Linking circularity metrics at product and society level (LinCS)

PATRICIA VAN LOON, SAAMET EKICI, STEVE HARRIS, MICHAEL MARTIN, SJOERD HERLAAR, TOMAS RYDBERG, DEREK DIENER, MARCUS LINDER

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Linking circularity metrics at product and society level (LinCS)

Final report

Authors: Chalmers Industriteknik (Patricia van Loon, Saamet Ekici),
IVL (Steve Harris, Michael Martin, Sjoerd Herlaar, Tomas Rydberg), and
RISE (Derek Diener, Marcus Linder)

SWEDISH ENVIRONMENTAL
PROTECTION AGENCY

Order
Phone: + 46 (0)8-505 933 40
E-mail: natur@cm.se
Address: Arkitektkopia AB, Box 110 93, SE-161 11 Bromma, Sweden
Internet: www.naturvardsverket.se/publikationer

The Swedish Environmental Protection Agency
Phone: + 46 (0)10-698 10 00
E-mail: registrator@naturvardsverket.se
Address: Naturvårdsverket, SE-106 48 Stockholm, Sweden
Internet: www.naturvardsverket.se

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Preface

The European Commission has adopted the Circular Economy Package to stimulate Europe's transition towards a circular economy. Through reusing, remanufacturing, and recycling of products and thereby closing the loop of product lifecycles, it will bring our society both environmental and economic benefits fostering a sustainable economic growth[1].

A three-year research project called LinCS had as aim to understand the conditions needed for a circular model to be sustainable, both at micro as well as macro level (including rebound effects). After an extensive literature review, ten different case studies were conducted in which the environmental, economic, and circularity performance of a product in a linear and circular business model were quantified. Macro-economic modelling was then performed to assess potential secondary effects and explore the benefit for Sweden when transitioning towards a circular economy. Policy implications following from the project are outlined.

The project was financed by the Swedish Environmental Protection Agency's (Naturvårdsverket) environmental fund (miljöforskningsanslaget) where the main aim is to finance research and produce knowledge for the benefit of the Swedish Environmental Protection Agency and the Swedish Agency Marine and Water Management. This report is written by Patricia van Loon and Saamet Ekici from Chalmers Industriteknik, Steve Harris, Michael Martin, Sjoerd Herlaar and Tomas Rydberg from IVL Swedish Environmental Research Institute and Derek Diener and Marcus Linder from RISE. The authors are solely responsible for the content.

The Swedish Environmental Protection Agency, March 2021

[1] https://ec.europa.eu/environment/circular-economy/

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Summary

The LinCS research project aimed to generate knowledge and understanding on the environmental and financial implications of circular products and circular economy at micro and macro level. It also sought to consider and review potential rebound effects. While circular economy is promoted as a promising solution that will decouple economic growth from environmental degradation, empirical evidence and academic research on the sustainability of circular economy and circular business models is in an embryonic form. Hence, the following research questions were posed:

1. What factors/variables impact the environmental performance of circular products/circular business models?
2. Under what circumstances/conditions are circular products/circular business models environmentally and economically preferred compared to linear ones?
3. How can circular business models be improved in order to be sustainable?
4. What are suitable indicators to monitor the environmental effects of CE at the micro and macro level?
5. Which policies need to be introduced/altered that prevent/reduce the proliferation of unsustainable CE and support sustainable CE products?

The research started with an extensive systematic literature review that mapped current knowledge and knowledge gaps on the environmental impact of circular products and circular business models. Despite the large interest of researchers on circular economy, the review only identified 54 papers that quantified the environmental impact of a circular versus linear product or system. Many of these papers focused on the environmental impact of the reuse or remanufacturing process but did not include key aspects of circular economy such as product design specific to the circular economy, or circular business models. Hence, there is a clear need for more research on the environmental impact. Based on the review, several product characteristics can be distilled that have a strong role in determining whether a product is suitable for the circular economy. In other words, these characteristics help to determine whether the increased circularity of a product is likely to lead to reduced environmental impact compared to the production of new products. These characteristics include 1) the extension of the product life, 2) the contribution of the manufacturing stage to the total life cycle environmental impact compared to other stages, 3) innovation frequency, 4) deterioration impacts during the life cycle including wear, 5) usage intensity, and 6) obsolescence. In particular, white goods were highlighted in the literature as being less suitable, due to their large share of environmental impacts in the use phase and because there has historically been a high degree of energy-efficiency innovation. For other groups of products, such as consumer electronics, the results are more ambiguous as it depends on the usage intensity and speed of innovation.

Given the clear lack of studies assessing the environmental impact of circular products including the key aspects of circular product design and circular business models, ten case studies were conducted as part of the LinCS project in which the environmental, economic, and circularity performance of a product in a linear and circular business model were quantified. The majority of the case studies included circular product design and circular business models. The case studies show that the circular offer reduced the greenhouse gas impacts significantly in all but one case (where the rental business model led to increased emissions from transport for the customer and was highly dependent on rental location). Most cases resulted in a 50 to 60 % reduction. Based on the results we conclude that the recovery process or business model that enables life extension is usually less material- and energy-intensive. We further argue that with the expected transition towards renewable energy sources, the focus will likely shift away from greenhouse gas emissions to other environmental impacts. Material intensity will become more central, with the associated impacts of extraction and mining processes, as well as impacts on biodiversity. As a consequence, it is likely that the superior performance of circular products will become even more apparent in the future.

The case studies further showed that profitability is an issue for some, but not all, manufacturers. In many cases, the costs of the circular model were estimated to be lower than in the linear case, mainly because less items need to be manufactured to fulfil the same level of demand, reducing manufacturing costs significantly. However, the revenue that can be generated in the circular model compared to the linear model is also lower, meaning that in some cases the profitability became lower. In many cases, the price customers pay for the circular product was set significantly lower than the linear product. More knowledge is needed to help companies set the correct price that can make their circular offer profitable and economical attractive.

Macro-economic modelling was then performed to assess potential secondary effects and explore the benefit for Sweden when transitioning towards a circular economy. Multi-Regional Input Output (MRIO) modelling was used to understand the link between product level changes and macro level impacts. To model potential rebound effects, three alternative spending scenarios were modelled for the estimated financial savings from using more circular products. None of these resulted in higher impacts than the current situation, however, the impact of the scenarios was highly variable and almost as high in one case. This highlights a potential rebound effect depending on how savings are spent and the importance of considering (e.g. in policy and research) future levels of disposable income of consumers. The results also suggest that there is a limit to what can be achieved with circularity and that more traditional reductions in energy and improvements in resource efficiency are still required.

For policy makers we note that, in order to accelerate the transition to circular economy, one aspect can be to utilise a societal functions framework to track, monitor and develop targeted policy instruments. We utilized and developed a societal functions framework consisting of: housing and infrastructure; nutrition, mobility, consumables, services, healthcare, and communication. Indicators can be developed to track each societal function and each system level (from product level, to product group and the societal function it provides) so that the impact to deliver each societal function within a country can be tracked and mitigation measures applied. Monitoring of this would allow increased knowledge and remediation action on the possible emergence of rebound effects, such as where a product has increased macro impacts (e.g. through increased consumption) despite product level efficiency improvements (or where one functions impact decreases but leads to an increase in another, e.g. increasing impact of online videos). Similarly, knowledge on the use phase, including statistics on the use and associated impact of repair facilities, spare parts, and second-hand reuse, can be improved.

For researchers we note that more research is needed on how innovation is affected in the circular economy and what its role can be for sustainable circular products. We further note that knowledge is lacking on consumer behaviour in the circular economy, both in terms of how people behave and react towards circular product design (e.g. modularity and upgradability) and circular business models as well as the impact of circular products and business models on consumption levels. Many of these challenges align with similar issues highlighted in research on product service systems for which there are many parallels, but where further research is also required.

Finally, many of the challenges and potential pitfalls of circular products are because they currently need to operate within a linear market and a system that is currently based on cheap fossil fuels, where the cost and impact of raw material extraction is undervalued and underestimated. As we have noted above, the overwhelming evidence is that circular products have enormous potential to reduce impacts, but their fostering requires careful management and monitoring to avoid potential rebound effects.

Sammanfattning

Forskningsprojektet LinCS syftade till att skapa kunskap och förståelse för de miljömässiga och ekonomiska konsekvenserna av cirkulära produkter och cirkulär ekonomi (CE) på mikro- och makronivå. Projektet försökte också överväga och se över potentiella rebound-effekter. Medan cirkulär ekonomi lyfts fram som en lovande lösning för att frikoppla ekonomisk tillväxt från miljöpåverkan, så är empiriska bevis och akademisk forskning om hållbarheten i cirkulär ekonomi och cirkulära affärsmodeller en tidig fas. Därför ställdes följande forskningsfrågor:

1. Vilka faktorer/variabler påverkar miljöprestandan hos cirkulära produkter/cirkulära affärsmodeller?
2. Under vilka omständigheter/förhållanden är cirkulära produkter/cirkulära affärsmodeller miljömässigt och ekonomiskt att föredra jämfört med linjära?
3. Hur kan cirkulära affärsmodeller förbättras för att bli hållbara?
4. Vilka indikatorer är lämpliga för att utvärdera miljöeffekter från cirkulär ekonomi på mikro- och makronivå?
5. Vilka policys behöver införas/ändras som förhindrar/minskar spridningen av ohållbar cirkulär ekonomi och stöder hållbara CE-produkter?

Forskningen inleddes med en omfattande systematisk litteraturgenomgång som kartlade nuvarande kunskapsläge och aktuella kunskapsluckor om miljöpåverkan av cirkulära produkter och cirkulära affärsmodeller. Trots forskarvärldens stora intresse för cirkulär ekonomi identifierades endast 54 artiklar som kvantifierade miljöpåverkan från cirkulära kontra linjära produkter eller system. Många av dessa artiklar fokuserade på miljöpåverkan av återanvändnings- eller återtillverkningsprocesser. Men, de inkluderade inte viktiga aspekter av cirkulär ekonomi som exempelvis produktdesign specifik för den cirkulära ekonomin, eller cirkulära affärsmodeller. Därför finns det ett tydligt behov av mer forskning om miljöpåverkan från cirkulära produkter och system. Baserat på litteraturgenomgången kan flera produktegenskaper som har viktiga roller i avgörandet om en produkt är lämplig för den cirkulära ekonomin identifieras. Dessa egenskaper bidrar till att avgöra om en produkts ökade cirkularitet kommer att leda till att miljöpåverkan minskar jämfört med produktionen av nya produkter. Dessa egenskaper omfattar 1) förlängning av produktens livslängd, 2) tillverkningsfasens bidrag till den totala miljöpåverkan under livscykeln jämfört med andra faser, 3) innovationsfrekvens, 4) försämringseffekter under livscykeln inklusive slitage, 5) användningsintensitet och 6) när produkten anses vara för gammal (obsolet). I synnerhet betonades vitvaror i litteraturen som mindre lämpliga, på grund av deras stora miljöpåverkan i användningsfasen och eftersom det historiskt har funnits en hög grad av energieffektivitetsinnovation inom vitvaror. För andra produktgrupper, till exempel hemelektronik, är resultaten mer tvetydiga eftersom de beror på användningsintensitet och innovationshastigheten.

Med tanke på den tydliga bristen på studier som bedömer de cirkulära produkternas miljöpåverkan, inklusive nyckelaspekterna cirkulär produktdesign och cirkulära affärsmodeller, så genomfördes tio fallstudier som en del av LinCS-projektet. I dessa fallstudier kvantifierades en produkts miljö-, ekonomi- och cirkularitetsprestanda i en linjär och cirkulär affärsmodell. De flesta fallstudierna omfattade cirkulär produktdesign och cirkulära affärsmodeller. Fallstudierna visar att det cirkulära erbjudandet minskade växthusgaspåverkan avsevärt i alla utom ett fall (där hyresaffärsmodellen ledde till ökade utsläpp från transporter för kunden och var starkt beroende av uthyrningsplats). De flesta fall resulterade i en minskning med 50 till 60 procent. Baserat på resultaten drar vi slutsatsen att återanvändningsprocessen eller affärsmodeller som möjliggör livslängdsförlängning vanligtvis är mindre material- och energiintensiva. Vi hävdar vidare att med den förväntade övergången till förnybara energikällor kommer fokus sannolikt att flyttas från utsläpp av växthusgaser till andra miljökonsekvenser. Materialintensiteten kommer att bli mer central, med tillhörande effekter från utvinnings- och gruvprocesser, såväl som påverkan på biologisk mångfald. Som en följd av detta är det troligt att cirkulära produkters överlägsna prestanda kommer att bli ännu tydligare i framtiden.

Vidare visade fallstudierna att lönsamhet är ett problem för vissa tillverkare, men inte alla. I många fall uppskattades kostnaderna för den cirkulära modellen vara lägre än i det linjära fallet, främst på grund av att färre artiklar måste tillverkas för att uppfylla samma efterfrågan, vilket minskar tillverkningskostnaderna avsevärt. Dock är de intäkter som kan genereras i den cirkulära modellen jämfört med den linjära modellen också lägre, vilket innebär att lönsamheten i vissa fall blev lägre. I många fall sattes det pris kunderna betalar för den cirkulära produkten betydligt lägre än den linjära produkten. Mer kunskap behövs för att hjälpa företag att sätta rätt pris som kan göra deras cirkulära erbjudande lönsamt och ekonomiskt attraktivt.

Därefter utfördes makroekonomisk modellering för att bedöma potentiella sekundära effekter och undersöka nyttan för Sverige vid omställningen till en cirkulär ekonomi. MRIO-modellering (Multi-Regional Input Output) användes för att förstå sambandet mellan förändringar på produktnivå och påverkan på makronivå. För att modellera potentiella rebound-effekter modellerades tre alternativa utgiftsscenarier för de uppskattade ekonomiska besparingarna från att använda mer cirkulära produkter. Inga av dessa resulterade i större effekter än den nuvarande situationen, men effekterna av scenarierna var mycket varierande och nästan lika höga i ett fall. Detta belyser en potentiell rebound-effekt beroende på hur besparingar används och vikten av att överväga framtida nivåer av disponibel inkomst för konsumenterna (t.ex. inom politik och forskning). Resultaten tyder också på att det finns en gräns för vad som kan uppnås med cirkularitet och att det fortfarande krävs mer traditionella minskningar av energi och förbättringar av resurseffektiviteten.

För beslutsfattare konstaterar vi att en aspekt kan vara att använda en ram för samhällsfunktioner för att spåra, övervaka och utveckla riktade policy-instrument, för att påskynda övergången till cirkulär ekonomi. Vi använde och utvecklade en samhällsfunktionsram bestående av: bostäder och infrastruktur;

näring, rörlighet, förbrukningsvaror, tjänster, hälso- och sjukvård och kommunikation. Indikatorer kan utvecklas för att spåra varje samhällsfunktion och varje systemnivå (från produktnivå till produktgrupp och den samhällsfunktion den tillhandahåller) så att effekten av att leverera varje samhällsfunktion inom ett land kan spåras och begränsningsåtgärder tillämpas. Övervakning av detta skulle möjliggöra ökad kunskap och åtgärder om den eventuella uppkomsten av rebound-effekter, till exempel när en produkt har ökat makropåverkan (t.ex. genom ökad konsumtion) trots effektivitetsförbättringar på produktnivå (eller där en funktionspåverkan minskar men leder till en ökning av en annan, t.ex. ökande påverkan av onlinevideor). På samma sätt kan kunskapen om användningsfasen, inklusive statistik om användningen och tillhörande effekter av reparationsanläggningar, reservdelar och second-hand-återanvändning förbättras.

För forskare konstaterar vi att det behövs mer forskning om hur innovation påverkas i den cirkulära ekonomin och vilken roll den kan spela för hållbara cirkulära produkter. Vi konstaterar vidare att kunskap saknas om konsumenternas beteende i den cirkulära ekonomin, både när det gäller hur människor beter sig och reagerar på cirkulär produktdesign (t.ex. modularitet och uppgraderbarhet) och cirkulära affärsmodeller samt cirkulära produkters och affärsmodellers inverkan på konsumtionsnivåerna. Många av dessa utmaningar ligger i linje med liknande frågor som lyfts fram i forskning om produkttjänstsystem för vilka det finns många paralleller, men där ytterligare forskning också krävs.

Slutligen beror många av de utmaningar och potentiella fallgroparna med cirkulära produkter på att de för närvarande måste verka på en linjär marknad och ett system som för närvarande bygger på billiga fossila bränslen, där kostnaderna och effekterna av råvaruutvinning är undervärderade och underskattade. Som vi har noterat ovan är det bevisat att cirkulära produkter har en enorm potential att minska effekterna, men deras främjande kräver noggrann hantering och övervakning för att undvika potentiella rebound-effekter.

