency. However, published environmental assessments estimating the actual impact of these so-called circular outcomes are inconclusive. This paper presents the results of a systematic literature review of previous environmental assessments on circular products and circular business models, focusing on the tighter technical loops including reuse, refurbishment, and remanufacturing. Mapping reveals factors that influence the environmental impact of circular products and other aspects that should be incorporated in environmental assessments. Even though 239 papers were identified that discuss the environmental impact of circular products and/or circular business models, the far majority only considers a traditional product in a traditional sales model that is remanufactured and compares the impacts of remanufacturing with manufacturing new products. While it is important to quantify the impacts of remanufacturing, it is remarkable that product design strategies for circular economy (e.g. design for remanufacturing, upgradability, modularity) and product-service systems or other types of circular business models are usually not considered in the LCA studies. A lack of studies of products with so-called circular designs that are utilized within circular business models is apparent. In addition, many assessments are static analyses and limited consideration is given to future increases in the share of renewable energy. One can thus question how well the available environmental assessments quantify actual circular products/offerings and the environmental performance gains they could provide in a circular economy. The results show that there is an urgent need for more LCAs done in a way that better captures the potential benefits and deficiencies of circular products. Only then will it be possible to make robust claims about the environmental sustainability of circular products and circular business models and finally circular economy in total.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

With the growing world population and increasing material consumption, the pressure on the environment is far from being sustainable. Circular economy (CE) is one concept suggesting that it is possible to reduce the pressure on the environment without limiting the economy. This can be achieved by recapturing value present in a product at its end-of-life and recirculate it in the market via e.g. reuse and recycling (EMF, 2013). Not surprisingly, the concept has received a lot of attention in the recent years. China was one of the first countries to utilize the concept in development of state strategies (McDowall et al., 2017) while the European Commission argues that it *"has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy"* (EC, 2012) and has adopted a CE action plan to close product life-cycle loops via reuse and recycling (EC, 2020).

* Corresponding author. Chalmers University of Technology, 412 96, Göteborg, Sweden.
E-mail addresses: patricia.van.loon@chalmers.se (P. van Loon), derek.diener@ri.se (D. Diener), steve.harris@ivl.se (S. Harris).
[1] This work has been conducted while working at Chalmers Industriteknik.

https://doi.org/10.1016/j.jclepro.2020.125627
0959-6526/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

While circular economy as a named concept, field and megatrend is relatively new, it builds on theories from established disciplines, including industrial ecology (Harris and Prittchard, 2004; Chertow, 2007), environmental economics (Ayres, 1998), closed-loop supply chains (Guide and Van Wassenhove, 2001), and cradle-to-cradle design (McDonough and Braungart, 2002). Circular economy is further tangled with other concepts such as the performance economy, blue economy, natural capitalism, regenerative design, and biomimicry (EMF, 2015). Due to its eclectic nature, it can be argued that circular economy is a bundle of ideas rather than clear concept (Lazarevic et al., 2016). However, at its core, the circular economy refers to the recirculation of goods and materials, i.e. via reuse at product level (for example repair and refurbishment), reuse at component level (such as remanufacturing), and reuse at material level (recycling) (Zink and Geyer, 2017). Thus, while targeting results at the economy or region level, the real change is to be realized at micro level, with firms and individuals producing, distributing and utilizing products and materials in a more ‘resource-effective’ way. In theory, there are a great number of strategies to achieving these changes, with new circular product design and performance-based business models making up the core of suggestions for manufacturing firms (EMF, 2013b).

However, whether such strategies always deliver the promised results is debated. Some scholars question the suggested link between circular economy and environmental impact reduction (for example Agrawal et al., 2016; Geyer et al., 2015; Murray et al., 2017). A workshop on the potential effects of promoting circular economy via policies concluded that circular economy can have a positive or a negative environmental effect, depending on outcomes on the micro level (Lucas et al., 2016). Indeed, the impacts of CE strategies are promising but mixed and scantly investigated. Some researchers have argued that certain components of a circular economy, such as product-service-systems (Agrawal and Bellos, 2016; Mont, 2004; Tukker, 2015), reuse (Cooper and Gutowski, 2015), and remanufacturing (Gutowski et al., 2011; Peters, 2016) are not panaceas for environmental sustainability. So far, the environmental performance of circular business models is unclear, and the available literature is scant (Bocken et al., 2016; Manninen et al., 2018).

Based on the limitations of current knowledge on the links of CE strategies to environment impact outcomes, there is a clear need for research to learn about the environmental impact of circular products and circular business models and to compare them against the traditional linear offerings. With this need in mind, we pose the following questions: (1) what do we know about the environmental performance of circular products and circular business models compared to linear ones? (2) what does this mean for future life cycle assessments (LCA) of circular products/business models? We notice that many environmental assessments of so-called circular products are actually products performing in states of design and systems that are geared towards linearity (e.g. sales model and conventional product design) and there is a clear lack of studies assessing the environmental performance of products designed for circular economy and offered in a circular business model. We further conclude that a good knowledge base exists on the environmental impact of the remanufacturing versus manufacturing activities itself but a lack of knowledge regarding environmental impacts of circular products from a life cycle perspective including effects of return transport, energy-efficiency improvements, and consumption.

This paper conducts a systematic review of studies assessing the environmental impact of so-called circular products and circular business models. The systematic literature review method is explained in the next section called ‘Methods’. The identified papers are summarized in the next section focusing on key factors that impact upon the environmentally preferred strategy. We distill characteristics that have a determining role in whether circular products are sustainable and reflect on the limitations of the LCA assessments on circular products and business models so far in the ‘Analysis and discussion’ section. Finally, in the conclusion section, suggestion for future research towards the environmental performance of circular products and circular business models is provided.

2. Methods

In order to map the current knowledge and evidence on the environmental performance of circular products and business models, a systematic literature review with content analysis was conducted. We focus on studies that investigate the impacts of ‘slowing resource cycles’ that extend the utilization period of products via for example direct reuse or remanufacturing and reuse rather than closing them via recycling (Bocken et al., 2016b) as larger environmental impact gains are to be expected from so-called tighter loops. While processes like remanufacturing may alter the product in some manner, it keeps the product intact meaning it requires fewer changes to recover value as opposed to recycling, which involves breaking the product down to the material or substance level and starting over. Hence, as general rule, it is argued that remanufacturing results in higher environmental savings than recycling (EMF, 2013b), though proof supporting this distinction is lacking (Sehnem et al., 2019). However, considering this differentiation, for the purpose of this study, we exclude studies on recycling and focus instead on papers that quantify the environmental impact of so-called circular products and solutions, those that aim to achieve reuse of the product or its components via direct reuse or remanufacturing.

The systematic literature review process and principles as outlined by Tranfield et al. (2003) was followed. A systematic literature review has as aim to “*map and evaluate the body of literature to identify potential research gaps and highlight the boundary of knowledge*” (Braz et al., 2018). The research was constructed following the three stages of the systematic literature review process: stage 1 - planning the review, stage 2 – conducting the review, and stage 3 – reporting and dissemination.