List of abbreviations

CE	Circular Economy
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LE	Life Extension
LFR	Linear Flow Ratio
MCI	Material Circularity Indicator
MF	Material Footprint
MFA	Material Flow Analysis
MRIO	Multi-Regional Input Output
OEM	Original Equipment Manufacturer
PSS	Product-service system
SF	Societal Functions
TCO	Total Cost of Ownership

1 Introduction

With the growing world population and increased material consumption, the pressure on the environment is far from sustainable. It is hence of utmost importance to reduce our environmental impact. Circular economy (CE) is one concept that suggests that we can reduce the pressure on the environment while still growing our economy by recapturing value still present in a product at its end-of-life and recirculate this product on the market via e.g. reuse, remanufacturing, or recycling. Not surprisingly, it has received a lot of attention in the recent years. 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). The CE action plan presents a set of interrelated initiatives to establish a strong and coherent product policy framework that will make sustainable products, services, and business models the norm and transform consumption patterns so that no waste is produced in the first place. This product policy framework will be progressively rolled out, while key product value chains will be addressed as a matter of priority. Further measures will be put in place to reduce waste and ensure that the EU has a well-functioning internal market for high quality secondary raw materials.

Despite the clear focus of governments on CE, some scholars are questioning the link between CE and environmental impact (for example Agrawal et al. 2016; Geyer et al., 2015; Murray et al., 2017). A recent workshop on the potential effects of promoting CE via policies concluded that CE can have a positive or a negative environmental effect (Lucas et al., 2016). Also at micro level, the environmental impact of circular business models is unclear and the available literature is scant (Bocken et al., 2016). There is an urgent need for more research to establish under which circumstance CE is beneficial for the environment or when it might lead to a higher environmental footprint. The potential issues and unintended negative consequences of CE at micro level (i.e. product or individual firm level), can lead to disappointing (even negative) results at macro level.

Hence, in the LinCS project, the environmental impact of product circularity and circular business models where products are recirculated via e.g. reuse, refurbishment, remanufacturing at micro level was studied with the aim to first understand the conditions needed for a circular model to be sustainable and then to complement this with and understanding of the economic performance of circular business models. In the next step, the macro level impacts of transitioning to a CE were assessed, considering potential secondary effects, such as changes in consumption (i.e. rebound effects).

Given the lack of clear definitions of CE, circular products, and circular business models and the large field of CE, we will first explain the scope of our research and discuss what we mean with terms like circular products and circular business models (given our scope) (Section 1.1). We then discuss the research questions and outline of the report (Section 1.2).

1.1 Circular products and circular business models

CE as a concept, field and megatrend is relatively new but builds on theories from different disciplines, including industrial ecology (Chertow, 2007), environmental economics (Ayres, 1998), closed-loop supply chains (Guide and Van Wassenhove, 2001), and cradle-to-cradle design (McDonough and Braungart, 2002). CE 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 is argued that CE is a bundle of ideas rather than a clear concept (Lazarevic et al., 2016). Nevertheless, it can be argued that the core of CE refers to the recirculation of goods and materials, i.e. closing the loop 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).

In this study, we focus on investigating the impacts of so-called '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 (Sehmen et al., 2019). However, considering this differentiation, for the purpose of this study, we focus on quantifying the environmental impact of so-called circular products and circular business models, those that aim to achieve reuse of the product or its components via direct reuse or remanufacturing.

Extending product life via reuse or remanufacturing might be best achieved if a product design tailored to CE and a business model designed for CE is selected (EMF, 2013a). Many different strategies are suggested and, as mentioned above, these strategies can be seen as a bundle of ideas rather than a clear concept. Circular product design strategies can include design for product durability, design for reuse, refurbish, remanufacture, and recycle, design for disassembly, repair, and assembly (EMF, 2013b; Bakker et al., 2014b; Bocken et al., 2016), design for upgradability and emotional durability (Den Hollander et al., 2017; Bocken et al., 2016). Business models tailored to CE might include aspects of product-service systems (Tukker, 2004), industrial symbioses (Chertow, 2007), leasing, renting, or sharing, among others. This research does not attempt to define 'circular products', 'circular product design' or 'circular business models' as many different definitions are proposed and used in literature, by academics and in industry. However, for clarity, we refer in this report to circular products to indicate products that (compared to their linear counteroffer) have extended product life, are reused, refurbished, or remanufactured. Further, circular product design refers to one or more of the circular product design strategies above, i.e. where changes in product design are made to make it better suitable for extended product life and/or recirculation. Similarly, circular business models refer to business models with aspects tailored to CE, as opposed to the linear sales model.

1.2 Research questions and outline of the report

The research questions as posed in the project application were:

1. What factors/variables impact the environmental performance of circular products/circular business models?
2. Under what circumstances/conditions are circular products/circular business models environmentally and economically preferred compared to linear ones?
3. How can circular business models be improved in order to be sustainable?
4. What are suitable indicators to monitor the environmental effects of CE at the micro and macro level?
5. Which policies need to be introduced/altered that prevent/reduce the proliferation of unsustainable CE and support sustainable CE products?

The next chapter presents the results from the literature review. Previous case studies on the environmental impact of circular products are collected and summarised and learnings in terms of factors/variables that impact the environmental performance of circular products are distilled (answering research question 1). We also summarise learnings from literature regarding how LCAs on circular products should be conducted or considered.

In Chapter 3, we present case studies of circular products and their linear counterpart and assess each case on environmental impact, economic performance including costs for customers, and assess the circularity degree of the two offers quantitatively. The ten case studies give insights into when circular products and circular business models are economically and environmentally preferred (answering research question 2), while also noting improvement potentials (research question 3).

Chapter 4 presents a literature study on circularity indicators and environmental assessment methods at micro, meso, and macro level and models how changes on micro-level might lead to macro-level impacts when impacts such as changes in product use, energy-efficiency, and customer behaviour are included (answering research question 4). The chapter also presents a potential framework for modelling the transition to CE.

Finally, Chapter 5 presents an overview of legislation in Europe and Sweden promoting and affecting CE and provide suggestions from industry for policy changes to accelerate CE in a sustainable way (research question 5). Chapter 6 concludes the project with outlining areas that need further research as well as further policy recommendations.

2 Systematic literature review

This chapter reviews studies that assessed the environmental impact of circular products to collect evidence on how environmentally sustainable circular product and circular business models are and under which circumstances. The chapter highlights factors, distilled from literature, that might impact the environmentally preferred strategy to close the loop and discuss the implications for future Life Cycle Assessments (LCAs) of circular products. The chapter starts by outlining the method used (Section 2.1) before previous research is summarised (Section 2.2). The literature review results are analysed and discussed in Section 2.4 before conclusions are presented in Section 2.5.

2.1 Method: systematic mapping

A systematic mapping with content analysis is conducted. Systematic mapping (Bates et al., 2007; Clapton et al., 2009) is applied to review academic literature and to map current knowledge and evidence on the environmental performance of circular products. Systematic mapping is suitable for developing new theories or understanding of open-ended, policy-based questions such as identifying the barriers to a certain relationship (James et al., 2016). It is particularly relevant to environmental science since it can answer questions like "*what evidence exists concerning...?*" (Haddaway et al., 2016), for example what evidence exists concerning the relationship between CE and environmental impact. It catalogues all available evidence to both describe the state of knowledge and to identify where lack of evidence exists (James et al., 2016). The mapping is combined with a narrative synthesis of the study findings and categorization of the identified variables.

The systematic literature review process and principles as outlined by Tranfield et al. (2003) was followed. The aim of a systematic literature review is to "*map and evaluate the body of literature to identify potential research gaps and highlight the boundary of knowledge*" (Braz et al., 2018). A detailed description of the systematic literature review process applied can be found in van Loon et al. (2021).

# 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

273 papers 93 case studies

Figure 1: Overview of systematic literature review (van Loon et al., 2021)

The findings were first published as a conference paper (van Loon et al., 2019) and discussed with academics at two international conferences focusing on life cycle assessment and sustainable production; the European Roundtable for Sustainable Consumption and Production (ERSCP) in Barcelona, Spain in October 2019 and the Life Cycle Management (LCM) conference in Poznan, Poland in September 2019. The findings were further discussed with (mainly) Swedish industry, including automotive industry, consumer electronics, fashion, fast-moving consumer goods, furniture, white goods, among others. Changes to the text have been made based on their comments and suggestions. The findings are thereafter published as journal paper (van Loon et al., 2021).

2.2 Existing evidence on the environmental impact of circular products

We summarize the papers in three sections; 1) papers that discuss products that exist with a product design and business model that is not modified, i.e. it is made for a linear product (no circular strategy) (Section 2.2.1). This mainly refers to direct reuse and product life extension strategies like repair or remanufacturing where no changes to product design or business models are made, 2) papers that discuss products with a product design intended for circular use such as design for remanufacturing, design for long life, design for disassembly, design for modularity, design for upgradeability, etc. (Section 2.2.2), and 3) papers that discuss products that are offered with a circular business model such as pay-per-use, leasing, servicitized business models etc. (Section 2.2.3). We did not identify any papers that quantified the environmental impact of a product that is both designed for CE and offered with a circular business model.

2.2.1 Environmental impact of recirculated products with linear product design and business model

Large environmental benefits are found when products are assumed to be reused directly without any major work done to the product and no energy is consumed during the use phase. The basic assumption is that the environmental impacts of manufacturing the products remain equal while the use phase is assumed to be twice as long. For example, Low et al. (2016) calculated the environmental impact of reusing flat panel display monitors. Since the use phase is excluded, the authors concluded that reuse led to less resources and material used in the production process, resulting to environmental benefits. Woolridge et al. (2006) assessed the benefits of cotton and polyester clothing reuse by calculating the energy use of salvation army operations in the UK. The authors concluded that the total energy use of collecting, sorting, baling, selling and distributing used clothing is a fraction (2.6 % for cotton and 1.8 % for polyester) of that of the energy required to manufacture them from primary materials.

While many non-energy consuming products are used significantly shorter than their technical lifespan and the environmental benefit of using these products longer are considerable, other products have characteristics that make it more difficult to determine the best strategy. Several studies explored the optimal age to replace energy-consuming products. Kim et al. (2003) presented a life cycle optimization study of mid-sized (ICE) vehicles of year models 1985–2020 (assuming continued emissions standards in the US) and concludes that the optimum lifetime varied from 2–18 years depending on yearly mileage (6, 12, 24k miles) and category (energy, CO2, CO, NMHC, NOx). This illustrates the importance of assumptions and impact categories used and notes the possible drawbacks of increasing fuel efficiency with lighter but more environmentally burdened materials. In a similar study, Kim et al. (2006) suggested an optimal lifetime of 2–18 years for refrigerators for Energy, GWP, and cost categories and again illustrated the importance of energy efficiency improvement and function deterioration (reduced efficiency over time) assumptions. De Kleine et al. (2011) presented a life cycle optimization study of residential air conditioning equipment and concluded that while replacement was justified for GHG and energy use at intervals of 3–8 years, the service quality and frequency determining operating efficiency degradation were especially important to the energy performance and the resulting optimal lifetime. Bakker et al. (2014) determined the optimal usage duration of a product (refrigerator and laptop) by calculating the environmental impact, assuming that the product is replaced once during its lifespan by a more energy efficient one. The authors concluded that the optimal lifetime for today's refrigerators and laptops are significantly longer than their average lifetimes. Perez-Belis et al. (2017) looked at the replacement of products with a more energy efficient product with or without the need for repair. The authors concluded that the optimal replace/repair/upgrade strategy depended on the consumer behaviour which made it impossible to define an optimal strategy for all situations. Manufacturing, use phase, and waste disposal stages are included in a LCA study on refrigerators, TVs, and air conditioners (Tasaki et al., 2013). The authors concluded that lifetime extension is mainly beneficial for products that have a relatively high environmental impact in the manufacturing and disposal stage compared to the environmental impact in the use phase. Other factors that impact the optimal lifespan from an environmental point of view were the energy improvement in new models and consumer behaviour (i.e. use intensity of the product) (Tasaki et al., 2013). On the other hand, Bobba et al. (2016) performed a LCA on vacuum cleaners and showed that extending the product life of vacuum cleaners will almost always lead to environmental benefits, unless the new replacement vacuum cleaner is 25 % more energy efficient.

Iraldo et al. (2017) presented results from LCC and LCA on three types of energi-intensive equipment; refrigerators, freezers, electric ovens. They identified a number of studies that assessed the environmental and economic value of durability and asked *is durability a good thing for energy-intensive products?* When considering energy-consuming products, the savings in material and production by extending the product life should be weighed against the use of an older and in many cases less energy-efficient product than when acquiring a new efficient product earlier. The authors assume that in case of a standard (i.e. non-extended product lifespan) product, a new more energy-efficient model is purchased and used for the remaining time period whereby the environmental impacts are proportionally allocated to the time period. Iraldo et al. (2017) showed that the durable products mainly saved on environmental impact categories that had a large impact from the manufacturing phase, including human toxicity, freshwater ecotoxicity, and mineral, fossil and renewable resource depletion. On the other hand, environmental impact categories that depended on the energy consumption during the use phase showed a worse environmental impact for extended product life, for example climate change, even if only a minor energy efficiency improvement was reached. The authors concluded that small efficiency improvements (5–20 %) are enough to justify replacement environmentally. Economically, much larger efficiency improvements were required due to the purchase price representing a large part of the total life cycle costs.

Iraldo et al (2017) and Ardente and Mathieux (2014) concluded that the most environmentally friendly strategy depended mainly on:

1) the lifetime of the products,
2) energy consumption of the product,
3) impacts due to lifetime extension (i.e. from adding material and resources during repair and remanufacturing), and
4) efficiency of the replacement product.

For example, product life extension of cell phones seemed beneficial from an environmental point of view since a large share of the impacts were generated in the manufacturing stage that can be reduced if products are used longer, while on the other hand, washing machines can be better replaced on time due to the increased energy efficiency in the new product (Kwak, 2016). Similarly, Intelkofer et al. (2010) assessed life cycle energy use and a number of replacement scenarios for computers and household appliances and recommended longer lives (than the normal 4 years) for computers (manufacturing is large part of total), but on the other hand shorter lives for washers and dishwashers (with a relative high share in the use phase). Gutowski et al. (2011) assessed the energy savings reached through remanufacturing of 25 different product types. Resulting energy savings from remanufacturing (assuming it allows an equally long second life) showed 8 cases where energy was saved, 6 that did not, and 11 cases that were too close to call. The authors concluded that remanufacturing generally resulted in life cycle energy savings for products that do not require energy during use (or require very little energy). However, remanufacturing generally did not result in energy savings for products that have a large energy requirement in the use phase or for which energy efficiency is increasing significantly for newer generations. When the use phase was included in the environmental assessment because of energy efficiency improvements or product deterioration over time (Figure 2), the environmental benefit of remanufacturing became less positive.

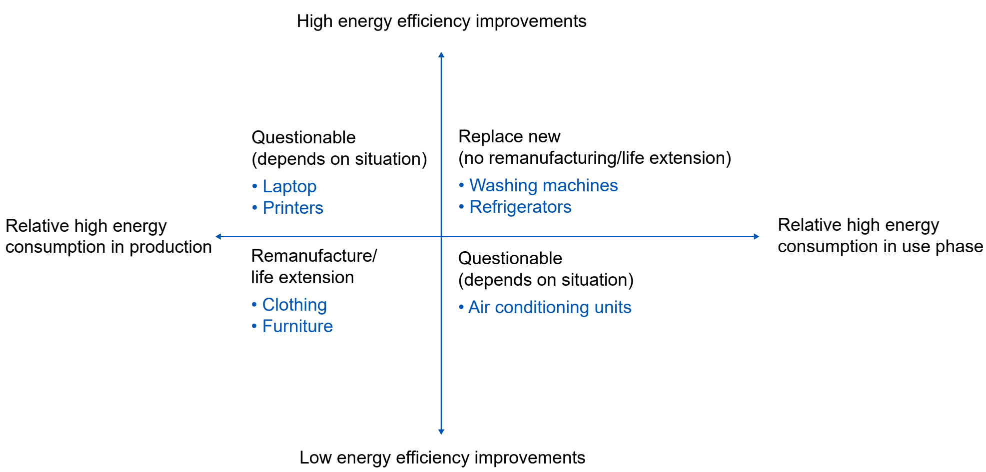

Figure 2: Environmental optimal strategies for repair/remanufacturing versus buying new for different product categories (based on Downes et al., 2011; Cooper and Gutowski, 2015).

Considering the deterioration of products over time, the optimal lifespan from an environmental point of view can even become shorter (Kim et al., 2006). Deterioration of energy-consuming products is not often included in LCA studies. One exception is Kim et al. (2006) who studied optimal lifespans for refrigerators. Based on the limited knowledge on deterioration, they assumed that the energy consumption of refrigerators will be 20 to 24 % higher after 20 years of use. The authors concluded that deterioration had a significant impact on the optimal lifetime. It depended, however, on the type of product, if deterioration should be included in the environmental assessment.

Declining lifespans for some consumer electronic products are alarming, especially since the energy efficiency gains of some of these products have made the production phase represent a bigger swath of the product's burden (Bakker et al., 2014). These products can be environmentally viable for even longer time periods in renewable energy economies. As an example, Bakker et al. (2014) concluded that the optimal lifetime for refrigerators and laptops in regards to environmental impacts should be 20 and 7 years compared to the current 14 and 4 year lifetimes (in the Netherlands), respectively. These optimal lifetimes would be invariably even longer if the electricity mix was more renewable (no mix indicated in the study). What if the electricity mix is (assumed to be) renewable? Surprisingly, while Iraldo et al. (2017) noted electricity mix being an important parameter, no electricity mix was explicitly stated (electricity was 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). In fact, most studies did not mention any impact from changing to more renewable energy sources despite renewable energy being advocated as part of CE (EMF, 2013a). We argue, in line with Haupt and Zschokke (2017) that it is important to consider larger (societal/macro) changes towards CE when modelling the environmental impact of circular products on micro level, including the shift to more environmentally friendly energy mixes. Only then can it be determined whether CE should be enforced (on longer term) or not.

A few more studies look at the effects of remanufacturing. In general, it is argued that remanufacturing yields benefits in terms of resource efficiency compared to manufacturing new products (Allwood et al., 2011; Sundin, 2004; Ijomah et al., 2007). Several LCAs and other environmental assessment studies quantified the environmental impact of remanufacturing. Van Loon and Van Wassenhove (2018) assessed the CO_2 emissions of remanufacturing chassis products, assuming that a remanufactured product replaced a new product, and found a positive impact on the environment. Benton et al. (2017) studied a diesel generator set and Gao et al. (2017) a turbocharger. Both concluded that remanufacturing recoverd most of the embodied energy and therefore led to significant environmental benefits. Similarly, Afrinaldi et al. (2017) and Liu et al. (2016) calculated a significant lower energy consumption when remanufacturing a cylinder block due to the reuse of materials in the remanufacturing process compared to using raw materials in the production process of new engines. Smith and Keoleain (2004) assessed remanufactured engines and although their LCA of the production process was more detailed, they too ignored the use and disposal phase. Hence, large environmental savings were observed when remanufacturing. Kwak and Kim (2016) showed that remanufacturing alternators could save between 70 and 35 % (depending on the yield rate) of the GHG emissions associated with new production. Finally, Warsen et al. (2011) quantified the life cycle impacts of new versus remanufactured manual auto transmissions and noted 30–45 % reductions for all categories (including AP, EP, GWP etc).

Remanufacturing a complete vehicle was assessed by Latham (2016) who found large environmental benefits when comparing the environmental impacts of the remanufacturing process with the manufacturing process, but when emissions were included during the use phase, remanufacturing led to higher impacts than for new vehicles. The authors argued that this will change in the future because old engines with low emissions standards will be phased out, making remanufacturing obvious from an environmental point of view.

The impact of remanufacturing on the overall demand and consumption of products was included in some environmental assessments published in operations research journals. In these studies, the assumption was made that the environmental impact of remanufacturing a unit of product was less than producing a new unit (e.g. Esenduran et al., 2016; Shi et al., 2016). However, due to the higher demand, the absolute environmental performance of a system with and without remanufacturing was less clear. Remanufacturing items with a relatively high environmental impact during the use phase, like electronics, led to higher environmental impacts, due to the higher supply/demand (Esenduran et al., 2016; Liu et al., 2017). Remanufacturing drives down the prices of the product, which increases sales (Raz et al., 2017). Both the remanufactured products as well as the new products are affected by this. The optimal price of the new product becomes lower due to remanufacturing increasing both demand for remanufactured products and new products (negative cannibalization). This leads to an overall higher energy consumption, since the impact of increased consumption was higher than the savings from substituting some new products with remanufactured products (Raz et al., 2017; Xiong et al. 2016). However, Shi et al. (2016) argued that the emissions per revenue generated is a better proxy for environmental impact and showed that remanufacturing then scored better than manufacturing only new items.

2.2.2 Environmental impact of recirculated products with circular product design

Few studies explored the environmental impact of products designed for CE, through design strategies such as design for durability, design for repair, design for remanufacturing, etc. What can be considered as optimal design strategy in terms of energy use depends on product characteristics. If the energy efficiency improvement is negligible, designers should focus on durability of the product, while designers should focus on modularity and upgradeability if large energy efficiency improvements are expected (Cooper and Gutowski, 2015). The possibility to upgrade products during use might improve the energy efficiency of products on the market and therefore be the optimal product replacement strategy. Aziz et al. (2016) proposed the development of an upgrade plan early in the design process to determine what upgrades are needed and when they are needed during the use phase. Via several scenarios that map potential upgrade paths a design can be created that allow such future upgrades. This plan can also be used to calculate the potential environmental impacts of each of these scenarios in order to determine the likely environmental impact of an upgradeable product in an early phase.

Kerr and Ryan (2001) calculated the environmental benefit of remanufacturing photocopiers compared to manufacturing new ones. They find that modular copy machines can save more environmental impact than non-modular ones. Kwak and Kim (2016) assessed the environmental impact of remanufacturing desktop PCs whereby the assumption was made that some parts will need to be replaced during remanufacturing due to changing customer preferences. The authors showed that remanufacturing indeed required significantly less GHG emissions than manufacturing new desktop PCs, but this advantage could be completely offset by the impacts from the use phase if large energy-efficiency improvements have been made since the old model came on the market. Considering the energy-efficiency improvements over time and the average lifespan of desktop PCs, the remanufacturing of desktop PCs is likely not beneficial. However, in theory product design can be optimized for remanufacturing and more research towards the impact of product design on the value of remanufacturing in terms of environmental impact is still needed (Kwak and Kim, 2016).

Krystofik et al. (2017) assessed office furniture. Since the use phase does not consume energy and a substantial part of the material can be saved during remanufacturing, the authors found that remanufacturing led to environmental benefits. Furniture is susceptible to changes in fashion, making the product outdated if not upgraded in the remanufacturing process. With design for upgradability, the product could be upgraded to meet current demand and hence resulting in a longer lifespan, reducing environmental impact per use. Kaddoura et al. (2019) quantified the environmental impact of a door handle of a waste inlet. The authors showed that by redesigning the door handle to make it repairable, the lifespan of the door handle can be prolonged, hence resulting in lower environmental impacts.

These studies showed insight into the role of circular product design on the life cycle environmental impact of products, but more research is needed to understand which circular product design strategy will have a positive impact and in which circumstances. Some circular design strategies might have negative consequences, for example design for durability might result in the selection of more robust materials and components and hence leading to larger impacts in the production phase. It is argued that this additional impact is usually overcome by the longer duration of use (Downes et al., 2011), but evidence is lacking, and more research is needed.

2.2.3 Environmental impact of circular business models

A handful of studies assessed the environmental performance of servicized or product-service systems (PSS) as compared to traditional sales business models. Tornese et al. (2018) assessed the environmental impacts of pallets that are shared in a pooling system compared to using pallets one time. The authors found that the impacts of repair were very minor compared to manufacturing new pallets, but the overall impact depended on the handling and loading conditions of the pallets as well as transportation distances in the pooling system. A comparable study by Tua et al. (2019) calculated the impacts of a pooling system for reusable plastic crates for the transportation of fruit and vegetables. The authors found that the crates will have to be used at least three times to result in lower environmental impacts than single-use crates.

Bech et al. (2019) discussed the environmental impacts of a PSS system of army T-shirts. PSS resulted in longer use of the t-shirts through repurposing and together with washing less and at lower temperature, the GHG emissions were significantly reduced. Kaddoura et al. (2019) assessed a business model where the manufacturer retained ownership over the beach flags and event tents and refurbished and reused them several times versus a sales business model where the items were only used once. Hoffmann et al. (2020) discussed the environmental impacts of a pay-per-use system for cloth diapers and compared them with disposable diapers. Lindahl et al. (2014) assessed the environmental impact of three PSS systems. First, core plugs for paper mills in which the authors found that PSS increased the number of times such items were reused and hence reduces the environmental impact. Second, the authors compared exterior building cleaning methods and argued that service reduces the cleaning time and again hence reduces the environmental impact. Third, the authors discussed durable soil compactors manufactured and maintained in a PSS which also resulted in lower environmental impact than a comparable linear business model with shorter lifespans. However, from the paper it was unclear what the contribution of new technologies versus PSS offers was regarding changes in the usage behavior of the product.

Business models where the ownership of the product remained with the company in combination with a pay-per-use pricing structure were classified as a servicizing business model by Agrawal and Bellos (2016). It is argued that such a business model would encourage the Original Equipment Manufacturer (OEM) to reduce their production volume and hence contribute to resource efficiency. Because customers pay depending on the usage of the product, this might discourage the use of the product. On the other hand, people that use products infrequently might be earlier inclined to use the product if they do not have to buy the product (Agrawal and Bellos, 2016). Similarly, sharing of products as a circular business model, provided access to under-utilized products and intensified therefore the use of products (Frenken, 2018). One of the biggest advantages of the sharing economy might be that the number of products in the economy, and hence space required, can be reduced without reducing welfare. There are few papers available that assessed the environmental impact of sharing/sharing economy and there is almost no empirical data available to assess the environmental impact. The rebound effect and additional environmental impacts from transportation and checking/cleaning/repairing the products need to be included in any environmental assessment of sharing models (Frenken, 2018). Also, changes in customer behaviour (also called rebound effects) need to be included in environmental assessments to capture the full environmental effects of shifting to circular business model (Dal Lago et al., 2017). For example, instead of comparing a kilometre travelled with the car with a kilometre travelled by train, it would be better to calculate the environmental impact of the "average transport behaviour during one year" (Goedkoop et al., 1999 in Kjaer et al., 2016). The new offer might substitute other products than the initial product and finding data on this substitution/ rebound effect is challenging in the early design phase (Kjaer et al., 2016).

2.3 Key factors environmental impact of circular products

Based on the environmental assessments of circular products identified and summarized above, several product characteristics are identified that seem to have a determining role in whether a product will be suitable for CE, meaning that recirculating such product will likely reduce the greenhouse gas emissions (assuming the current electricity mix, see also the discussion in Section 2.4.4.) compared to producing only new products.

A first prerequisite for circular products is the possibility to extend product life. If products could be used longer than they are today, either directly or via a refurbishment or remanufacturing step, the impacts of material extraction and manufacturing could be spread over a longer period/higher utility. Especially impacts from products that have a long remaining lifetime when disposed by the first user can be reduced if subsequent uses are possible. However, the environmental benefit of using products longer depends on more factors. Products that have a high share of their total environmental impact in the manufacturing stages will benefit more from product life extension. On the other hand, products with a high share of the impacts from the use phase, will increase the environmental impacts and hence reduce or diminish the environmental benefit of product life extension if the product life is extended, that is, if new products exhibit better use-phase energy-efficiency. If during this lifetime extension, additional maintenance and repair (or any other form of work to keep the product functioning and in use) is needed, the benefits of extending product life might be reduced/diminished by the environmental impacts of these maintenance activities.

Products might deteriorate over time, resulting in higher energy or resource consumption over time compared to when the product came on the market. If deterioration is large, it might be better to replace the product rather than keep using the product inefficiently. If new products become more energy efficient, it might also be better to replace the product rather than extending the use. Closely related to this is the use intensity. Heavily used energy-consuming products have a relatively larger share of the environmental impacts in the use phase. If products deteriorate over time or more energy-efficient products are available, it might be better for a frequent user to switch to a newer model while low-intensity users better remain with the current product.

When a product is replaced is for a large part determined by customer choices regarding when to dispose the product. Such a choice might have aesthetic, economic, functional, technical, or social reasons (Burns, 2010; van Loon et al., 2017). When a customer perceives products as obsolete, the products may be discarded and hence has an impact on the environmental footprint of the product. Products in an innovative market are often discarded far before their technical lifespan is reached and hence efforts to extend the technical lifespan are meaningless if products are not used that long.

The studies reviewed indicate that some product categories might be more suitable for CE than others, with especially white goods being less suitable (Table 1). White goods have a large share of their environmental impact in the use phase. In combination with a high degree of innovation related to energy consumption of white goods, replacement led to lower environmental impacts than reuse and remanufacturing. For other groups of products, like consumer electronics, the best strategy to reduce environmental impact depends on their use intensity and speed of innovation and can be either replacement or product life extension depending on the circumstances. The impact of innovation in CE on environmental impact needs to be explored further.

Table 1: Overview of case products and papers in each category (van Loon et al., 2021).

	Traditional product with traditional sales model assessed			**Circular product with traditional sales model assessed**			**Traditional product with circular business model assessed**		
CE perspective	**Leads to lower environmental impact**	**Higher or lower, depends on conditions**	**Leads to higher environmental impact**	**Leads to lower environ-mental impact**	**Higher or lower, depends on conditions**	**Leads to higher environ-mental impact**	**Leads to lower environ-mental impact**	**Higher or lower, depends on condi-tions**	**Leads to higher environ-mental 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] Tue 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).

Product design influences the lifetime of the product, maintenance needs, repair activities, energy and resource consumption during use, as well as possibilities for recirculation. Product design can enable upgrades that in turn can keep the product longer relevant and hence mitigate obsolescence (Cooper, 2010). Product design can further enable the possibility to incorporate innovations in energy-efficiency through replacing energy-consuming parts of old products on the market with design for modularity and upgradability. However, the environmental implications of design for modularity and upgradability need further research, especially to the impact of these design strategies on customer demand. Many uncertainties also exist around the impact of circular business models on the overall environmental impact. Circular business models change user behaviour in unforeseen ways. For example, how long products are used and level of intensity might depend on if the product is purchased, leased, or used on a pay-per-use basis. Not much knowledge exists on how products are used. Hence, more research is needed to understand usage behaviour in order to collect relevant data needed to conduct quantitative environmental assessment of circular business models and circular products.

2.4 What does this mean for future LCAs on circular products?

Even though there are various environmental impact assessment methods, LCA is considered the leading tool to assess environmental impacts of circular products (Haupt and Zschokke, 2017). When applying LCA to circular products, a couple of potential issues occur, not least because both LCA and CE concepts are still developing (den Uijl, 2016). The lack of clear definitions and methodologies currently makes it difficult to conduct an LCA on circular products. Without guidelines, many decisions need to be taken by the LCA practitioners, leaving room for interpretation differences. This has led to criticism on unclear goal and scopes, incomplete functional units, and scenarios that cut-off potentially relevant life cycle phases or apply burden to the first manufacturing (Peters, 2016).

2.4.1 Including the full lifecycle

Many LCA studies take a relative narrow look on the environmental impact of new products and the impacts of remanufactured products, whereby the impacts stemming from material extraction and manufacturing are completely assigned to the first use (Figure 3). Note that in many cases (especially for non-consuming products) distribution and use are assumed to be equal and are therefore eliminated from the LCA study.

Figure 3: Assignment of environmental impact to new and remanufactured products in LCA studies.

Just looking at the steps preceding the remanufactured product ignores the fact that a new product is needed in the first place to be able to remanufacture. Even if multiple lifecycles are possible, a new product will always be needed to start the circle, unless we assume infinitive loops which are highly unrealistic in practice. One way to overcome this issue is to look at the whole process (i.e. the whole of Figure 3) when studying the impact of circular business models. An example of an LCA study taking this perspective is provided by Guvendik (2014). Under supervision of Guinée, he applied LCA to assess circular product designs of a smartphone. Assuming that a circular smartphone would be used twice as long as the current smartphone with a refurbishment step halfway and where end-of-use phones will be used to harvest still functioning parts to be used in the production of new phones, they applied a replacement chain method to calculate the environmental impact of using the phones over a period of six years. First, an estimation was made on the duration of use of the various components and parts and consequently how many components could be used in six years. Second, an estimation of the reusability of the components at their end-of-use is made. The reuse of components would mean that less components need to be produced as 'new' phones are assembled from a combination of new and reused parts. Third, the environmental impact is calculated of all components linked to the usage of the phone for 6 years.