2.1. Stage 1 – planning the review

A research protocol that outlines the search strategy and inclusion and exclusion criteria was developed and discussed by the authors of this paper in early 2018. Since the purpose of the literature search was to find evidence on the environmental performance of circular business models and circular products, a wide and cross-disciplinary focus was taken. Hence, a broad array of keywords were included in the search, consisting of circular economy, circular products, circular business models, closed-loop supply chains, remanufacturing, refurbishment, upgradability, and product life extension in combination with environmental impact, LCA, or environmental performance (see Fig. 1). Recycling is not the focus of this study and therefore not included in the keywords. Boolean operator AND was used to combine keywords from the first column with keywords from the first row, while keywords within the same column or row were separated with the operator OR. Papers were searched in early 2018 using Scopus and the search is updated (using the same search string) with recent papers in early 2020. Scopus is one of the largest multidisciplinary databases with over 70 million documents and is found suitable as principle search system for systematic literature reviews (Gusenbauer and Haddaway, 2019). It covers a variety of disciplines including management, engineering, economics, social science, and environmental science (Scopus,

# hits in Scopus	Environmental impact	LCA	Environmental performance
Circular economy	380	220	95
Circular products	5	0	1
Circular business models	15	7	3
Closed-loop supply chains	74	11	22
Remanufacturing	191	46	50
Refurbishment	105	59	31
Upgradability	3	2	1
Product life extension	4	0	1

1326 papers

Removing duplicates and screening title

273 papers

Assessing paper on content and quality using the pre-defined criteria. Main inclusion criteria: quantitative environmental assessment of circular products or business models, case study.

54 papers, 93 case studies

Fig. 1. Data collection and selection process.

2020), providing a relevant database for the topic of this study. The search was limited to keywords hits in either title, abstract or keywords, papers written in English, and published in journals. The reference lists of the identified papers were further checked and discussions with academic colleagues[1] were held to identify papers that we might have missed in the search.

2.2. Stage 2 — conducting the review

After removing the duplicates and reviewing the title, 273 articles were identified that could potentially fit the scope. Those were further screened by first abstract and followed by full text on eligibility based on the inclusion, exclusion, and quality criteria. In line with earlier research (i.e. Kaddoura et al., 2019) we find that many of the papers on CE have a qualitative approach and mention the environmental impact and importance of environmental aspects in relation to circular products or circular economy in general without quantifying the environmental impact and without studying real industrial cases. In order words, many of the papers found that have "environmental impact" or "environmental performance" in the title, abstract or keywords do not present an environmental assessment themselves but rather discuss that it could have important implications on the environment. For the purpose of this study in which we map the evidence regarding environmental impact of circular products and circular business models, we limit the papers to those that quantify the environmental impact of circular products/business models (i.e. those discussing a case study or practical application) to establish how much, where, and what evidence exists. We focus on micro-level impacts excluding papers that discuss environmental impacts of cities or regions transitioning towards circular economy. Only 54 of these 273 papers quantify the environmental impact of one or several circular products, resulting in 93 cases.

2.3. Stage 3 — reporting and dissemination

The cases were classified based on product type studied, noted product design strategies and business models for circular economy, the inclusion of rebound effects and effect of transition to low-carbon energy. The results were summarized. A list of all papers and cases and the classification can be found in the supplementary data. Together, the papers and their descriptions represented a collection of analyses of circular products. This collection provided two main insights; (1) indications of how circular products and circular business models might fare environmentally and what characteristics of the product systems are important to environmental performance outcome and (2) insights into how analyses are done. From the assessment of the analyses, we generate lessons learned related to methods and approaches to assessing environmental impact of circular products and business models.

3. Results

The papers provide a collection of analyses of products that undergo so-called circular processes (see Table 1). This collection gives us indications of the potential environmental sustainability of 'circular' products. Given the apparent lack of studies on the environmental impact of products designed for circular economy and within a circular business model, we summarize this collection in three sections considering what circular strategy (design or business model) is observed for the circular outcomes analyzed; (1) products that exist with a design and business model that is not modified - it is made for a linear product (no circular strategy), (2) products that have a design that is 'intended' for circular use (circular product design) and (3) products that are offered within an alternative circular business model. Note that we did not identify papers that quantified the environmental impact considering both a circular product design AND a circular business model. Table 1 provides an overview of the papers and moreover case products in each category.

3.1. Summary of papers looking at recirculating but without changing products design or business model

A few papers calculate the environmental impact of reusing products (direct reuse) compared to manufacturing them new. Woolridge et al. (2006) assess the benefits of cotton and polyester clothing reuse by calculating the energy use of Salvation Army operations in the UK. Perhaps unsurprisingly, they conclude that the total energy use of collection, sorting, baling, selling and distribution the used clothing is a fraction of the energy required to manufacture them from primary materials. Low et al. (2016) calculate the environmental impact of reusing flat-panel display monitors via second-hand sales and conclude that reuse leads to less material and resources used in the production process leading to environmental benefits. However, the use phase is out of scope, which is notable for a product that uses energy during use.

More papers explore the environmental impact of recirculating products via refurbishment or remanufacturing and compare the impacts of such process against the impacts of producing new counterparts. Benton et al. (2017) (diesel generator set) and Gao et al. (2017) (turbocharger) conclude that remanufacturing recovers most of the embodied energy and therefore leads to significant environmental benefits. Similarly, Afrinaldi et al. (2017) and Liu et al. (2016) demonstrate significant energy savings when remanufacturing a cylinder block due to the reuse of materials compared to using raw materials in the production of new engines. van Loon and Van Wassenhove (2018) assume that a remanufactured chassis product replaces a new one and find that remanufacturing results in a reduction in CO_2 emissions. Smith and Keoleian (2004) and Zheng et al. (2019) similarly conclude a large reduction in environmental impact from remanufacturing engines.

[1] Discussions took place during conferences (i.e. the European Roundtable for Sustainable Consumption and Production 2019 in Barcelona and the Life Cycle Management Conference 2019 in Poznan) as well as informal discussion utilizing existing networks.

Table 1
Overview of case products and papers in each category.

Circular economy perspective	Traditional product with traditional sales model assessed			Circular product with traditional sales model assessed			Traditional product with circular business model assessed		
	Leads to lower environmental impact	Higher or lower, depends on conditions	Leads to higher environmental impact	Leads to lower environmental impact	Higher or lower, depends on conditions	Leads to higher environmental impact	Leads to lower environmental impact	Higher or lower, depends on conditions	Leads to higher environmental impact
Reuse	Books[1], clothing[2,3,4], furniture (desk, chair)[3], consumer electronics (laptop, flat-panel monitor, smartphone)[5,6,7], recycling bin[8], toner cardridges[3], storage locker[8].	Consumer electronics (desktop control unit, laptop, monitors)[3]	White goods (refrigerator)[9]				Clothing (t-shirt)[10], crates[11], diapers[12], event tent[8], flag[8]	Pallets[13]	
Remanufacturing	Automotive components (cylinder block, electric vehicle battery, engine, alternator, transmission)[14,15,16,17,18,19,20,21,22,23,24,25,26], bearings[27], consumer electronics (cell phone, LCD monitor, LCD projector)[28,30], compressor[29], loading machines[31], machine tools[32], paper folding machine[33], server[34], telecommunication equipment[35].	Automotive component (electric motors, engines, tires)[3], consumer electronics (video game console)[36], vehicle[37], white goods (refrigerator)[38].	Mobile phone[39], white goods (refrigerators, dishwasher, washing machine)[3,28].	Copier[40], office furniture[41].	Desktop PC[22].				
Lifetime extension	Consumer electronics (laptop, computer, cell phone)[42,43,44], vacuum cleaner[45].	Airconditioning[46,47], consumer electronics (TV)[47], LED lamps[48], vacuum cleaner[49], vehicle[50].	White goods (dishwashers, oven, refrigerators, washing machines)[43,44,47,51]	Waste collection inlet[8]	Consumer electronics (laptop)[53]		Core plugs[54], building cleaning[54], soil compactor[54]		