The inclusion of impacts from non-reusable products is important for a fair and realistic LCA. If products are transported after use to a collection and sorting centre for potential reuse, the environmental impact of transporting should be included for both the products that are reusable as well as products that are deemed non-reusable and are discarded in the sorting process. However, this requires additional data which can be challenging to collect, especially in early phases.

2.4.2 Changes in customer behaviour and consumption (rebound effects)

Although rebound effects are mentioned in a few papers, rebound effects are not yet addressed nor incorporated in environmental assessments. This while it is acknowledged that rebound effects will lead to a higher use of materials, more consumption, even if CE is widely implemented (Korhonen et al., 2018). The mere availability of lower-priced reused and remanufactured products means that consumers can afford to buy and consumer more (Zink and Geyer, 2017). It is therefore important to understand in how far the presence of reused and remanufactured products replaces the manufacturing of new products. Looking at literature, some suggestions are made on how to include rebound effects in environmental assessments. One way is to parameterize buying habits and assess the degree in which used products replace new products based on economics (Thomas, 2011). Farrant et al. (2010) suggested distinguishing between different groups of consumers. The authors assumed, based on a survey, that persons shopping regularly at second-hand markets actually do buy less new products while persons shopping only occasionally at second-hand markets are only marginally reducing the consumption/purchasing of new products per purchase. However, as discussed above, the mere availability of cheaper used products increases consumption. Further, the presence of second-hand markets and knowing that a good price can be asked for the product after use, increases the willingness to buy it in the first place as it reduces the moral burden. The same could be said for services. For example, if transportation services (such as Mobility-as-a-Service) are more accessible (cost and location wise), one would be more likely to utilize more transport, increasing consumption of transport service.

It is currently difficult to know in how far the acquisition of a remanufactured or other recirculated item replaces a new item. Several customer segments exist, some of which see a remanufactured item and new items as perfect substitutions, while others will never buy a remanufactured product and always opt for the new product. Research to the various customer segments and their sizes is in its infancy (Abbey et al., 2015). In addition, the sales of new products might be affected by introducing remanufactured products, leading to higher overall sales and therefore environmental impacts for the firm (Ovchinnikov et al., 2013). Hence, there is a need to study consumption changes in order to understand how it affects the *absolute* system wide environmental impact of transitioning towards CE.

2.4.3 Relevant environmental impact categories within CE

While the study attempts to collect knowledge on environmental impact, most conclusions are based on greenhouse gas emissions due to limitations in the collected studies. The change to circular products also has an effect 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 e.g. the study on tools sharing Martin et al. 2020). Therefore, knowledge on different environmental impact categories needs to be extended and combined.

What environmental impact categories should be used to assess products in a CE? The metrics are to be chosen dependent on the goal and scope of the study or LCA (Jeswani et al. 2016). Here, we discuss not one LCA and one goal and scope but LCA practice for circular processes, begging a more general approach. A CE demands reduced material throughput leading to less environmental impact. A general suggestion is to use many categories as to decrease the tendency to miss something significant (Ardente and Mathieux, 2014). Most of the studies cited in previous sections addressed only a few categories, with Global Warming Potential (GWP) being the most-widely used output-based aggregate and energy use being the most widely used input-based indicator. Other commonly used categories include Acidification, Eutrophication, Photochemical Oxidant Creation Potential (POCP), Ozone Depletion Potential (ODP) and Human and Terrestrial Eco-toxicity as well as other indicators material use, and waste. Notably, the environmental impacts most often measured, GWP and energy use, as well as Acidification and POCP are focus areas due to their prevalence in the fossil-based economy. In CE, these same impacts should be less prevalent and perhaps not nearly as important. Energy use can be especially misleading. Like other raw measures, it is not a measure of environmental impact per sé as the process of energy production results in a great variation of amounts and types of environmental impact. Using energy use to compare products or product systems, especially if those products may occur in different places or times, may provide misleading indication of the relative environmental impact of the products.

2.4.4 Impact of larger societal/macro changes towards CE

The environmental profile of a product will change over time. Are we interested in the environmental impacts of products now, or those that occur in CE or both? While it may be counter-intuitive to disregard impacts that occur now in today's economy, it may be relevant to consider impacts in another time, i.e. in (future) CE. For example, a circular and remanufacturable washing machine is not necessary a wanted product environmentally with today's electricity mix but may be in a CE. This highlights a challenge and possible limitation of LCA for assessing products for CE which as a vision, suggests and requires a global spatial perspective and a long, if not unknown temporal perspective.

Many studies report the environmental impact of circular products assuming the current existing electricity mix. While this is not wrong, it ignores the transition towards a more decarbonized electricity mix. In other words, our knowledge about the environmental impact of circular products in the longer term is limited. The question if product life extension is the way forward and under which circumstances in CE is not yet answered. It has been suggested that larger societal/macro changes towards CE are important when modelling the environmental impact of circular products on micro level, including the shift to electricity production with lower carbon intensity (Haupt and Zschokke, 2017; Richter et al., 2019). Future research should therefore consider CE transition aspects in order to provide a complete and coherent picture of the environmental impact of circular products compared to linear products.

2.5 Conclusion

This chapter mapped and synthesized the available knowledge on the environmental impact of circular products and circular business models. Large deficits in the existing evidence were shown and discussed. The review showed that the remanufacturing process itself, compared to the manufacturing process, normally results in reduced environmental impact. However, the environmental impact of the remanufacturing versus manufacturing process is only one piece to the puzzle, and more knowledge is needed to answer the question whether CE will improve resource-efficiency and decouple economic growth from environmental degradation. The review showed that broader life cycle impacts, energy-efficiency improvements and degradation, and rebound effects deserve more attention in academic literature.

The review also clearly indicated a clear lack of studies on the environmental impact of circular products including circular product design and/or circular business models. Given that these are central concepts within CE, the lack of studies is shocking. It is widely argued that circular product design strategies such as design for durability, repairability, upgradability, modularity, etc. contribute positively towards CE, however the effect of circular product design on aspects such as consumer behaviour and consequent environmental impact is poorly researched. Also the impact of circular business models on consumption behaviour is not yet included in the environmental assessments. Many studies assume a static world where the transition towards circular products and circular business models has no impact on consumption. Hence, we see an urgent need for a better understanding of the environmental impact of circular products and consequently we call for future LCAs to study the role of circular product design, circular business models, energy-efficiency improvements and degradation, innovation, and consumption changes.

3 Micro-level modelling

In this chapter, the sustainability of circular products and circular business models at micro-level are explored. Through a selection of a wide variety of case products, and the careful assessment of the environmental and economic performance of each of the circular versus linear counter products, insights are created on the relationship between circular products and sustainability. The goal is to understand the conditions (and boundaries) under which circular products are sustainable or fundamentally more sustainable than their linear counterparts.

In line with our scope (Chapter 1) and the literature study (Chapter 2), we focus on products that are recirculated through one of the tighter loops, with direct reuse, product life extension, refurbishment, or remanufacturing. In many cases, these products will be recycled at the end-of-life. Recycling is therefore included in the analysis even though it was not the main focus.

The methods used in the micro-level assessment are described (Section 3.1.) and the case studies are presented (Section 3.2). In each case study, the product is introduced, the linear business model/product and the circular counteroffer are described. The two offers are then compared on economic impact, circularity degree, and environmental impact. The learnings from the case studies are summarised (Section 3.3).

3.1 Methods

As mentioned in the previous chapter, LCA can be considered as leading tool to assess the environmental impact of circular products (Haupt and Zschokke, 2017). Because the correlation between environmental impact and circularity measurements is not yet thoroughly established (see also our discussion in Chapter 4), we argue, in line with Niero and Kalbar (2019) that circularity and environmental indicators should be used complementary to each other and ideally be coupled for decision making. Hence, we use LCA to study the environmental impact, a circularity metric to study how circular a certain product is, and Life Cycle Costing (LCC) for studying the economic performance. The methods applied are explained below.

3.1.1 Circularity metric

Multiple circularity metrics have been developed in the last years with different purposes in mind. Some on macro level, measuring CE progress on city or national level (e.g. Gravagnuolo et al., 2019; Mayer et al., 2019), while others focus on industrial symbiosis (e.g. de Abreu Ferreira et al., 2019). We refer to Section 4.2.1. for an overview of existing circularity indicators or to one of the recent reviews on circularity indicators for a complete overview (Saidani et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019). Here, we discuss the required specifications of a circularity metric for use in this study and then present the selected metric.

METRIC REQUIRED SPECIFICATIONS

There seems to be increasing consensus that a product-level circularity metric should capture the recirculation of products, components, and materials, i.e. all end-of-life options to close the loop (Saidani et al., 2017; Franklin-Johnson et al., 2016; Moraga et al., 2019; Linder et al., 2017), preferably in a single metric (Cayzer et al., 2017). Recirculation is arguably the core of CE (Saidani et al., 2017; Zink and Geyer, 2017). Through circulation, value is captured that otherwise is lost in the so-called linear economy (EMF, 2013a). The metric should therefore capture additional value generated through recirculation.

Besides recirculation, product life extension is another key concept within CE to increase the useful life of a product and thereby preserve the product value over a long time period (Linton and Jayaraman, 2005). Design for extended use / design for longevity / durability is a frequently mentioned design strategy for products within CE (Bakker et al., 2014; Cooper, 2005; Selvefors et al., 2019; van Nes and Cramer, 2006). In addition to keeping the product functioning, the product must remain relevant to retain its value (Box, 1983). To keep the product functioning and useful, it should be possible to update products to compete with new products on the market. For instance, the introduction of a new phone model might make the old one obsolete. Emotional durability that increases attachment to a product is therefore seen as part of the design strategies for CE (Bocken et al., 2016). Den Hollander et al. (2017) argue that "*prolonging and extending useful lifetime by preserving embedded economic value is the most effective way to preserve resources*". CE's goal is to *"keep products, components, and materials at their highest utility and value at all times"* (Bocken et al., 2017). A circularity metric should capture the value of long useful lifetimes (Elia et al., 2017). Because obsolescence, wear and tear and down cycling are seemingly unavoidable at our current level of technology, we expect few, if any at all current products to achieve 100 % circularity. Hence, products should be designed for recycling to make good use of the resources embedded in the product after use (den Hollander et al., 2017; Bakker et al., 2014).

Stahel (2006) suggested measuring sustainable economic productivity as the "*economic value achieved per unit of resource consumed"*. He argued that for consumers, the economic value can be based on the sales prices at the point of sales. He further argued that services led to more intense or longer use of the product and hence to a higher economic value. Unfortunately, no guidance is provided on how to calculate the value of services. The economic value is divided by the weight of the newly added parts and materials when considering the value-per-weight ratio for remanufacturing, implying that only virgin material should be included in the denominator. This should not only include virgin material used in the production process, but also additional resources used during recovery and/or repair activities (Walker et al., 2018).

THE METRIC

We have chosen to follow Stahel's suggestion to measure sustainable economic productivity as the "*economic value achieved per unit of resource consumed*". Stahel argued that the economic value can be based on the sales prices at the point of sales and that services lead to more intense or longer use of the product and hence to a higher economic value. The economic value is then divided by the weight of the newly added parts and materials when considering the value-per-weight ratio for remanufacturing, implying that only virgin material should be included in the denominator.

We call the circularity metric Linear Flow Ratio (LFR)

$$LFR = \frac{economic\ value\ over\ lifetime\ product}{virgin\ material\ input\ over\ lifetime\ product}$$

The LFR is based on the concept of an ideal circular product, i.e. a fictional product that indefinitely maintains its value without any virgin material. It captures the total generated value per virgin material input. To illustrate the LFR, we plot the product price function, $v(t)$, of a hypothetical time dependent product (Figure 4). Obviously, many different possibilities exist but for illustration purposes we assume a product that is remanufactured twice before being recycled. An initial product price, v_0, is assumed and plot the value in exchange on a horizontal time axis, t. As argued above, the product will lose its economic utility over time. This loss is depicted as the slope of a linear value function, $v'(t) = \frac{\Delta v}{\Delta t}$. Actors can reduce the slope of $v(t)$ by various activities, e.g. repairs, remanufacturing, maintenance and upgrades. These activities increase product prices at different times t_1 and t_2. Ultimately, the product reaches its end-of-life at time t_3 and the product is sold for its end-of-life (often scrap) value, v_S. If a product maintains a high value during its lifespan, over time, it provides a greater total surplus. To calculate the LFR, the product price function, $v(t)$, is integrated; i.e. $\int_0^t v(t)dt$.

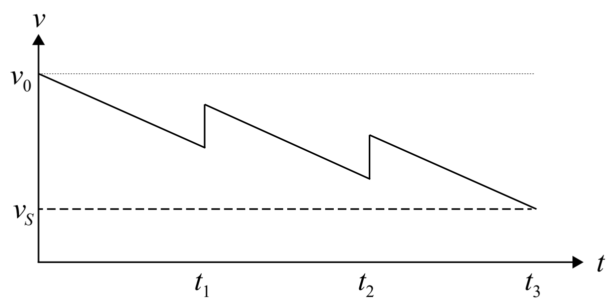

Figure 4: Plot of the Linear Flow Ratio

The materials, or components, needed to produce a product or to keep the product functioning during its lifespan can be sourced from virgin or reused material or a combination of the two. Since the use of virgin material should be prevented, through circulation of products, components, and materials, the total generated value per virgin material input is considered. The LFR calculates how much value in exchange will be provided per one unit of linear material costs ($C_{virgin\ material}$). This is expressed as:

$$Linear\ Flow\ Replacement = \frac{\int_0^t v(t)dt}{\sum_0^t C_{virgin\ material}}$$

In the case of service-based business models, there is no initial sales price to base the calculation on. Instead, we use the concept of total revenues as a starting point (i.e. leasing fees x leasing durations or renting fee). This amount is then linearly depreciated, like the case described above.

For the metric, economic value serves essentially as a proxy for resource scarcity and environmental impact. Compared to other mass-based measures, it opens the possibility to distinguish between different forms of product life extension and recovery (giving more credits for refurbishment compared to remanufacturing or recycling). After all, tighter loops are valued higher in CE (i.e. the so-called 'power of the inner circle') because, in theory, less work needs to be done to the product if it can be reused compared to remanufactured or recycled (EMF, 2013a).

3.1.2 Life Cycle Assessment

Life cycle assessments (LCA) investigate the environmental impacts related to a product or a system during its whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including material production, manufacturing, transport, use and maintenance, and end-of-life (Figure 5). LCA is a widely used and accepted method for studies of environmental performance of various products and systems, for more details on how an LCA is performed and what parts it contains, see Appendix A. The LCA in this report is performed in accordance with ISO 14040:2006 and ISO 14044:2006 standards.

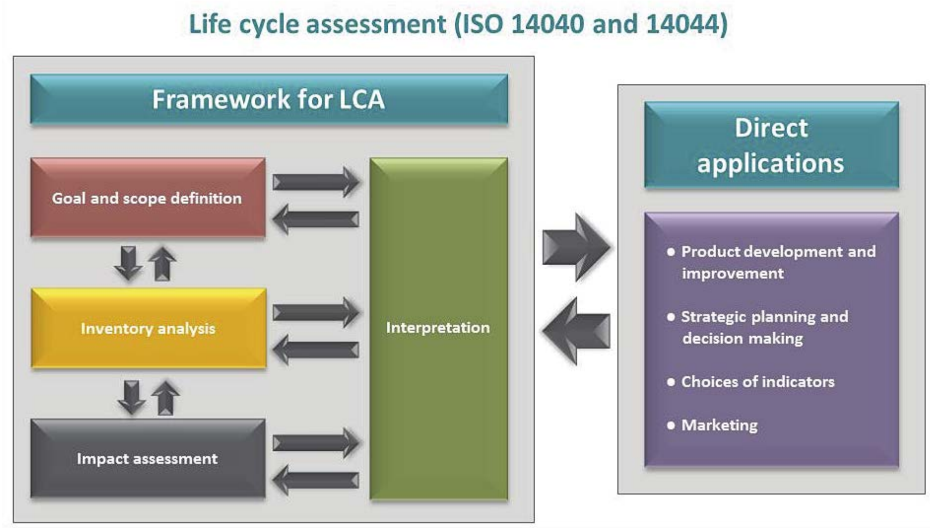

Figure 5: A schematic overview of a life cycle, illustration of the LCA system.