[1] Thomas (2011), [2] Farrant et al. (2010), [3] Gutowski et al. (2011), [4] Woolridge et al. (2006), [5] Andre et al. (2019), [6] Low et al. (2016), [7] Makov and Font Vivanco (2018), [8] Kaddoura et al. (2019), [9] Kim et al. (2006), [10] Bech et al. (2019), [11] Tua et al. (2019), [12] Hoffmann et al. (2020), [13] Tornese et al. (2018), [14] Afrinaldi et al. (2017), [15] Liu et al. (2016), [16] Benton et al. (2017), [17] Bobba et al. (2018), [18] Cusenza et al. (2019), [19] Gao et al. (2017), [20] Lonca et al. (2018), [21] Smith and Keoleian (2004), [22] Kwak and Kim (2016), [23] Van Loon and Van Wassenhove (2018), [24] Warsen et al. (2011), [25] Xiong et al. (2020), [26] Zheng et al. (2019), [27] Diener and Tillman (2015), [28] Esenduran et al. (2016), [29] Biswas and Rosano (2011), [30] Cheung et al. (2018), [31] Lishan et al. (2018), [32] Du et al. (2012), [33] Peters (2016), [34] Ardente et al. (2018), [35] Goldey et al. (2010), [36] Wang et al. (2017), [37] Latham (2016), [38] Liu et al. (2017), [39] Raz et al. (2017), [40] Kerr and Ryan (2001), [41] Krystofik et al. (2017), [42] Bakker et al. (2014), [43] Intlekofer et al. (2010), [44] Kwak (2016), [45] Bobba et al. (2016), [46] De Kleine et al. (2011), [47] Tasaki et al. (2013), [48] Richter et al. (2019), [49] Perez-Belis et al. (2017), [50] Kim et al. (2003), [51] Ardente and Mathieux (2014), [52] Iraldo et al. (2017), [53] Sabbaghi and Behdad (2017), [54] Lindahl et al. (2014).

However, these studies ignore the use (and disposal phase) which essentially means that the results are representative only if the efficiency of a new engine is the same as the refurbished one. Kwak and Kim (2016) further showed that remanufacturing alternators saves between 70 and 35% (depending on the remanufacturing yield rate) of the greenhouse gas emissions associated with new production and Warsen et al. (2011) assessed life cycle impacts of remanufactured versus new manual auto transmissions and find 30–45% reductions for all categories.

In general, it can be argued that the remanufacturing process yields benefits in terms of resource-efficiency compared to the manufacturing process (Allwood et al., 2011; Sundin, 2004; Ijomah et al., 2007), but one can question the benefits if the remanufacturing processes allow less efficient, energy-demanding units to be economically repaired and renewed, hence allowing them to live longer and potentially resulting in more environmental impact than if they had been replaced with new ones or by none at all (Linder et al., 2018). Several researchers looked into the question whether it would be better to keep using a product or to switch to newer models with improved efficiency in the use phase. Gutowski et al. (2011) assessed the energy savings reached through remanufacturing 25 different product types. Resulting energy savings from remanufacturing (assuming it allows an equally long second life) was a mixed bag with 8 cases that saved energy, 6 did not, and 11 to close to call. They concluded that remanufacturing generally results in life cycle energy savings for products that do not require energy during use (or require very little), however, remanufacturing generally does not result in energy savings for products that have a large energy requirement in the use phase and for which the energy-efficiency is increasing significantly for newer generations. Similarly, Iraldo et al. (2017) presents LCA results from three types of energy-intensive equipment; refrigerators, freezers, and electric ovens. When considering energy-consuming products, the savings in material and production by extending the product life are weighed against the use of an older and in many cases less energy-efficient product. They illustrated, in line with Ardente et al. (2018), that durable products mainly save on environmental impact categories associated with the manufacturing phase, e.g. human toxicity, freshwater ecotoxicity, and resource depletion. On the other hand, environmental impact categories related to energy consumption during the use phase show a larger environmental impact for extended product life. For some product cases, life cycle climate change reductions can be achieved when new replacement products are only minutely more energy-efficient than their older counterparts. They note that small efficiency improvements (5–20%) in the use phase are enough to justify replacement environmentally. When the use phase is included in the environmental assessment in order to include energy-efficiency improvements or product deterioration over time, the environmental benefit of remanufacturing some products becomes less positive. For example, De Kleine et al. (2011) and Kim et al. (2006) argue that deterioration in operating efficiency, like that seen when residential air conditioners or refrigerators become older and less energy-efficient, significantly reduces the optimal lifetime of the product and hence should be included in the environmental assessment.

Some consideration has been made to what product characteristics determine the most environmentally friendly strategy, extend or replace with new. Iraldo et al. (2017) and also Ardente and Mathieux (2014) concluded that the most environmentally friendly strategy depends mainly on a few factors:

1) the lifetime of the products,
2) energy consumption of the product,
3) impacts due to lifetime extension, and
4) efficiency of the replacement product.

For example, extending the product life of smartphones is beneficial from an environmental point of view since a large share of the impacts are generated in the manufacturing stage. On the other hand, washing machines are a type of product that might be better replaced due to the increased energy-efficiency in the new product (Kwak, 2016). Similarly, Intlekofer et al. (2010) assessed replacement scenarios for computers and household appliances and recommended longer lives (than the normal 4 years) for computers (manufacturing is a large part of the total environmental impacts), but on the other hand shorter lives for washers and dishwashers (with a relatively high energy use in the use phase). Tasaki et al. (2013) conducted a relatively similar assessment on refrigerators, TVs, and air conditioners and concluded that lifetime extension is mainly beneficial for products that have a comparably higher environmental impact in the manufacturing stage than the use phase. Cheung et al. (2018) argues that LCD projectors should only be remanufactured if newer models are not significantly more energy-efficient. Bakker et al. (2014), on the other hand, concluded that the optimal lifetime for today's refrigerators and laptops in regards to environmental impacts are significantly longer than their average lifetimes.

Another factor that impact the optimal lifespan from an environmental point of view is consumer behavior, i.e. usage intensity of the product (Tasaki et al., 2013). Perez-Belis et al. (2017) argued that the environmental impact depends on consumer behavior which makes it impossible to define one optimal strategy that holds in all situations. Bobba et al. (2016) showed in their LCA on vacuum cleaners that extending the product life of vacuum cleaners will in almost all cases lead to environmental benefits, unless the new replacement vacuum cleaner is 25% more energy-efficient.

It is important to note that these conclusions are greatly dependent on the type of energy source used, a point that is conspicuously absent – not even mentioned in many of these studies. Iraldo et al. (2017) notes electricity mix being an important parameter in their literature review, though no electricity mix is explicitly stated (electricity is only discussed in regards to price), and the sensitivity related to this parameter is not discussed (even though energy-efficiency and other factors are assessed thoroughly). While the burdens resulting from extending the life of energy intensive products via remanufacturing is amplified if the product is used in fossil-based systems (internal combustion engine vehicles) or fossil-heavy regions, these burdens can become negligible if the product is to be used in fossil-free (low-carbon) systems or regions. Most studies do not specify the exact energy mix used in their LCA and provide no sensitivity analysis on the impact of the chosen energy mix on their results (see supplementary data) making it difficult to explore the impact of changing energy mixes on this conclusion. One exception is Richter et al. (2019), who include decarbonization of the electricity mix in their LCA study on LED lamps. They show that the assumption on electricity mixes influences the outcome of replace early versus increase durability. The conclusion that energy consuming products with fast technological advancement should be replaced early, like for LED lamps, is dependent on the electricity mix. In a decarbonized electricity context, it appears better to increase the lifespan of the lamps.

Another key point that deserves further discussion is the assumption about reused products replacing new ones and not merely adding available units to the pool/stock. The studies above usually assume that a reused or remanufactured product substitutes a newly manufactured product. A more nuanced view is taken in operation research literature, where the impact of remanufacturing on the overall demand and consumption of products is included in the environmental assessments. Remanufacturing drives down the prices of the product, which increases sales (Raz et al., 2017), both through imperfect substitution as well as re-spending money elsewhere on other products (Makov and Font Vivanco, 2018). A 1:1 perfect displacement, as is often assumed in environmental assessments, is not realistic (Peng et al., 2020; Makov and Font Vivanco, 2018). Rebound effects lead to an overall higher environmental impact when the impact of increased consumption is higher than the savings from substituting some new products with remanufactured products (Raz et al., 2017; Xiong et al., 2016). Due to the higher overall demand the absolute environmental performance of a system with and without remanufacturing are less clear, even if the environmental impact of remanufacturing a unit of product is significantly lower than producing a new unit (e.g. Esenduran et al., 2016; Shi et al., 2016). It is likely that remanufacturing items with a relatively high environmental impact during the use phase leads to higher system wide environmental impacts due to the higher supply/demand (Esenduran et al., 2016; Liu et al., 2017). On the other hand, a study on smart phones (Makov and Font Vivanco, 2018) show that while rebound effects diminish some of the environmental benefits of the circular system, it still leads to lower environmental impact in total in most, but not all, cases. More research towards the rebound effects and how it influences the environmental performance of circular products and circular economy in general is urgently needed.

3.2. Summary of papers looking at recirculating coupled with a new (circular) product design

Few environmental studies include possible (circular) design changes in their assessment. A good circular product design from an energy use point of view depends on the product characteristics: if the product is subject to no or very small energy-efficiency improvements, designers might want to focus on durability of the product, while on the other hand, designers might want to prioritize modularity and upgradability of energy consuming parts if large energy-efficiency improvements are to be expected (Cooper and Gutowski, 2015). Kerr and Ryan (2001) assessed the environmental impact of remanufacturing a photocopier compared to producing a new one. They found that a copy machine with a modular design can reduce the environmental impact further than a non-modular conventional design, although in both cases remanufacturing leads to significant environmental savings. Their study is however indicative and focuses only on the impacts of the manufacturing/remanufacturing process itself. Kwak and Kim (2016) assessed the remanufacturing of desktop PCs assuming that some parts need to be replaced in the remanufacturing process due to obsolescence including changing customer preferences. They showed that while the remanufacturing process requires significantly less greenhouse gas emissions than manufacturing new desktop PCs, this advantage can be completely offset by the usage impacts if a significant amount of energy-efficiency increase was realized between the two models. Taking into account the average lifespan of desktop PCs and the energy-efficiency improvements over time, the authors argue that remanufacturing is not beneficial. However, they also argue that product design can be optimized to improve the benefits of remanufacturing and that further research towards product design and the value of remanufacturing is needed (Kwak and Kim, 2016). Similarly, Sabbaghi and Behdad (2017) argue that the environmental impact of remanufacturing versus manufacturing new computers heavily depend on the repairability and reusability of the product.

Krystofik et al. (2017) assessed the environmental impact of remanufacturing office furniture – a no energy consuming product susceptible to fashion changes, making the products obsolete if they cannot be upgraded during the remanufacturing process. The authors argue that design for upgradability allow the product to meet current demand and hence results in a much longer lifespan reducing the environmental impacts per use. Kaddoura et al. (2019) quantify the environmental impact of another no energy consuming product, a door handle of a waste inlet. They show that by redesigning the door handle to make it repairable, the lifetime of the door can be prolonged hence resulting in lower environmental impacts.

3.3. Summary of papers looking at recirculating coupled with a new (circular) business model

Few studies empirically investigate the environmental performance of servicized or product-service systems (PSS) as compared to traditional ownership models. A servicized business model is one in which the ownership of the product remains with the company in combination with a pay-per-use pricing structure (Agrawal and Bellos, 2016). Tornese et al. (2018) assess the impacts of reusing pallets in a pooling system compared to using pallets only once. They found that the CO_2 emissions of repair is only a fraction of the emissions of manufacturing new pallets and the overall environmental impact depends largely on the handling/loading conditions of the pallets and transportation distances. Tua et al. (2019) show that reusable plastic crates for transportation of fruit and vegetables will have to be used three times in a pooling system to have lower environmental impacts than single-use crates. Using renewable energy in the reconditioning process would improve the environmental performance of reusable crates further. Bech et al. (2019) shows that a PSS system of T-shirts for the army which result in product life extension through longer use and repurposing of the T-shirts and where T-shirts are washed less and at a lower temperature, will reduce the greenhouse gas emission significantly, even though the environmental impact of one T-shirt is higher due to increased durability and quality. Kaddoura et al. (2019) quantify the environmental impact of a beach flag and event tent when sold and used one time versus a business model where the manufacturer retains the ownership and refurbishes and reuses the items several times. Hoffmann et al. (2020) explores the environmental impact of having a pay-per-use system for cloth diapers versus using disposable diapers. Lindahl et al. (2014) shows the environmental impact of three product-service systems and compares them to their linear counterpart sales offer. In their first case study, the authors study core plugs for paper mills and argue that PSS increases the number of times such core plug is reused and hence the environmental impact is reduced. In their second case study, they compare different exterior building cleaning methods and argue that the service will reduce the time needed for cleaning and therefore reduce the environmental impact. Thirdly, they compare soil compactors where more durable soil compactors are manufactured and maintained in the PSS system. Also here, an environmental benefit is shown compared to producing a linear product that has a shorter lifespan. However, from the paper it is unclear in how far new technologies are the reason for the environmental impact and in how far the PSS offers really made a difference in the usage behavior of the product.

It is argued that PSS would stimulate the original equipment manufacturer (OEM) to reduce their production volume and therefore contribute to resource-efficiency. Because customers pay depending on the usage of the product, it is anticipated that consumers will use the product less frequent. On the other hand, people with low usage intensity might be more inclined to use the product if they can pay for only their use and not have to buy the product (Agrawal and Bellos, 2016). These changes in customer behavior contribute to rebound effects and should be included, or at least considered, in environmental assessments to capture the full environmental effects of shifting to circular business models

(Dal Lago et al., 2017; Kjaer et al., 2018). The new offer might also substitute other products than the initial product and finding data on this substitution and rebound effect is challenging, especially in the early design phase (Kjaer et al., 2016). Demand for a product depends on the pricing of the product and hence pricing decisions and subsequent demand should be included in environmental calculations (Agrawal and Bellos, 2016). To complicate things further, the scant research available has shown that the reliability and energy-efficiency of the product might change when companies shift from a linear to a circular business model (Agrawal and Bellos, 2016, 2016b).