3.1.3 Economic Assessment

Even if circular business models help to reduce the environmental footprint, other barriers might occur limiting the company from going in this direction. Many companies have established profitable circular business models, however, with only 8.6 % of the world being currently circular (Circle Economy, 2020), mainstream industry is not yet transforming to a circular way of working. Barriers and drivers that influence the implementation of circular business models at large scale are currently being researched (Bressanelli et al., 2019; van Loon and Van Wassenhove, 2020). Profitability is a key requirement of business and several studies have shown that manufacturing companies struggle with finding a profitable circular business model (e.g. Agrawal et al., 2019; Van Loon et al., 2018; 2020). There are economic challenges that prevent the realization of circular business models without additional incentives from government (Genovese et al., 2017). Research shows that most people are unwilling to pay more for circular (refurbished/recovered) products (Guide and Li, 2010; Abbey et al., 2015), yet the costs for consumers in a circular versus linear business model is not often assessed. It is argued that a combined view on profitability for the company and total costs for consumers is needed to assess the economic viability of the circular business model (van Loon and Van Wassenhove, 2018; 2020).

Consequently, we apply the concept of Life Cycle Costing (LCC) and Total Cost of Ownership (TCO) to assess both the profitability of the circular versus linear model for the manufacturer as well as the total costs of both models for consumers. For each of the activities and steps in the linear and circular business models, important cost components are identified and compared. An example of activities in a circular business model, in this case repeated leasing with remanufacturing, and the cost components for LCC and TCO are shown in Figure 6.

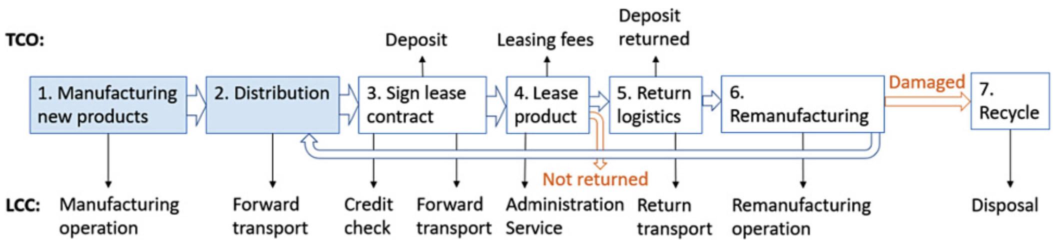

Figure 6: Activities in a repeated leasing with remanufacturing business model (van Loon and Van Wassenhove, 2020).

Which cost components are included in each calculation depends on the business model. In the case of repeated leasing with remanufacturing (Figure 6), the following equations are applied to calculate the Total Cost of Ownership (TCO) for customers as well as Net Present Value (NPV) for the company:

$TCO = tP_l$ and

$$NPV = \frac{1-\propto^t}{1-\propto} P_l - \left(\frac{1}{n} C_m + C_{tf} + \frac{1-\propto^t}{1-\propto} C_a + c \propto^t C_{tr} + \frac{n-1}{n} C_r + \left(\frac{1}{n} - (1-c)\right) \propto^t C_d\right)$$

Where t is the leasing duration, P_l the leasing fee, $\propto$ the discount factor, n the number of leases one get out of one product, C_{tf} the forward transport costs, C_a the monthly/yearly administration costs per leasing contract, c the collection rate, C_{tr} the return transport costs, C_r the remanufacturing costs, and C_d the disposal or recycling costs. The TCO and LCC are compared over the same period of use, meaning that the same function is provided in both scenarios to allow a fair assessment. Hence, in case of inequal lives, the replacement chain method is applied to calculate the revenue, costs, and profit for the least common life. For more information on the equations to calculate the TCO and LCC, we refer the reader to van Loon and Van Wassenhove, (2018) and van Loon et al. (2018;2020).

3.2 Circular product cases

Ten different case studies were performed on products that can be described as a circular product (Chapter 1) and circularity, environmental impact, and economic impact were evaluated. Given the clear lack of environmental case studies that include aspects of circular product design and/or circular business models (see Chapter 2), our selection of case studies focused on these aspects. Six cases include circular product design aspects and six cases include circular business model aspects (Table 2). Naturally, the selection of case studies was dependent on the willingness of companies to collaborate. Data was collected in collaboration with experts at the company and in a few cases, it builds upon earlier conducted LCAs at the company.

Table 2: Overview of case studies selected for micro-level modelling

Case product	Circular product design aspects included in case study	Circular business model aspects included in case study
Bearings	No	No
Beer kegs	Yes	Yes
Chainsaws	Yes	Yes
Chairs	No	Yes
Jeans	No	No
Kitchens	Yes	Yes
Leisure boats	No	No
Lights	Yes	Yes
Signs	Yes	Yes
Woollen sweaters	Yes	No

Each of the cases is summarized below, starting with a brief overview of the linear product, the (envisioned) circular counteroffer, followed by the economic, circularity, and environmental performance. The cases are presented alphabetically.

3.2.1 Bearings

The first case discusses the remanufacturing of bearings. The specific case product is a compact tapered rolling bearing to be mounted on the wheel shaft of an electric passenger train.

LINEAR SCENARIO

Assuming solely new bearings being mounted on a train, a new bearing is installed every 1 200 000 kilometres travelled distance. The outer and inner ring, the rollers, the spacer ring, and the backing ring are produced from recycled steel scrap, i.e. no virgin material is used. This means that roughly between 70 and 90 % of the bearing is made from recycled content (Table 3). The polymer cage is produced from a granulate product made of polyamide (PA66) and glass fibres. The polymer spacer is made of polyphthalamide.

Table 3: Compact tapered roller bearing components (adapted from Fernandez, 2012).

Component	Total weight (kg)	Virgin Material	Recycled materials
Outer ring	10.5		Steel
Inner ring	9.34		Steel
Rollers	6.09		Steel
Spacer ring	0.612		Steel
Backing ring	0.95		Steel
Polymer cage	0.256	Polyamide PA66 and glass fibers	
Polymer spacer	0.17	Polyphthalamide	
Internal seal	0.4	Rubber-steel	
External seal	0.4	Rubber-steel	
Grease	0.2	Grease	

Other materials used in the production process include solvents, oil, water, nitrogen, sodium chloride, sodium carbonate, nitric acid, and methanol. At the end-of-life, the steel components are recycled, grease is incinerated, and the polymer components are disposed in landfill.

CIRCULAR SCENARIO

A bearing is remanufactured twice, once at 1 200 000 and once at 2 400 000 before it is scrapped at 3 000 000 kilometres. During remanufacturing, the seals and grease are removed and recycled. The other components are inspected and reused in the remanufacturing process if they meet the requirements. Detergent is used to clean the bearing and its components and rust inhibitor coating and sand is used in the remanufacturing process.

To compare the two scenarios, the functional unit is defined as *the use of one rotating element (compact tapered roller bearing) mounted on the wheel shaft of a train during 6 000 000 kilometres*. This distance represents twice the average life length of the bearing (including remanufacturing) before it fails. In the linear scenario it covers the use of five bearings.

ECONOMIC ASSESSMENT

The price of a remanufactured bearing is approximately half the price of a new bearing, e.g. if the new bearing is sold for 2 000 SEK the remanufactured bearing costs 1 000 SEK. Since the first-time remanufacturing bearing can go the same distance as a new bearing, the value for customers of the remanufactured bearing is good, i.e. the customer gets the same value/utility but for a much lower price.

The scenarios assessed are the linear case where customers buy a new bearing and discard and recycle them after use, the circular case where bearings are remanufactured after use, and the third case is covering the scenario of a bearing being bought back for remanufacturing (Figure 7). The linear scenario is the most profitable for the manufacturer. Note that data is realistic but has been changed to preserve confidentiality.

There are interesting insights given in this scenario. The pricing of new products is higher than for the remanufactured ones, which leads to higher profitability in the linear case. Questions that arise are whether offering the remanufactured products to a higher or same price as its linear version could be a viable move or not. Since the same functionality is promised with a new and first-time remanufactured bearing, namely a bearing which can run for 1 200 000 kilometres before needing to be taken back for maintenance and remanufacturing, the same price might be feasible, improving the profitability of the remanufacturing case.

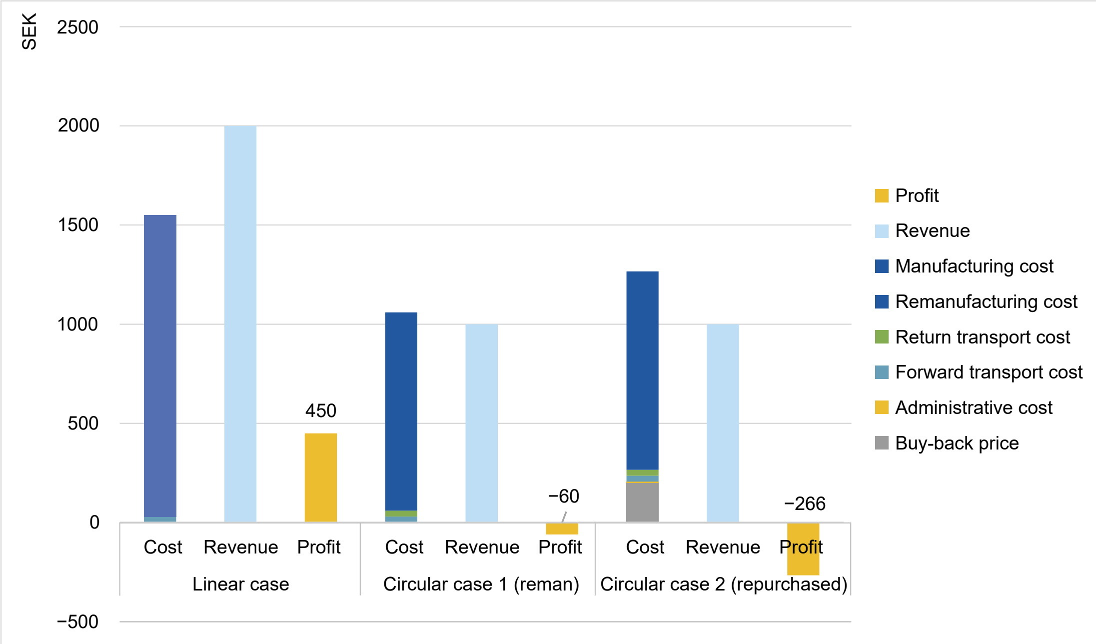

Figure 7: Profitability estimation of three use cases of new versus remanufactured bearings.

CIRCULARITY ASSESSMENT

Calculating virgin material costs: since the amount of virgin material used in manufacturing and remanufacturing is limited (less than 10 to 30 % in case of new products, and even less in remanufactured products), the virgin material costs are relatively low. Assuming that the seals and grease together cost 200 SEK and the polymer spacer and polymer case 100 SEK, the virgin material costs of a new product equals 300 SEK and for a remanufactured product 200 SEK.

Calculating economic value: the price one pays for an old used bearing is the same regardless if the bearing can be remanufactured or need to be recycled; in both cases it is steel scrap value. With a total weight of 17.5 kg of steel scrap in a bearing and a scrap price of 1 SEK / kg for steel[2,3,4], the end-of-life value can be estimated to 17.5 SEK. The sales prices and estimated lifespans are summarised in Table 4. The various input data along the lifespan of the bearings are seen in Table 5 and Figures 8 and 9.

[2] https://www.recycla.se/sv/skrotpriser/skrotpriser-jaern/

[3] https://www.ws-skroten.se/metallpriser

[4] https://www.skrotpriset.se/

Table 4: Input data circularity calculation of bearings.

	Linear case – a newly manufactured bearing	Circular case – a bearing that is remanufactured
Lifespan	1 200 000 km	3 000 000 with remanufacturing at 1 200 000 and 2 400 000
Economic value	Assumption: sales price of new bearing is 2 000 SEK	A remanufactured bearing is half the price of a new bearing, i.e. 1 000 SEK.
End-of-life value	17.5 SEK	17.5 SEK
Remanufacturing	-	Price paid for a used bearing equals end-of-life value
Virgin material costs	300 SEK	200 SEK

Table 5: Input data x and y axes for circularity calculation.

x-as lifespan in km	y-as linear case (value in SEK)	y-as circular case (value in SEK)
0	2 000 SEK sales price new bearing	2 000 SEK sales price new bearing
1 200 000	17.5 SEK End-of-life value 2 000 SEK sales price new bearing	17.5 SEK acquisition price 1 000 SEK sales price remanufactured bearing
2 400 000	Idem 1 200 000 km	Idem 1 200 000 km
3 000 000	-	17.5 SEK end-of-life value 2 000 SEK sales price new bearing
3 600 000	Idem 1 200 000 km	-
4 200 000	-	Idem 1 200 000 km
4 800 000	Idem 1 200 000 km	-
5 400 000	-	Idem 1 200 000 km
6 000 000	17.5 SEK End-of-life value	17.5 SEK End-of-life value

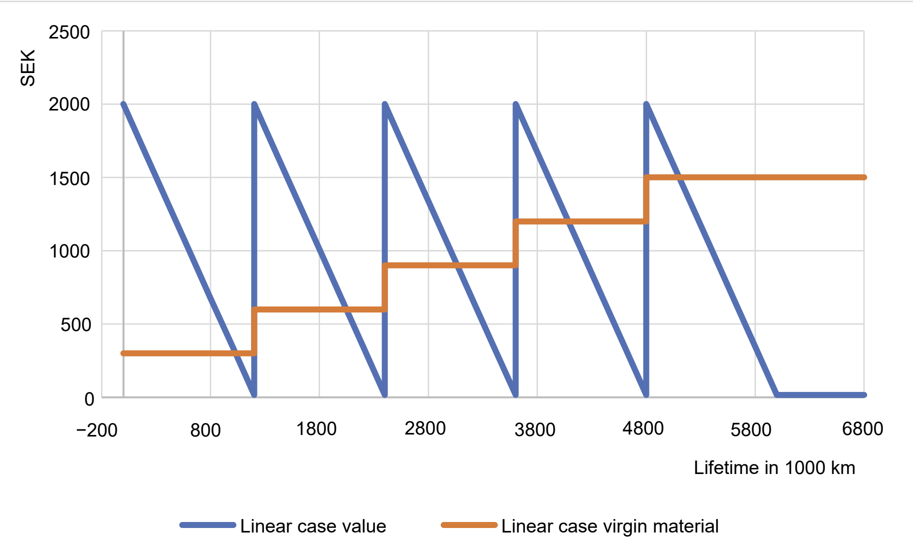

Figure 8: Circularity calculation of linear scenario, i.e., five new bearings.

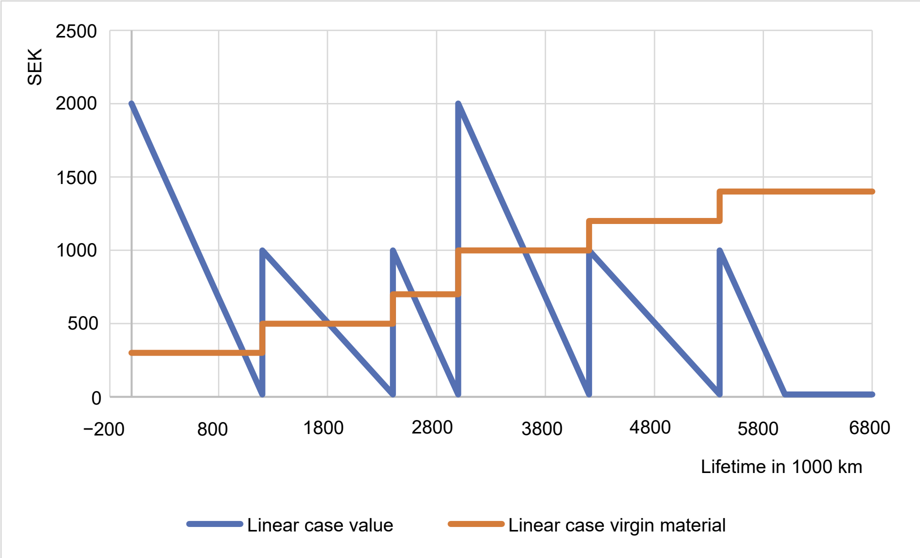

Figure 9: Circularity calculation of circular scenario, i.e., two new bearings that each is remanufactured twice.

The linear case results in an LFR of 4 035 while the circular case results in an LFR of 3 038. Due to the high share of recycled content in the linear product and the significant lower price of remanufactured bearings compared to new bearings, the linear manufactured bearing scores better on the LFR. However, the number of bearings needed to cover the 6 million kilometres is only two for the remanufacturing scenario versus five for the linear case. This shows that if companies can introduce commercially viable circular business models there is great potential in reducing the number of products and hence saving on material consumption. A higher price for remanufactured bearings would improve both the profitability as well as the circularity score.

ENVIRONMENTAL IMPACT

The results of the LCA showed that the resource savings in terms of material and primary energy was over 60 % for the remanufactured bearing. The total GWP of the remanufactured bearing is considerably less than the new bearing and results in a reduction of 60 % in GWP (Figure 10). The major cause from this is the reduction of energy involved in the manufacturing of the new bearing.