In principle, PSS shift the focus from product to the function it provides or its availability, which means that the environmental impact should be calculated over the function delivered (including related environmental impacts of required products and activities to deliver the function) instead of calculating the environmental impact over one product. It is argued that the selection of the functional unit in a PSS is therefore an arbitrary process (Dal Lago et al., 2017). While PSS is a relative new concept, selecting the right functional unit is a key concept in LCA practice and is presented in even early LCA handbooks. For example, functional units as 'watching TV for 1 h' (Guinée et al., 2002, Part 3 p 78), '1000 h of light' (Guinée et al., 2002, Part 3 p 82), or '20 m^2 of wall covering with a thermal resistance of 2 m^2 K/W, with a colored surface of 98% opacity, not requiring any other painting for 5 years' (Guinée et al., 2002, Part 2a p22) are described, referring clearly to the function or performance instead of the product.

4. Analysis and discussion

The collection of studies gives us insights not only into products and the potential of circular products in regards to reducing (relative) environmental impact, they also give us insights into the common methods and norms followed when conducting LCA of products.

4.1. Key factors for determining environmental impact of circular products

Based on the assessments of circular products collected (and listed in section 3), several product or industry characteristics can be identified that seem to have a determining role in whether a product will be suitable for a circular economy, meaning that recirculating such products will reduce the environmental impact compared to producing only new products.

- Extending product life: A first prerequisite to reduce a product's environmental impact is the ability to extend product life via extended usage duration, reuse and/or remanufacturing. Extending the life of products can result in greatly reduced environmental impacts; more overall function is achieved while the impacts from material extraction and manufacturing stay – depending on what components have to be replaced to achieve reuse – close to the same. As a general rule, it is beneficial to extend the life of products that have a relatively high share of total environmental impacts in the manufacturing phase while, it is not beneficial to extend the life of products that have a relatively high share of environmental impacts in the use phase, that is, if new products exhibit better use-phase energy-efficiency.
- Efficiency and environmental burdens during use: Some products deteriorate over time, leading to higher energy or resource consumption than when the product just came on the market. If the deterioration is relatively large, the product can perhaps better be replaced instead of being used rather inefficiently. Similarly, if new products have become more energy-efficient due to new innovative technologies, it will be better to replace the product instead of extending the use of inefficient old technologies. The exact moment of replacement that leads to the lowest environmental impact depends on the electricity mix and usage intensity. Heavy used energy-consuming products have a relative larger share of the environmental impacts in the use phase. It might therefore be better for a heavy user to switch to a newer model while low-intensity users might be better off by keeping their current product.
- Point of obsolescence: When exactly the product is replaced does not only depend on the technical lifespan of the product (i.e. how long the product functions), it is for a large part also determined by the user. Customers might decide to no longer use the product for different reasons; aesthetical, economical, functional, technological, or social reasons (Burns, 2010). When the customer perceives the product as obsolete, the product may be discarded. Products in innovative markets might be discarded far before its technical lifespan is reached and efforts to extend the technical lifespan are meaningless if the product is not used that long.

The collection of studies seems to indicate that some products might be more suitable for circular economy than others, with in particular white goods being less suitable (see Table 1). White goods have a relatively high environmental impact in the use phase which leads, in combination with the high degree of innovation in terms of reached energy-efficiency, to replacement being the more optimal strategy above product life extension through reuse and remanufacturing. For another group of products, the most optimal strategy in terms of environmental impact depends on usage behavior (intensity of use) and innovation speed and can be either product life extension or replacement depending on the circumstances. The impact of innovation on environmental impact need to be explored further.

As widely argued, a manufacturing company can invest in designing their products/business in such way that some of the above-mentioned impacts are minimized. Product design can influence the lifespan of the product, the maintenance and repair activities needed during the use phase, energy and other resource consumption in the use phase, and the recirculation possibilities (e.g. recycling) after use. Product design can also help to keep products relevant longer by allowing upgrades that will mitigate obsolescence (Cooper, 2010). For example, designing products with product life extension in mind including the necessary activities that need to be performed to reach that (such as design for disassembly and remanufacturing), might help in reducing the impacts from these activities. Energy-efficiency improvements can be incorporated in the 'old' product by replacing the energy-consuming components during remanufacturing via design for upgradability and modularity. However, as pointed out above, the environmental impacts of design for upgradability and modularity are ambiguous as these design strategies might also lead to additional demand from customers.

In a similar vein, business models may influence how products are used. For example, OEMs may incentivize product return leading to high return and reuse rates but also changing user behavior in unforeseen ways. However, that does not necessarily mean that the alternative to the OEM-controlled model results in only one use of the product. Independent remanufacturers and second-hand markets can also lead to high reuse-rates. Business models might further influence the usage duration depending on if people have purchased the product, are leasing the product, or are paying on a pay-per-use basis. Knowing what will happen with the product and how it will be used after putting it on the market can be very difficult. More research will be needed in order to be able to conduct quantitative environmental assessments of various circular business models.

4.2. Environmental impact assessments methods

While there are numerous environmental impact assessment methods, LCA is largely considered as the leading tool to assess the environmental impact of circular products (Haupt and Zschokke, 2017). However, when applying LCA to circular products, a couple of potential issues arise (Elia et al., 2017).

Peters (2016) argues that a long-term consequential LCA that looks at the environmental effects of remanufacturing systems (i.e. expanding system boundaries to calculate the environmental effect of a system where products are manufactured and remanufactured including remanufacturing yield rates etc. and compare them against a system where all products are manufactured new) is the most appropriate, realistic and accurate view. Unfortunately, due to data limitations, some LCA studies only compare a single new product with a successfully remanufactured product. Therefore, they only compare the direct impacts of the manufacturing and remanufacturing processes, but do not include the wider system impacts from products that cannot be successfully remanufactured. Similarly, new services and their related impacts (for example infrastructure and buildings) of a circular business model need to be included in the LCA for a fair comparison with linear business models (Kjaer et al., 2018).

Rebound effects, although mentioned in several papers, are so far (almost) not addressed and incorporated in the environmental assessments identified in this paper. It is argued, however, that even if circular economy would be implemented to its fullest extent, the rebound effects will lead to an overall growing use of materials and increasing our impact on the environment (Korhonen et al., 2018). For example, the availability of (cheaper) used products may merely increase consumption by allowing consumers to afford and own more products (Zink and Geyer, 2017). The question therefore becomes: *Does the availability of used products actually displace manufacturing of new products?* Several ways to include rebound effects in environmental assessments are suggested. Thomas (2011) suggests parameterizing individual's buying habits and proposes a set of equations which are to be an economics-based foundation for assessing to which degree buying used products replaces buying new in a given market. Farrant et al. (2010) takes a different approach and translates consumer behavior – as described via a survey – into levels of replacement of new production. They assume that purchases made by people that usually or always buy clothes at second-hand markets replace new production, whereas those purchases made by those who do it seldom, looking for "unnecessary" extra things, replace less new production (per purchase) as they are considered superfluous. However, one could consider that the mere availability of second-hand clothes that are cheaper increases purchasing power. Moreover, the presence of a second-hand market may increase the incentive of people to replace their "used" clothes with new ones, knowing that they can get some of their investment back and that the clothes will be used by someone else anyway (reducing moral burden). Research on the various customer segments and their sizes is in its infancy (Abbey et al., 2015). These types of outcomes demonstrate a limitation in especially assessments of relative environmental impact. This suggests a need to consider changes in consumption patterns and how it affects *absolute* system wide environmental impact.