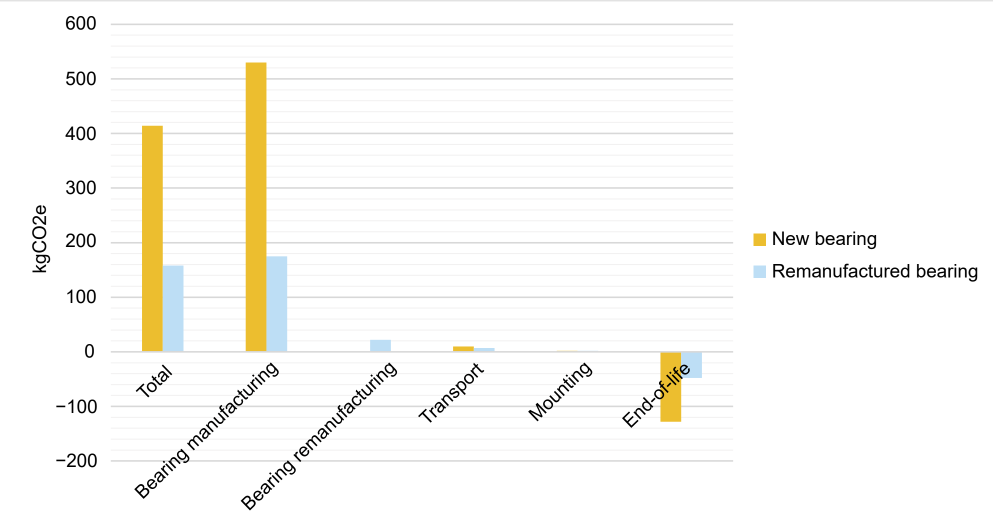

Figure 10: Comparison of GWP for the new bearing versus the remanufactured bearing

3.2.2 Beer kegs

In recent years, plastic beer kegs (bag in container) systems have continued to expand their market share for beverage markets (Market Intellica, 2019) often promoted as “one-way kegs” and “sustainable” solutions due to their lighter weight, ease of use, and recyclable nature. From an initial survey conducted, and through consultation with brewers, we found that brewers, pubs and restaurants are increasingly using plastic kegs due to their ease of use, lighter weight and alleged improvement on sustainability (Martin and Herlaar, forthcoming). This study is limited to the brewing (beer) industry where a keg is used to transport beer produced in Stockholm to a bar 100 km away where it is consumed.

By replacing conventional steel kegs, often used an average of 80 times before they are disposed of or their materials recycled (Cordella, 2008), with plastic kegs, it is unknown how the “one-way” kegs perform compared to steel kegs with regards to sustainability. Most of the one-way kegs available, like Petainer and KeyKegs, are partly to fully recyclable (Petainer, 2019; KeyKegs, 2019b). Nonetheless, this change indicates a move from a semi-circular system with steel kegs to a linear system with single-use plastic kegs. Inherently, whether a product can be recycled or whether a product is recycled significantly influences the environmental impact. Furthermore, now that breweries and distributors are held responsible for how they dispose of their kegs, this shift to a linear system brings a shift of burdens where beverage producers and consumers are responsible for the disposal of the kegs. While manufacturers highlight that plastic kegs do not need to be cleaned with chemicals, and are lighter, it is not apparent how these kegs contribute to a more resource-efficient industry.

While recycling options for plastic kegs are available in other EU countries, e.g., France, the UK, and the Netherlands, through specially designed deposit, crushing, and returning services, a specific recycling system for plastic kegs in Sweden is absent. With the magnitude of plastic kegs currently used in the Swedish beverage industry today, having more registered users than Norway and Denmark combined (KeyKegs, 2019a), the potential to improve this linear system is immense. Re-introducing circularity in the beverage industry can greatly reduce the waste stream these plastic kegs produce and allow manufacturers to get a grip on their resource use and waste production.

LINEAR SCENARIO

The linear system is the use of plastic kegs. We assess plastic kegs produced in The Netherlands from which they are shipped by truck to a brewery in Stockholm. The brewer fills the keg and transports it to a bar where it is consumed. The bar personnel then dispose of the empty keg where it enters the Swedish waste management system.

CIRCULAR SCENARIO

The conventional use of steel kegs for the beverage industry is the circular system is this study. We reviewed steel kegs produced in Italy, from which it is shipped to Stockholm. The brewer fills the keg and transports it to a bar where it is consumed. All steel kegs are then returned to the brewery where they are cleaned and refilled, which can be done an average of 80 uses before the keg enters the Swedish waste management system.

ECONOMIC ASSESSMENT

The total life cycle costs of both types of kegs are collected (Table 6). Following the approach used by Amienyo and Azapagic (2019) for beverage packaging solutions, the costs for manufacturing kegs including raw material costs and transportation to the brewer (i.e., retail price), costs for shipping kegs from brewer to user and back if needed, costs for serving beer from the kegs, costs for cleaning kegs including machinery materials and labour, and costs for disposal and recycling of kegs are included in the calculations. Steel kegs are on average filled 5.5 times per year, leading to a predicted lifetime of 14 years assuming 80 uses. Some kegs are lost during the process, meaning that 4 % more kegs are produced than strictly needed to fulfil demand.

Table 6: Costs for different keg solutions. All costs shown in SEK per keg. (Adapted from Martin and Herlaar, forthcoming).

Costs	Plastic Keg	Steel Keg
Retail price	170.0	885.0
Transportation costs	120.0	182.0
Cleaning costs	-	49.0
Serving costs	0.5	1.8
Disposal Costs	0.37	0.28

Comparing the costs for the same functional unit, i.e. per litre kegged, the results show that the steel kegs have lower costs (Figure 11). The transportation costs are higher for the steel kegs due to their weight and more frequent transportation needs back and forth between brewer and user, but this is outweighed by the significant lower manufacturing costs per litre kegged. Costs for cleaning, serving and disposal are relatively small in both cases. Despite the higher initial costs for steel kegs, the life cycle costs per litre kegged are lower due to a much longer lifetime and hence lower number of kegs manufactured. Overall, the costs for the plastic kegs are roughly 3 SEK more per litre of beer kegged.

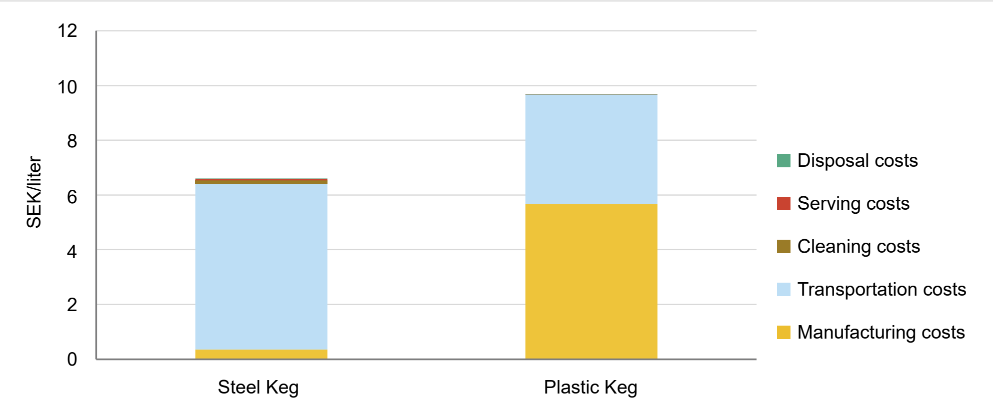

Figure 11: Life cycle costs per litre kegged for different kegging solutions (adapted from Martin and Herlaar, forthcoming).

The total costs of ownership (TCO) for the brewer, which excludes the serving and disposal costs but otherwise similar to above, shows a similar picture.

CIRCULARITY ASSESSMENT

Plastic kegs are significantly cheaper than steel kegs, 170 SEK versus 885 SEK for steel kegs. At the end-of-use the plastic keg has an end-of-life value of 8.5 SEK based on a commodity price of 11.4 SEK per kg PET. The steel kegs have an assumed end-of-life value of 46 SEK based on a commodity price of 6 SEK per kg for steel. Between each use, transportation back and forth (resulting in 182 SEK) and cleaning (resulting in 53 SEK) is needed to bring the product back to the same quality level / value as a new keg. The virgin material costs are estimated at 8.8 SEK for plastic kegs and 57.6 for steel kegs. The value of the keg and virgin material costs in the linear and circular scenario is depicted in Figure 12 and 13 respectively.

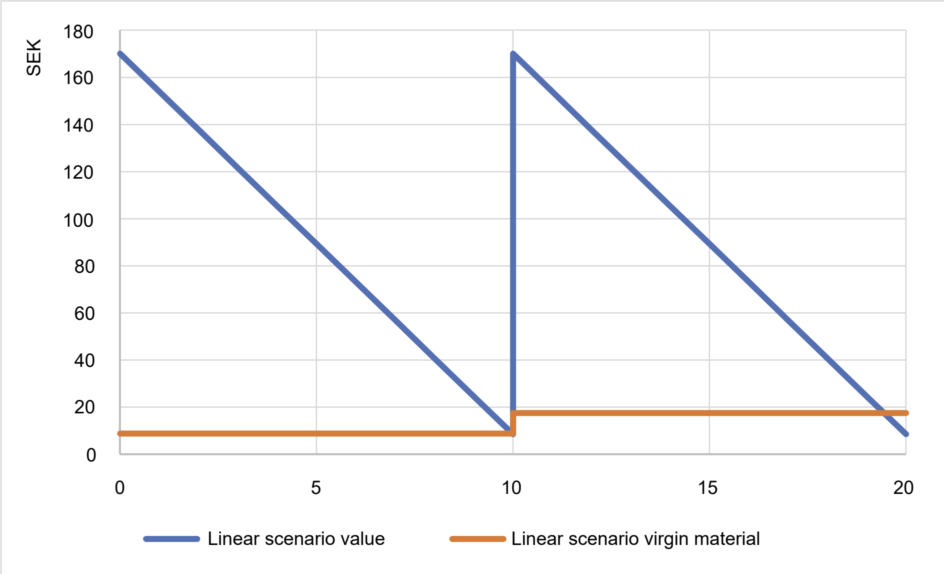

Figure 12: Circularity calculations of linear case of two plastic kegs

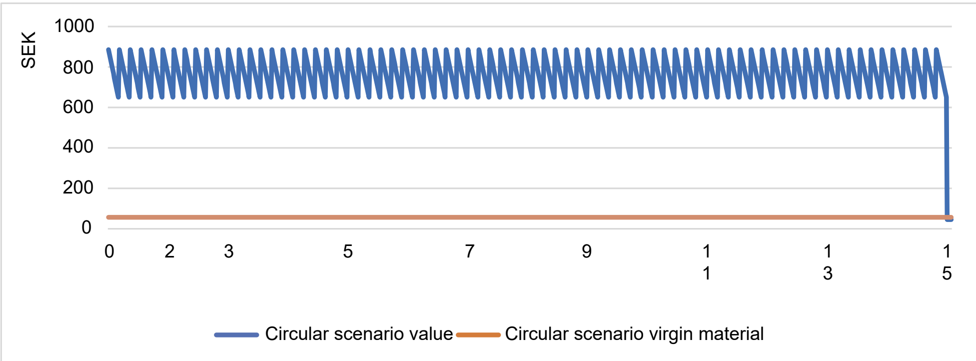

Figure 13: Circularity calculations of circular steel keg used 80 times

The linear plastic keg results in a score of two, while the circular steel keg results in 194. This significant improvement is both due to the significant lower virgin material use in the production of only one steel keg compared to 80 plastic kegs and due to the higher value, which is generated due to the relative high end-of-use value of a steel keg compared to a plastic keg. Much less work is needed to bring the steel keg to the same quality level as the new keg (i.e. after cleaning can be used again while the plastic keg needs to be recycled and manufactured again).

ENVIRONMENTAL ASSESSMENT

The environmental assessment was conducted to assess the environmental performance of a linear versus a circular system for beverage kegs (Figure 14). The functional unit was the transportation of 1 litre of kegged beer from the brewer to the bar. The system boundaries are cradle-to-grave, and as such include the production of both types of keg, their use-phase and the end-of-life phase. The production and cooling of the beer is assumed to be the same for both kegs, and therefore excluded.

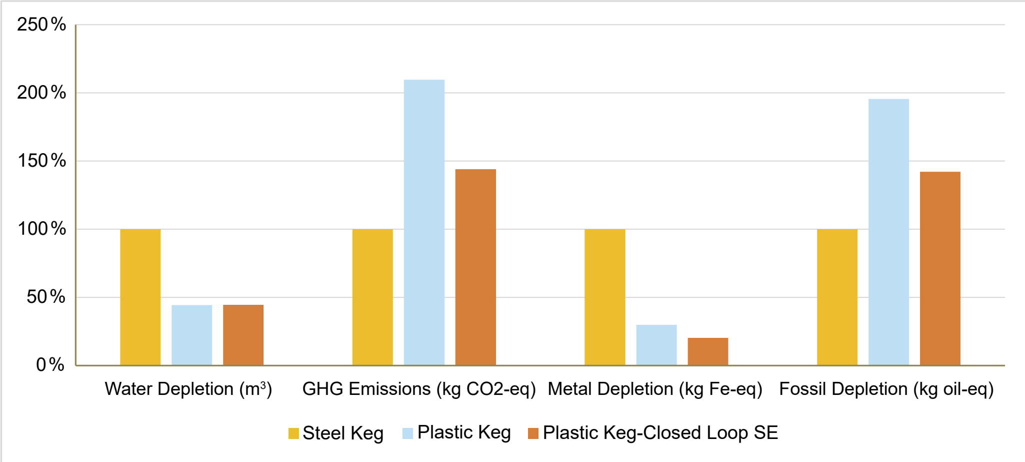

Figure 14: Environmental Impacts of steel kegs, plastic kegs and plastic kegs with closed-loop recycling. All results are normalized to 100 % for the steel kegs.

The results illustrate that the steel keg (circular) has significantly lower GHG emissions and potential fossil resource depletion. The plastic keg (linear) significantly improve the impacts compared to the steel keg on reduced water and metal depletion potential. A large share of the water depletion for the steel kegs derives from the use phase, including cleaning the keg. The plastic keg results are also higher for the fossil depletion category, primarily a result of the production of the keg with various plastics. Furthermore, the increase in GHG emissions for the plastic kegs derives primarily from the production of the keg, its transportation, and direct disposal (despite credits from incineration). Finally, the closed-loop plastic keg shows improvements compared to the baseline plastic keg scenario in all environmental impact categories. This is primarily due to a reduced requirement for virgin PET.

3.2.3 Chainsaws

A pay-per-use service allows users to rent garden tools for relatively short periods of time, for example one day. The pay-per-use business model gives access to various tools in a ‘smart’ unattended container. The locker only contains battery-driven garden equipment, targeting private customers who do not use these tools daily, and hence, it makes sense to share them rather than own them. The pay-per-use boxes are situated in the suburbs with gardens. An easy to reach location is preferred, for example a gas station.

The container has electronic locks to be unlocked with an app. After paying to rent a specific tool for a specific amount of time, a locker is unlocked. The tool is fully charged and ready to use. After the tool is returned, the dealer picks up the tool to check it, to charge the battery, and if needed to clean and repair it. The trial showed that there is usually no damage to the product. Occasionally the product is a bit sandy, and the chainsaw needs to be replaced or sharpened. All tools are so far returned.

This case describes a pay-per-use circular business model for chainsaws. During the pilot run in Sweden, customer surveys were conducted to better understand who the user is. Some people used it once as a test before deciding to buy the product. However, most users are 30- to 40-years-old, live in the suburbs, and are not the main chainsaw customers today. The pay-per-use model does not cannibalize sales of chainsaws to a large extent.

LINEAR SCENARIO

In the linear scenario, it is assumed that consumers would buy a consumer electric chainsaw as this is the most comparable product from a user's point of view. The usage intensity of each customer is assumed to be the same in the linear and circular case. In the base case, all users buy the electric chainsaw and alternative scenarios are where 50 or 25 % of the users would buy the chainsaw. The maintenance / spare parts sold over the lifetime of this chainsaw is usually negligible and therefore not included in the calculations. At the moment of sales, the following additional products are sold together with the chainsaw; one bar and one chain, one battery, one charger, and one safety chap. A summary of input data for the sales scenario is given below in Table 7 (also shown in the master thesis Heiska, 2019 part of this project).