Finally, it has been suggested that it is important to consider larger (societal/macro) changes towards CE when modelling the environmental impact of circular products on micro level. Harris et al. (2021) highlight the potential of the societal needs/functions framework to provide a meso level link between the micro and macro levels. This can additionally help link environmental assessment at the different levels and aid the analysis and monitoring towards CE. Future analysis also requires consideration of the shift to electricity production with lower carbon intensity (Haupt and Zschokke, 2017; Richter et al., 2019). While some argue that renewable energy is one cornerstone of the CE vision (EMF, 2013), most studies gathered do not explicitly assess electricity mix nor do they consider what effects changing to renewable energy sources would have. Regardless of one beliefs regarding renewable energy being part of CE or not, assessing a product's true long-term compatibility with CE should consider not only the current state of fossil-based energy system – in which one may be incentivized to innovate on short cycles and build short-lived products in order to gain 'energy-efficiency'— but future energy states as well.

5. Conclusions

This paper mapped and combined the knowledge available on the environmental impact of circular products and circular business models and showed large deficits in the existing evidence. While the studies show that the remanufacturing process itself, compared to manufacturing new items, results in many cases in lower environmental impact, these studies provide only one piece to the puzzle regarding the question whether CE will improve resource-efficiency. Broader impacts, from e.g. return transports and not reusable items, energy-efficiency improvements and degradation, and rebound effects complicate the answer. It is remarkable that, despite circular product design and circular business models strategies being central concepts within CE, there appear to be limited studies focusing on assessing their environmental performance. Product design strategies for circular economy, for example modularity, upgradability, repairability, etc., can, in theory, counteract some of the negative consequences of extending the product lifetime, but its effect on consumer behavior and hence the overall effect on environmental impact is poorly researched so far. Similarly, the effect of circular business models on consumption is not yet included in the environmental assessments. Most studies seem to assume a static world where the introduction of the circular product have no impact on consumption. Especially when considering circular business models, function instead of products need to be the unit of analysis implying the inclusion of potential changes in consumption. Hence, we see an urgent need for a better understanding of the environmental impact of circular products and call for papers that incorporate the role of circular product design, circular business models, and consumption into their environmental assessments.

Most papers focus on the environmental impact of circular products in today's world including the current existing electricity mix. While this is absolutely not wrong to do, it does ignore the transition towards a decarbonized electricity mix and hence limits the usefulness of the study to today's world. In order words, we do not know enough yet about the environmental impact of circular products in the long term, not even if product life extension is the way forward and under which circumstances. Larger societal CE changes, like switching to renewable energy, are not often incorporated into the environmental assessments of circular products. Future research should include, or at least reflect, on these aspects to provide a coherent and complete answer on the question whether circular products are indeed environmentally preferred to linear products or as importantly, how to make sure they will be.

To the best of our knowledge, this is the first paper that combined the available evidence and knowledge on the environmental impact of circular products and circular business models by collecting and assessing environmental assessments. The paper is limited to environmental impact of circular products and business models, taking a micro-level perspective, and excluding thereby the effects of transitioning toward circular economy at meso- and macro-level. Moreover, while it attempts to collect the knowledge on environmental impact, the majority of the conclusions, due to limitations in the collected studies, is based on greenhouse gas emissions. The change to circular products has not only an effect on greenhouse gas emissions but also on material and resource consumption, toxicity, particulate air pollution, acidification, eutrophication, waste generation, to name a few. What the most optimal strategy for a product is might differ depending on what environmental impact category one looks at (see for example a study on tools sharing, Martin et al., 2020) and knowledge on different environmental impact categories need to be extended and combined. This paper did further not discuss any implications on economic or social sustainability of circular products, which are important for a successful transition towards the circular economy. Instead we focused on mapping the existing knowledge on the environmental impact of circular products and business models and conclude that there is an urgent need for future LCAs to study the environmental impact of circular product design and circular business model including changes in consumption, return transport and not reusable items, and energy-efficiency improvements and degradation.

CRediT authorship contribution statement

Patricia van Loon: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Funding acquisition. **Derek Diener:** Methodology, Formal analysis, Investigation, Writing - original draft. **Steve Harris:** Formal analysis, Investigation, Writing - review & editing.

Declaration of competing interest

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

Acknowledgement

This work was supported by the Swedish Environmental Protection Agency (Research project LinCS, project no 802-0097-17).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125627.

References

Abbey, J.D., Blackburn, J.D., Guide, V.D.R., 2015. Optimal pricing for new and remanufactured products. J. Oper. Manag. 36, 130–146.
Afrinaldi, F., Liu, Z., Taufik, Zhang, H.C., Hasan, A., 2017. The advantages of remanufacturing from the perspective of eco-efficiency analysis: a case study. Procedia CIRP 61, 223–228.
Agrawal, V., Atasu, A., Van Wassenhove, L., 2016. 4 Obstacles on the Way to a Circular Economy. Huffington post. Available at: http://www.huffingtonpost.com/alliance-forresearch-on-corporate-sustainability-/4-obstacles-on-the-way-to_b_11019722.html. (Accessed 9 August 2017).
Agrawal, V.V., Bellos, I., 2016. Servicizing in supply chains and environmental implications. In: Atasu, A. (Ed.), Environmentally Responsible Supply Chains. Springer, Switzerland.
Agrawal, V.V., Bellos, I., 2016b. The potential of servicing as a green business model. Manag. Sci. 63 (5), 1271–1656.
Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: a white paper, Resources. Conserv. Recycl. 55 (3), 362–381.
Andre, H., Söderman, M.L., Nordelöf, A., 2019. Resource and environmental impacts of using second-hand laptop computers: a case study of commercial reuse. Waste Manag. 88, 268–279.
Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: method and application. J. Clean. Prod. 74, 62–73.
Ardente, F., Peiro, L.T., Mathieux, F., Polverini, D., 2018. Accounting for the environmental benefits of remanufactured products: method and application. J. Clean. Prod. 198, 1545–1558.
Ayres, R.U., 1998. Eco-thermodynamics: economics and the second law. Ecol. Econ. 26 (2), 189–209.
Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16.
Bech, N.M., Birkved, M., Charnley, F., Kjaer, L.L., Pigosso, D.C.A., Hauschild, M.Z., McAloone, T.C., Moreno, M., 2019. Evaluating the environmental performance of a product/service-system business model for merino wool next-to-skin garments: the case of armadillo merino. Sustainability 11, 5854.
Benton, K., Yang, X., Wang, Z., 2017. Life cycle energy assessment of a standby diesel generator set. J. Clean. Prod. 149, 265–274.
Biswas, W., Rosano, M., 2011. A life cycle greenhouse gas assessment of remanufactured refrigeration and air conditioning compressors. Int. J. Sustain. Manuf. 2 (2/3), 222–236.
Bobba, S., Ardente, F., Mathieux, F., 2016. Environmental and economic assessment of durability of energy-using products: method and application to a case-study vacuum clear. J. Clean. Prod. 137, 762–776.
Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A., Pfrang, A., 2018. Life cycle assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage 19, 213–225.
Bocken, N., Miller, K., Evans, S., 2016. Assessing the environmental impact of new circular business models. In: Conference "New Business Models" – Exploring a Changing View on Organizing Value Creation – Toulouse, France, 16-17 June.
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016b. Product design and business model strategies for a circular economy. J. Indust. Prod. Eng. 33 (5), 308–320.
Braz, A.C., de Mello, A.M., de Vasconcelos Gomes, L.A., de Souza Nascimento, P.T., 2018. The bullwhip effect in closed-loop supply chains: a systematic literature review. J. Clean. Prod. 202, 376–389.
Burns, B., 2010. Re-evaluating obsolescence and planning for it. In: Cooper, T. (Ed.), Longer Lasting Products: Alternatives to the Throwaway Society. Gower Publishing Limited, Farnham, England.
Chertow, M.R., 2007. "Uncovering" industrial symbiosis. J. Ind. Ecol. 11 (1), 11–30.
Cheung, C.W., Berger, M., Finkbeiner, M., 2018. Comparative life cycle assessment of re-use and replacement for video projectors. Int. J. Life Cycle Assess. 23, 82–94.
Cooper, T., 2010. Longer Lasting Products: Alternatives to the Throwaway Society. Gower, Farnham, UK.
Cooper, D.R., Gutowski, T.G., 2015. The environmental impacts of reuse: a review. J. Ind. Ecol. 21 (1), 38–56.
Cusenza, M.A., Guarino, F., Longo, S., Ferraro, M., Cellura, M., 2019. Energy and environmental benefits of circular economy strategies: the case study of reusing used batteries from electric vehicles. J. Energy Storage 25, 100845.
Dal Lago, M., Corti, D., Wellsandt, S., 2017. Reinterpreting the LCA standard procedure for PSS. Procedia CIRP 64, 73–78.
De Kleine, R.D., Keoleian, G.A., Kelly, J.C., 2011. Optimal replacement of residential air conditioning equipment to minimize energy, greenhouse gas emissions, and consumer cost in the US. Energy Pol. 39 (6), 3144–3153.
Diener, D.L., Tillman, A.-M., 2015. Component end-of-life management: exploring opportunities and related benefits of remanufacturing and functional recycling. Resour. Conserv. Recycl. 102, 80–93.
Du, Y., Cao, H., Liu, F., Li, C., Chen, Y., 2012. An integrated method for evaluating the remanufacturability of used machine tool. J. Clean. Prod. 20, 82–91.
Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751.
EMF, 2013. Towards the Circular Economy: Opportunities for the Consumer Goods Sector. Ellen MacArthur Foundation, UK.
EMF, 2013b. Towards the Circular Economy Vol 1. - Economic and Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation, UK.
EMF, 2015. Growth within: a Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation, UK.
European Commission, 2012. Manifesto for a resource-efficient europe. European commission. Available at: http://europa.eu/rapid/press-release_MEMO-12-989_en.htm. (Accessed 2 July 2019).
European Commission, 2020. EU circular economy action plan. Available at: https://ec.europa.eu/environment/circular-economy/. (Accessed 11 September 2020).
Esenduran, G., Kemahlioglu-Ziya, E., Swaminathan, J.M., 2016. Take-back legislation: consequences for remanufacturing and environment. Decis. Sci. J. 47 (2), 219–248.
Farrant, L., Olsen, S.I., Wangel, A., 2010. Environmental benefits from reusing clothes. Int. J. Life Cycle Assess. 15 (7), 726–736.
Gao, W., Li, T., Tang, Z., Peng, S., Zhang, H.C., 2017. Investigation on the comparative life cycle assessment between newly manufactured and remanufactured turbochargers. In: 24th CIRP Conference on Life Cycle Engineering, vol. 61, pp. 750–755.
Geyer, R., Kuczenski, B., Zink, T., Henderson, A., 2015. Common misconceptions about recycling. J. Ind. Ecol. 20 (5), 1010–1017.
Goldey, C.L.C., Kuester, E.-U.E., Mummert, R., Okrasinski, T.A., Olson, D.,

Schaeffer, W.J., 2010. Lifecycle assessment of the environmental benefits of remanufactured telecommunications product within a “green” supply chain. In: Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology. IEEE, p. 1e6. https://doi.org/10.1109/ISSST.2010.5507761.
Guide, V.D.R., Van Wassenhove, L.N., 2001. Managing product returns for remanufacturing. Prod. Oper. Manag. 10 (2), 142–155.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Sush, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht.
Gusenbauer, M., Haddaway, N.R., 2019. Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. Res. Synth. Methods 11 (2), 181–217.
Gutowski, T.G., Sahni, S., Boustani, A., Graves, S.C., 2011. Remanufacturing and energy savings. Environ. Sci. Technol. 45, 4540–4547.
Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consump. 26, 172–186.
Harris, S., Prittchard, 2004. Industrial ecology as a learning process in business strategy. Progr. Indust. Ecol. Int. J. 1 (1–3), 89–111.
Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy? – 63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. 22, 832–837.
Hoffmann, B.S., Morais, J.d.S., Teodoro, P.F., 2020. Life cycle assessment of innovative circular business models for modern cloth diapers. J. Clean. Prod. 249, 1–16. https://doi.org/10.1016/j.jclepro.2019.119364.
Ijomah, W.L., McMahon, C.A., Hammond, G.P., Newman, S.T., 2007. Development of design for remanufacturing guidelines to support sustainable manufacturing. Robot. Comput. Integrated Manuf. 23, 712–719.
Intlekofer, K., Bras, B., Ferguson, M., 2010. Energy implications of product leasing. Environ. Sci. Technol. 44 (303), 4409–4415.
Iraldo, F., Facheris, C., Nucci, B., 2017. Is product durability better for environment and for economic efficiency? a comparative assessment applying LCA and LCC to two energy intensive products. J. Clean. Prod. 140, 1353–1364.
Kaddoura, M., Kambanou, M.L., Tillman, A.-M., Sakao, T., 2019. Is prolonging the lifetime of passive durable products a low-hanging fruit of a circular economy? A multiple case study. Sustainability 11, 4819.
Kerr, W., Ryan, C., 2001. Eco-efficiency gains from remanufacturing: a case study of photocopier remanufacturing at Fuji Xerox Australia. J. Clean. Prod. 9, 75–81.
Kim, H.C., Keoleian, G.A., Grande, D.E., Bean, J.C., 2003. Life cycle optimization of automobile replacement: model and application. Environ. Sci. Technol. 37, 5407–5413.
Kim, H.C., Keoleian, G.A., Horie, Y.A., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Pol. 34, 2310–2323.
Kjaer, L.L., Pagoropoulos, A., Schmidt, J.H., McAloone, T.C., 2016. Challenges when evaluating Product/Service-Systems through life cycle assessment. J. Clean. Prod. 120, 95–104.
Kjaer, L.L., Pigosso, D.C.A., McAloone, T.C., Birkved, M., 2018. Guidelines for evaluating the environmental performance of Product/Service-system through life cycle assessment. J. Clean. Prod. 190, 666–678.
Korhonen, J., Honkasalo, A., Seppala, J., 2018. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46.
Krystofik, M., Luccitti, A., Parnell, K., Thurston, M., 2017. Adaptive remanufacturing for multiple lifecycles: a case study in office furniture. Resour. Conserv. Recycl. 135, 14–23.
Kwak, M., 2016. Assessing the greenness of product lifetime extension. ICIC Expr. Lett. Part B: Appl. 7 (2), 1–6.
Kwak, M., Kim, H., 2016. Modeling the time-varying advantages of a remanufactured product: is "reman" better than "brand new"? J. Mech. Des. 138, 1–18.
Latham, G., 2016. Vehicle Remanufacturing: Economic and Environmental Expansion of the Life Cycle. SAE Technical Paper 2016-01-1291.
Lazarevic, D., Valve, H., Kautto, P., 2016. What makes the circular economy? Expectations and visions for a European circular economy. In: 7th International Sustainability Transitions Conference, Wuppertal, Germany.
Lindahl, M., Sundin, E., Sakao, T., 2014. Environmental and economic benefits of integrated product service offerings quantified with real business cases. J. Clean. Prod. 64, 288–296.
Linder, M., Vanacore, E., Altmann, P., Dahllöf, L., Ljungkvist, H., 2018. Measuring product circularity as a means to promote resource productivity. Available at: https://www.ivl.se/download/18.72aeb1b0166c003cd0d2356/1544696760568/C345.pdf. (Accessed 16 July 2019).
Lishan, X., Weiling, L., Qinghai, G., Lijie, G., Guoqin, Z., Xiji, C., 2018. Comparative life cycle assessment of manufactured and remanufactured loading machines in China. Resour. Conserv. Recycl. 131, 225–234.
Liu, Z., Jiang, Q., Li, T., Dong, S., Yan, S., Zhang, H., Xu, B., 2016. Environmental benefits of remanufacturing: a case study of cylinder heads remanufactured through laser cladding. J. Clean. Prod. 133, 1027–1033.
Liu, Z., Tang, J., Li, B-y., Wang, Z., 2017. Trade-off between remanufacturing and recycling of WEEE and the environmental implication under the Chinese Fund Policy. J. Clean. Prod. 167, 97–109.
Lonca, G., Muggeo, R., Imbeult-Tretreault, H., Bernard, S., Margni, M., 2018. Does material circularity rhyme with environmental efficiency? Case studies on used tires. J. Clean. Prod. 183, 424–435.
Low, J.Z.C., Tjandra, T.B., Lu, W.F., Lee, H.M., 2016. Adaptation of the product structure-based integrated life cycle analysis (PSILA) technique for carbon footprint modelling and analysis of closed-loop production system. J. Clean. Prod. 120, 105–123.