Table 7: Overview of input data linear scenario

	Average value	Optimistic assumption	Conservative assumption
# of product sold per year	20	120	5
Lifetime of product [years]	10	20	5
User transport per sales	30 km	15 km	30 km
Spare parts	None	None	None

CIRCULAR SCENARIO

In the circular scenario, a professional electric chainsaw is rented out. It is estimated that the chainsaw is rented on average 20 times per year, with a maximum of 120 rentals per year. During each rental, the chainsaw is used for an average of 45 minutes. Each chainsaw comes with two batteries. The chainsaw is delivered with safety chap. The chain is replaced on average after every 20th use. In a more conservative scenario, the assumption is made that chains need to be replaced after 10 uses and that one pair of additional chaps are needed during the lifetime of the chainsaw. In the base case, each rental within a year is done by another unique customer. However, an alternative scenario is where customers rent the tools twice a year, leading to 20 rentals over 10 unique customers. The product lasts for about three to four years. The rental locker contains seven products and has an estimated life of 10 years. A summary of input data in the rental scenario is provided in Table 8.

Table 8: Overview of input data circular scenario (based on Heiska, 2019)

	Average value	Optimistic assumption	Conservative assumption
# of rents per year	20	120	20
# of unique customers per year	20	120	10
Lifetime of product [years]	4	4	3
User transport per rental	30 km	15 km	30 km
Spare parts	1 chain per year	6 chains per year (1 chain per 20 uses)	2 chains per year + 1 chap after 1.5 year.
# of products in locker	7	7	7
Lifetime of locker [years]	10	10	10

ECONOMIC ASSESSMENT

Customers pay 350 SEK to rent a chainsaw for one day (back in 2017). There is currently no subscription cost connected to using the tool, which means the one day using will be the only cost for the user. Assuming renting the garden tool for one day per year for 10 years (i.e. the average lifetime of the comparable linear product), the customer pays without discounting 3 500 SEK in total. The price for the garden tool if bought through list price is 2 300 SEK. However, the product, if bought with the same equipment as offered through the battery box, the comparable price is 7 500 SEK. This price then includes the chainsaw, one bar, one chain, one battery, one charger and one safety chap.

To set up a profitability calculation there is a need of identifying direct costs and revenues related to the service or product offered. As detailed cost data for the product was not retrievable within the project time, assumptions have been made in order to retrieve an understanding of what type of parameters are important to consider when discussing a potential profit or loss of a circular business model. To be able to compare the profitability of the linear scenario versus the circular, four different scenarios have been created:

- SC 1: Selling the chainsaw “over the counter”
- SC 2: The pay-per-use chainsaw for one month, used one time
- SC 3: The pay-per-use chainsaw for one month, used 6 times
- SC 4: The pay-per-use chainsaw for 24 months, used 20 times

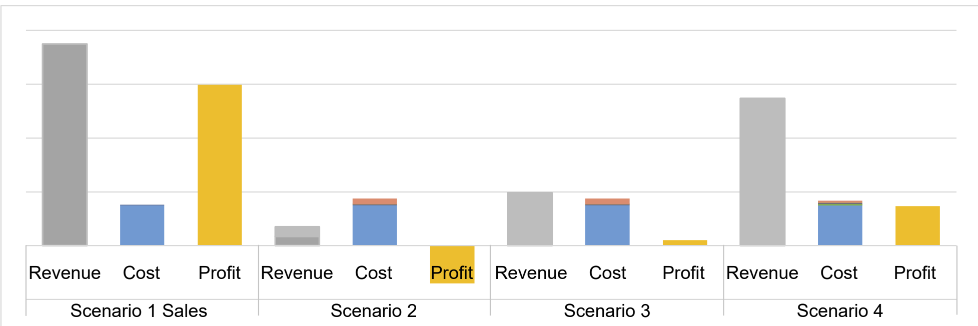

Figure 15: Estimation of revenue, costs, and profit for the four scenarios of selling and renting a chainsaw. Due to integrity reasons, the company’s detailed figures are not shown in the graph.

The results of the analysis of the four scenarios point out that the linear case is the most profitable (Figure 15). The three circular cases are not generating enough revenue to cover the cost of offering the service and product through the pay-per-use model. It shows that, with the cost structure assumed, the number of usages over a specific period is the key factor for generating profit. Alternatively, the company could introduce a subscription fee or increase the price per rent. The core challenge is creating a model which is both profitable and interesting for customers.

Figure 16 shows a scenario where a subscription fee was introduced to the offer. The assumed subscription fee allocated to the chainsaw per month increased the revenue and profit. The profit increased during the 24 months period of scenario four with 12 times and the single month profit in scenario three increased with 4.8 times. The same analysis could be made for changing the price per usage or the number of usages during a specific period. Both parameters will directly impact the revenue stream and increase the profitability.

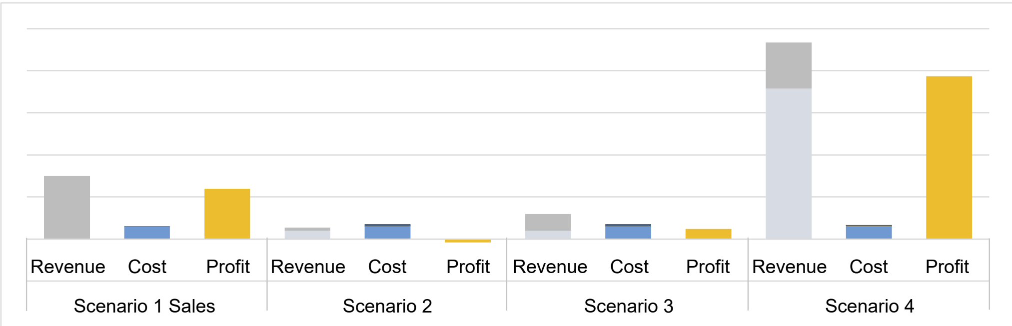

Figure 16: Estimation of revenue, costs, and profit for four scenarios of selling and renting chainsaws with subscription fees.

CIRCULARITY ASSESSMENT

The *economic value* of the circular model can be calculated based on the renting fee of 350 SEK a day. After the rent, the chainsaw can be used again after only a minor check and cleaning, meaning that the activity needed to bring the chainsaw to the same perceived value is limited. We assume an activity costs of 150 SEK for each check between rentals and hence have a lower point of 200 SEK. The economic value or utility for a chainsaw rented out for 4 years equals 298 000 SEK for 20 rentals a year (average scenario), 328 000 SEK for 120 rentals a year (optimistic scenario) and 223 500 SEK for 20 rentals during three years (conservative scenario). Taking the same timespan as in the linear comparative case, i.e., 10 years, we get 745 000 SEK for both the average and conservative scenario and 820 000 SEK for the optimistic scenario. The linear case, assuming the sales price of 2 000 SEK and a lifespan of 10 years, results in 10 000 SEK. End-of-life value is assumed to be zero in all cases.

Calculating virgin material costs: The chainsaws used in all scenarios consist of approximately 46 % steel, 32 % plastics, 14 % printed wiring boards, and 8 % cables. It is assumed that at the end of life, steel is recycled while plastics and silicone are incinerated. No data is available for the share of recycled versus virgin material used in the production process. The virgin material costs related to a chainsaw used in the circular scenarios are assumed to be 800 SEK, while the virgin material costs of the chainsaw used in the linear scenario are assumed to be 500 SEK.

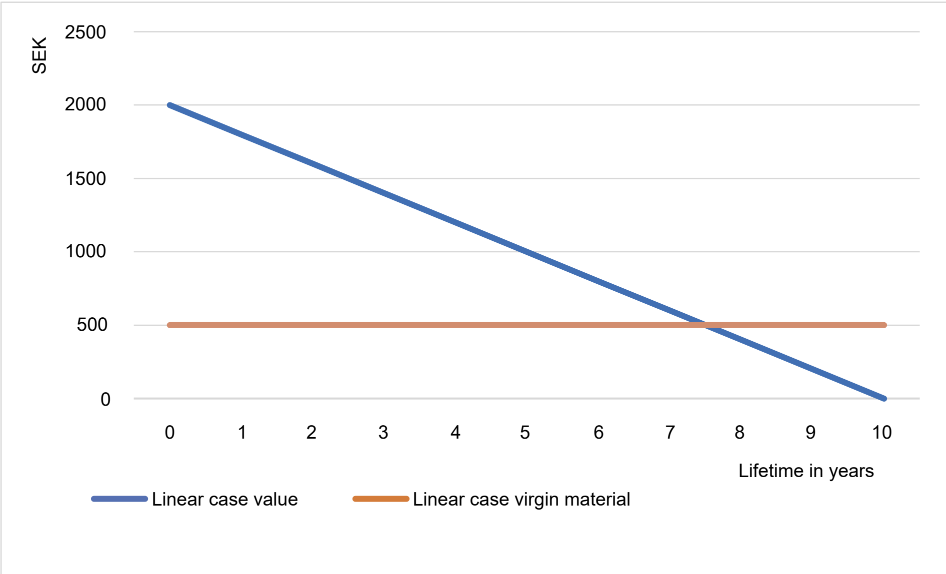

Figure 17: Circularity calculations of linear scenario: the purchase of one chainsaw used for 10 years.

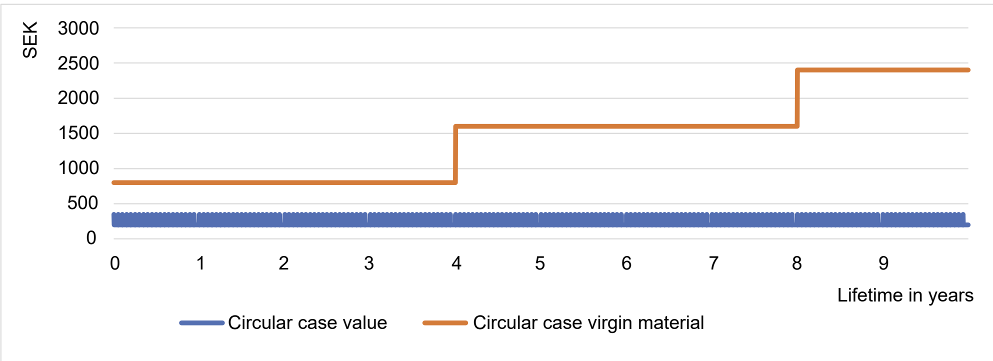

Figure 18: Circularity calculations of circular scenario: pay-per-use.

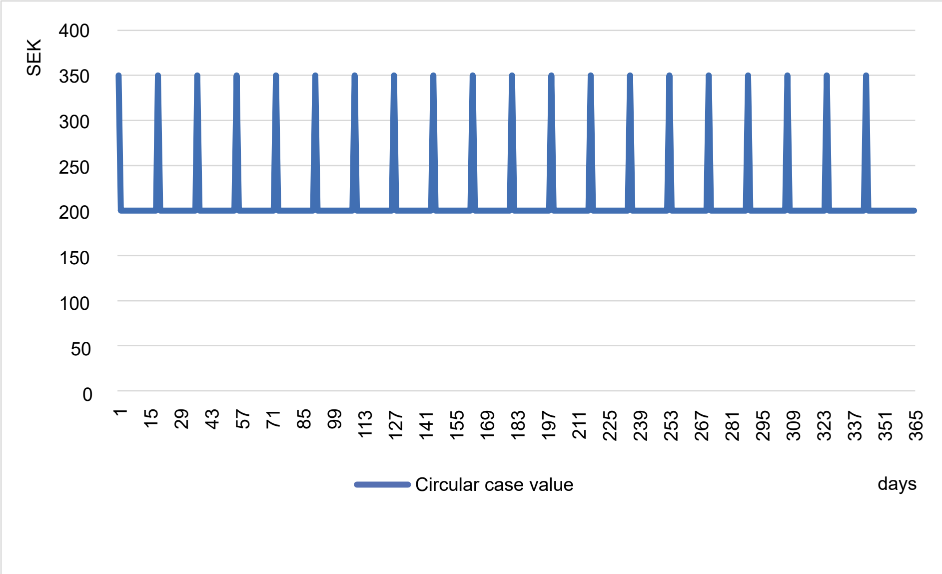

Figure 19: Closer look at circular case value (during one year).

The linear case results in an LFR of 20 while the circular case results in an LFR of 373, 410 and 279 for respectively the average, optimistic, and conservative scenario. This is a significant improvement reached through the higher value generated in the pay-per-use model compared to the linear sales model. Comparing over a period of 10 years, the sales of one chainsaw lead to a revenue of 2 000 SEK, while the circular pay-per-use model generates 70 000 SEK in the average scenario. Note that also the virgin material input in the circular case is higher due to the use of 2.5 sturdy chainsaws compared to one consumer chainsaw to cover 10 years of use in the linear case. However, based on the circularity metric used here, this additional use of virgin material is outweighed by the increase in utility by shifting towards the pay-per-use model.

ENVIRONMENTAL ASSESSMENT

While the rental service may have lower impacts in certain impact categories, it may be higher in others (Figure 20). For example, mineral resource scarcity and different toxicity potentials (both human and marine) are significantly lower in the Rental-basic scenario; due primarily to reduced materials and electronic components through less products available in the rental service. However, the rental service has higher GHG emissions and fossil resource scarcity potential compared to the sales alternative; due primarily to the user transportation. This was identified as a significant hotspot in the study, accounting for roughly 84 % of the contribution to the GHG emissions and fossil resource scarcity potential respectively). Furthermore, transportation by users has a substantial contribution to all other impact categories for the rental service. This indicates the importance of minimizing the distance of the depot for users.

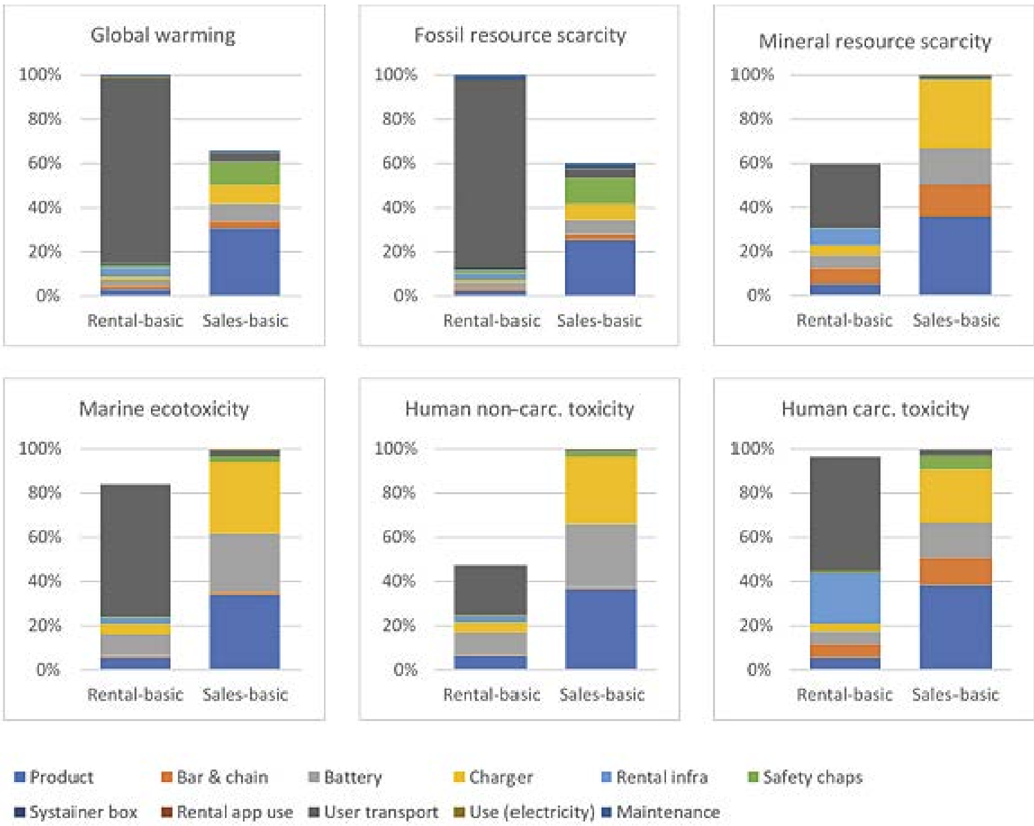

Figure 20: Comparison of environmental impacts for the basic rental and sales scenarios.

While the impacts of transportation dominate the basic rental scenario, the largest impacts from the sales scenario are primarily related to the product itself, i.e., the main product body, battery, charger, and accessories. In both scenarios, the use of the chainsaw results in only minor contributions to the environmental impacts, due to their short use durations and the relatively low impacts from the electricity system employed in the assessments, i.e., Swedish electricity mix. For the sales scenario, the potential impacts of the charger and the battery are relatively large.