Lucas, P., Kram, T., Hanemaaijer, A., 2016. Potential Effects of Circular Economy Policies in the EU and The Netherlands on Developing Countries. PBL Netherlands Environmental Assessment Agency. Available at: http://www.pbl.nl/en/publications/potential-effects-ofcircular-economy-policies-in-the-eu-and-the-netherlands-on-developing-countries. (Accessed 9 August 2017).
Makov, T., Font Vivanco, D., 2018. Does the circular economy grow the pie? The case of rebound effects from smartphone reuse. Front. Energy Resear. 6, 39.
Manninen, K., Koskela, S., Antikainen, R., Bocken, N., Dahlbo, H., Aminoff, A., 2018. Do circular economy business models capture intended environmental value propositions? J. Clean. Prod. 171, 413–422.
Martin, M., Heiska, M., Björklund, A., 2020. Environmental assessment of a product-service system for renting electric-powered tools. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.125245.
McDonough, W., Braungart, M., 2002. Cradle to Cradle: Remaking the Way We Make Things. North Point Press, New York.
McDowall, W., Geng, Y., Huang, B., Bartekova, E., Bleischwiz, R., Turkeli, S., Kemp, R., Domenech, T., 2017. Circular economy policies in China and europe. J. Ind. Ecol. 21 (3), 651–661.
Mont, O., 2004. Product-service Systems: Panacea or Myth? Lund University. PhD thesis.
Murray, A., Skene, K., Haynes, K., 2017. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics 140 (3), 369–380.
Peng, S., Yang, Y., Li, T., Smith, T.M., Tan, G.Z., Zhang, H.-C., 2020. Environmental benefits of engine remanufacture in China's circular economy development. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.9b02973.
Perez-Belis, V., Bakker, C., Juan, P., Bovea, M.D., 2017. Environmental performance of alternative end-of-life scenarios for electrical and electronic equipment: a case study for vacuum cleaners. J. Clean. Prod. 159, 158–170.
Peters, K., 2016. Methodological issues in life cycle assessment for remanufactured products: a critical review of existing studies and an illustrative case study. J. Clean. Prod. 126, 21–37.
Raz, G., Ovchinnikov, A., Blass, V., 2017. Economic, environmental, and social impact of remanufacturing in a competitive setting. Transac. Eng. Manag. 64 (4), 476–490.
Richter, J.L., Tähkämö, L., Dalhammar, C., 2019. Trade-offs with longer lifetimes? The case of LED lamps considering product development and energy contexts. J. Clean. Prod. 226, 195–209.
Sabbaghi, M., Behdad, S., 2017. Environmental evaluation of product design alternatives: the role of consumer's repair behavior and deterioration of critical components. J. Mech. Des. 139, 1–10.
Scopus, 2020. Content coverage guide. Available at: https://www.elsevier.com/__data/assets/pdf_file/0007/69451/Scopus_ContentCoverage_Guide_WEB.pdf. (Accessed September 2020), 8.
Sehnem, S., Vazquez-Brust, D., Pereira, S.C.F., Campos, L.M.S., 2019. Circular economy: benefits, impacts and overlapping. Supply Chain Manag.: Int. J. 24 (6), 784–804.
Shi, T., Gu, W., Chhajed, D., Petruzzi, N.C., 2016. Effects of remanufacturable product design on market segmentation and the environment. Decis. Sci. J. 47 (2), 298–330.
Smith, V.M., Keoleian, G.A., 2004. The value of remanufactured engines: life-cycle environmental and economic perspectives. J. Ind. Ecol. 8 (1–2), 193–221.
Sundin, E., 2004. Product and Process Design for Successful Remanufacturing. Doctoral thesis. Linköping, Sweden.
Tasaki, T., Motoshita, M., Uchida, H., Suzuki, Y., 2013. Assessing the replacement of electrical home appliances for the environment: an aid to consumer decision making. J. Ind. Ecol. 17 (2), 290–298.
Thomas, V.M., 2011. The environmental potential of reuse: an application to used books. Sustain. Sci. 6 (1), 109–116.
Tornese, F., Pazour, J.A., Thorn, B.K., Roy, D., Carrano, A.L., 2018. Investigating the environmental and economic impact of loading conditions and repositioning strategies for pallet pooling providers. J. Clean. Prod. 172, 155–168.
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br. J. Manag. 14, 207–222.
Tua, C., Biganzoli, L., Grosso, M., Rigamonti, L., 2019. Life cycle assessment of reusable plastic crates (RPCs). Resources 8, 110.
Tukker, A., 2015. Product services for a resource-efficient and circular economy - a review. J. Clean. Prod. 97, 76–91.
van Loon, P., Van Wassenhove, L.N., 2018. Assessing the economic and environmental impact of remanufacturing: a decision support tool for OEM suppliers. Int. J. Prod. Res. 56 (4), 1662–1674.
Wang, L., Cai, G.G., Tsay, A.A., Vakharia, A.J., 2017. Design of the reverse channel for remanufacturing: must profit-maximization harm the environment? Prod. Oper. Manag. 26 (8), 1585–1603.
Warsen, J., Laumer, M., Momberg, W., 2011. Comparative life cycle assessment of remanufacturing and new manufacturing of a manual transmission. Glocalized Solut. Sustain. Manufact. 67–72.
Woolridge, A.C., Ward, G.D., Philips, P.S., Collins, M., Gandy, S., 2006. Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Resour. Conserv. Recycl. 46 (1), 94–103.

Xiong, Y., Zhao, Q., Zhou, Y., 2016. Manufacturer-remanufacturing vs supplier-remanufacturing in a closed-loop supply chain. Int. J. Prod. Econ. 176, 21–28.
Xiong, S., Ji, J., Ma, X., 2020. Environmental and economic evaluation of remanufacturing lithium-ion batteries from electric vehicles. Waste Manag. 102, 579–586.
Zheng, H., Li, E., Wang, Y., Shi, P., Xu, B., Yang, S., 2019. Environmental life cycle assessment of remanufactured engines with advanced restoring technologies. Robot. Comput. Integrated Manuf. 59, 213–221.
Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21 (3), 593–602.