3.2.4 Chairs

This case describes the refurbishment coupled with selling and buy-back of chairs compared to selling new chairs. The chair consists of a steel frame made from a combination of recycled and virgin material and textile made from virgin material.

LINEAR SCENARIO

In the linear scenario, chairs are sold and at their end-of-life thrown away and recycled. The average usage duration is 15 years. Sometimes chairs are sold on consumer-to-consumer second-hand markets after an average age of 10 years. However, only a few chairs per month are sold, which means that only a small percentage is sold on the second-hand market. Once in use, the product is cleaned every now and then by the customer. There is no reason to assume that the cleaning performed by the customer would be different between a linear and circular business case and cleaning materials are therefore excluded in the analysis.

CIRCULAR SCENARIO

In the circular model, chairs are bought back for refurbishment. Chairs are first sold as normal in the linear case but are after a time bought by a certified third party that reupholster the chair (new textile, frame is reused) and sells them again. Reupholstering usually occurs locally. Taking the same type of customer as the general linear case customer, the average usage duration is an estimated 10 years.

ECONOMIC ASSESSMENT

For the economic assessment, several assumptions are taken. First, customers and their usage behaviour differ. Some buy a chair, use it for a certain period, discard it, and buy a new one. Others sell chairs on second-hand markets after use and another group buy second-hand chairs. Some customers prefer to upgrade their chairs during use by reupholstering the chair themselves or by third parties. Sensitivity analysis of the economic impact of these various types of customers is made, however, we only show the results of one type of customer, the one that buys a chair, uses it, discards it, and buys a new.

In the linear model, the chairs are manufactured, transported to the retailer, sold by the retailer, transported to the customer (by the customer), and finally discarded at the end-of-life. In the circular model, chairs are first manufactured, transported to the retailer, sold by the retailer, and transported to the customer just like in the linear case. However, after 10 years, the chair is bought back. A certain type of customer is targeted for this offer and the assumption is made that 80 % of the chairs can be bought back after first use. Chairs are transported to a refurbishment facility where chairs are checked on quality and if suitable, refurbished for second use. It is believed that roughly 95 % of the chairs can be successfully refurbished and sold again. These chairs are transported to the retailer, sold by the retailer, and transported to the customer. After the second use, roughly 50 % of the chairs are believed to return to the refurbishment facility of which 80 % are suitable for a third use. After the third use, no chairs are bought back and all of them are discarded by the customer. This process is illustrated in Figure 21.

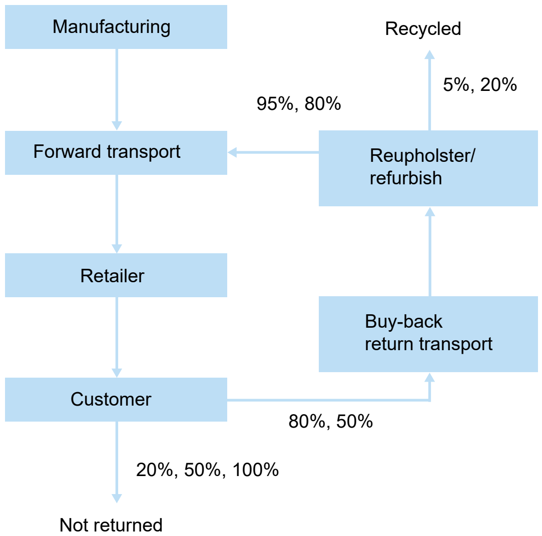

Figure 21: Overview of the steps in the circular scenario for chairs.

Given the collection and refurbishment success rate, it can be determined that one chair in the circular system is on average used 2 064 times. All chairs are used the first time, 76 % of the chairs are used for a second time, and 30.4 % of the newly manufactured chairs are used for a third time. To compare the profitability over the same timespan/the same function delivered, i.e., 30 years of using a chair, two chairs are needed in the linear system and 1.45 chairs in the circular system. The relative costs, revenue, and profit of the linear versus circular business model are shown in Figure 22.

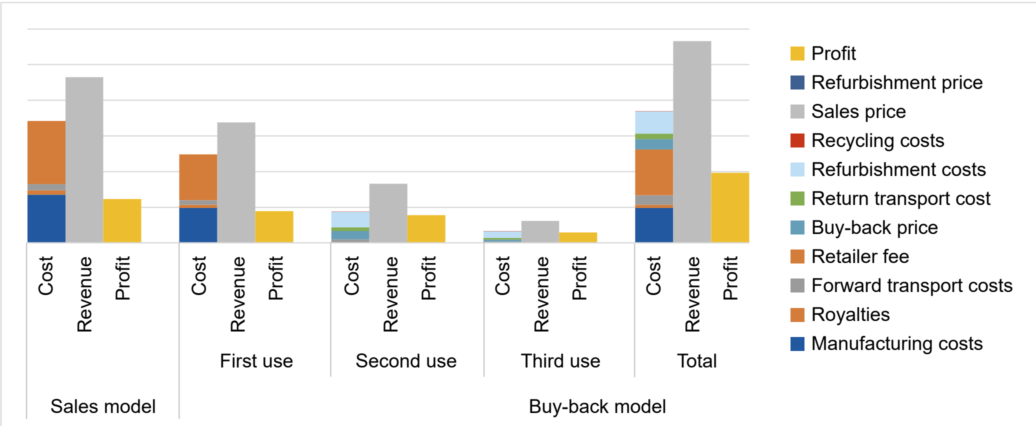

Figure 22: Costs, revenue, and profit for the manufacturer of the linear versus circular buy-back business model.

Profits for the manufacturer are higher for the buy-back model compared to the linear business model. The costs are also slightly higher, but due to the higher profit generated by the sales of some of the chairs for a second and third time, higher profits can be generated. Looking at the total cost of ownership (TCO) for customers in both scenarios (Figure 23), it can be seen that mainly the customer who buys the new chairs in the buy-back program has higher costs due to the shorter lifespan of the chair, while customer buying the second or third use chair have a lower TCO.

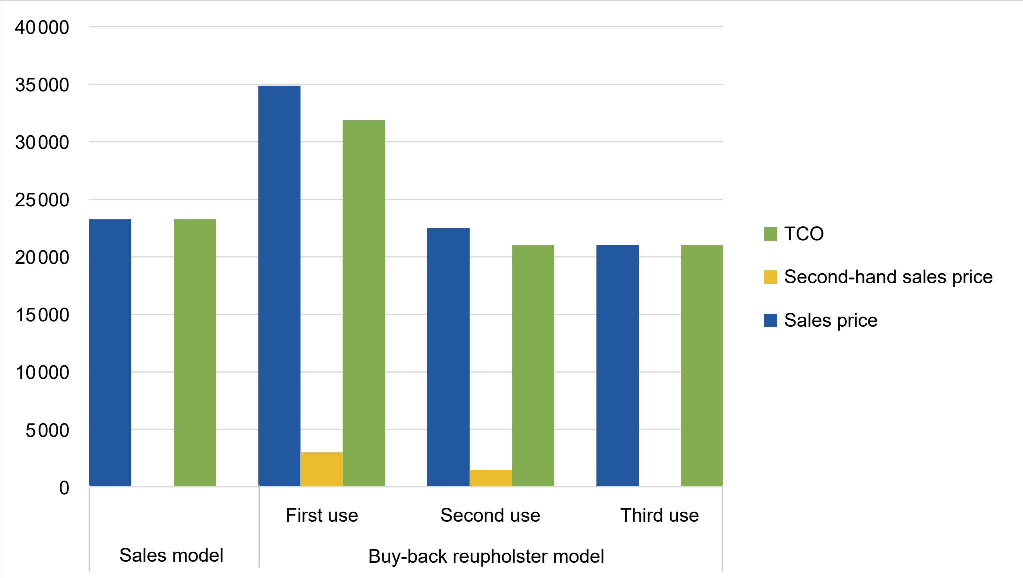

Figure 23: Total costs of ownership (TCO) in the linear versus circular business model.

CIRCULARITY ASSESSMENT

Calculating economic value: In the circular scenario, chairs are sold for the first time against the same sales price as in the linear system. After 10 years of use, chairs are bought back. The buyback price is based on average sales prices of used chairs on the second-hand market, although slightly lower as taking back can be seen as a service to customers. After refurbishment, chairs are sold for roughly 75 % of the original sales price. After 10 years, the chairs are bought back at a certain price, based on the average sales prices on the second-hand market. After the second refurbishment chairs are sold for roughly 60 % of the original sales price (Figure 25). The end-of-life value of chairs is assumed to be zero in all scenarios. The known second-hand market prices for certain ages of the chair are used to calculate the economic value of the linear scenario (Figure 24).

Calculating virgin material costs: It is assumed that the virgin material costs of manufacturing a new chair equals 1 900 SEK, while the reupholstering during the refurbishment adds 900 SEK.

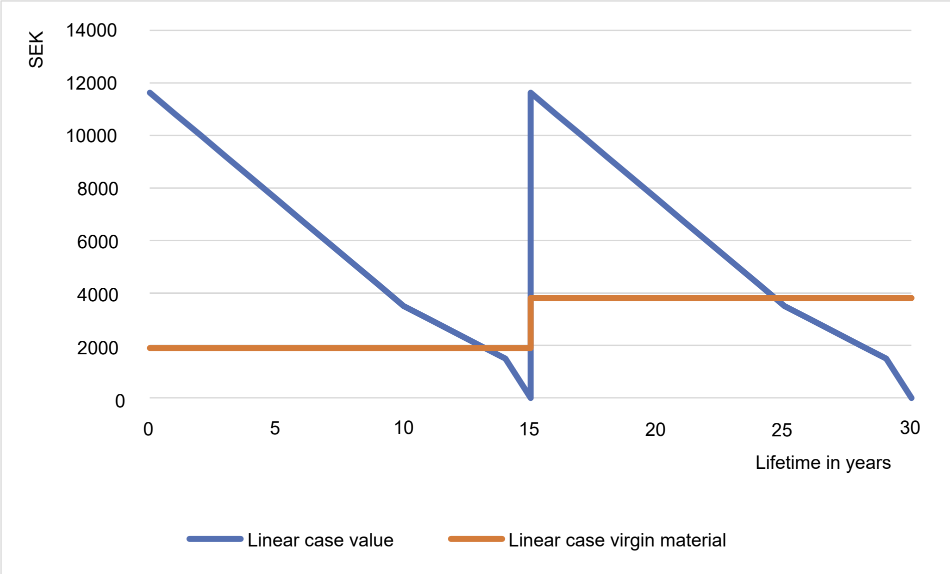

Figure 24: Circularity calculations of the linear case: selling chairs.

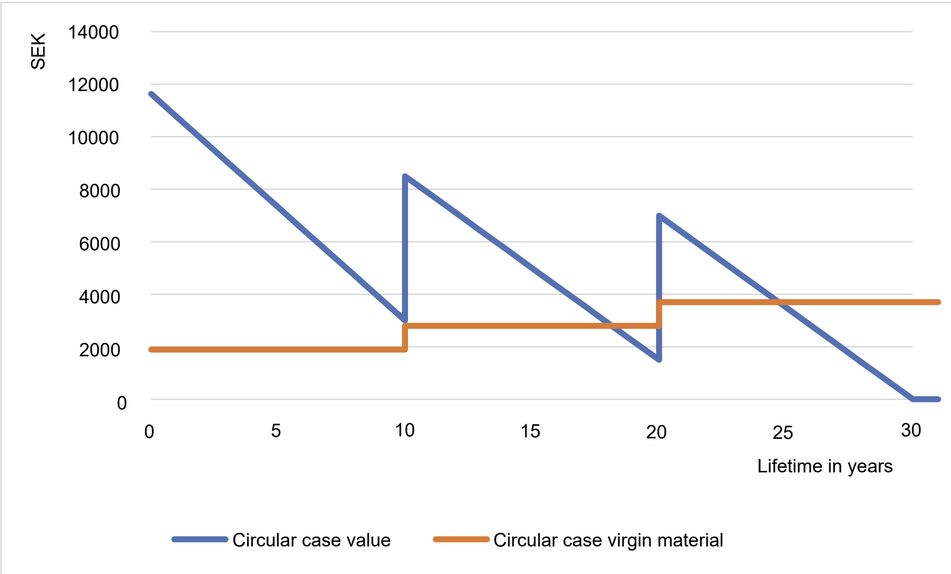

Figure 25: Circularity calculations of selling and buying back chairs for refurbishment.

The linear case results in an LFR of 45 while the circular case results in an LFR of 43. The virgin material costs to have a chair in use for 30 years is slightly lower in the circular case compared to the linear case. However, the economic value generated in the circular case is also lower, resulting in a lower circularity score.

ENVIRONMENTAL ASSESSMENT

The scenarios are modelled on their GWP and results are calculated per one year of using the chair. The first scenario presents the linear use of selling chairs which have been used for 15 years by one user. The second scenario assumes reupholstering after 10 years after which the chair can be used for another 10 years. The third scenario assumes two times reupholstering (after 10 and 20 years) and includes a total of 30 years of usage. Figure 26 shows a reduction of 6 % in GWP for the single upholstering and 25 % reduction for the scenario with two re-upholstering's.

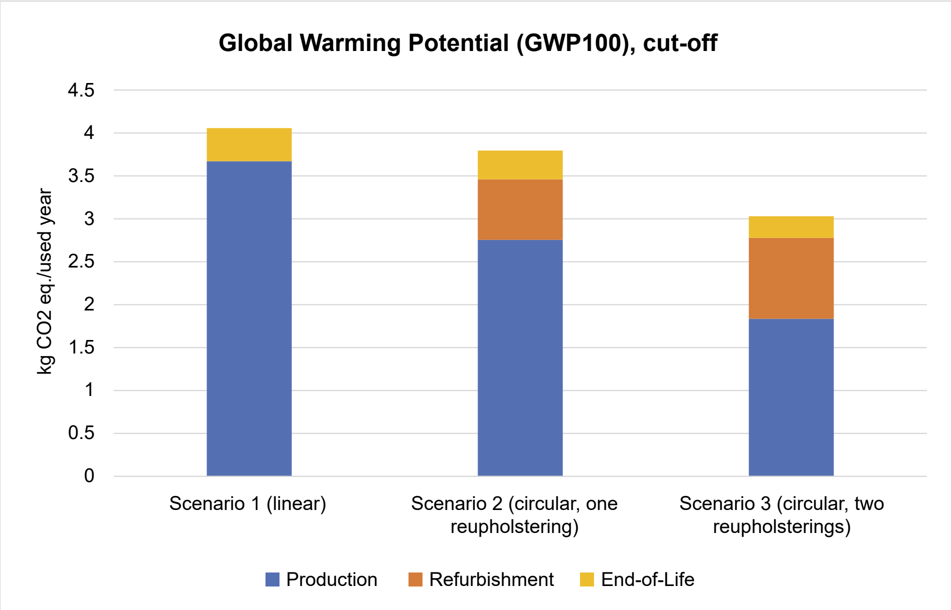

Figure 26: Global warming potential of reupholstering of chairs versus selling new.

3.2.5 Jeans

This case describes a sell, repair, and reuse concept of jeans. Customers can get their jeans repaired for free in the shop. Customers can further return jeans they do no longer need and get in return a 20 % discount on a new jean. The collected jeans are sorted and either repaired and resold in the repair shop or online or the fabric is reused in the manufacturing of other products such as caps and backpacks. (This case is also published as master thesis, part of the LinCS project, Nellström and Saric, 2019).

LINEAR SCENARIO

In the linear scenario, jeans are used by one customer and incinerated after use. The average usage period is defined 1.5 years.

CIRCULAR SCENARIO

In the circular scenario, jeans are reused three times before being discarded. After using the jeans for on average of 1.5 years, customers bring their jeans to the shop for reuse. The repair activities include washing, sewing, and steaming and require buttons, fabric, glue, hang tags, threads, and zippers. After repair, the jeans are reused by the same or another customer. At the end-of-life, after four lives on average, jeans are incinerated.

ECONOMIC ASSESSMENT

The average sales price of jeans in both the linear and circular case is assumed to be 1 399 SEK. The TCO of new versus repaired jeans is assumed to be equal. The discount customers get when handing in their old pair of jeans is not linked to whether the customers owned a new or repaired pair and is neither linked to if they buy a new or repaired pair. The TCO is in both cases 1 399 SEK for a pair of jeans used for 1.5 years.

CIRCULARITY ASSESSMENT

In the linear case the jeans are used for 1.5 year after which they are disposed and have therefore no end-of-life value. The virgin material costs are estimated based on the bill-of-material used in the LCA and combined with commodity prices that are available online. The total virgin material cost of producing one pair of jeans is estimated at 19 SEK (Figure 27).

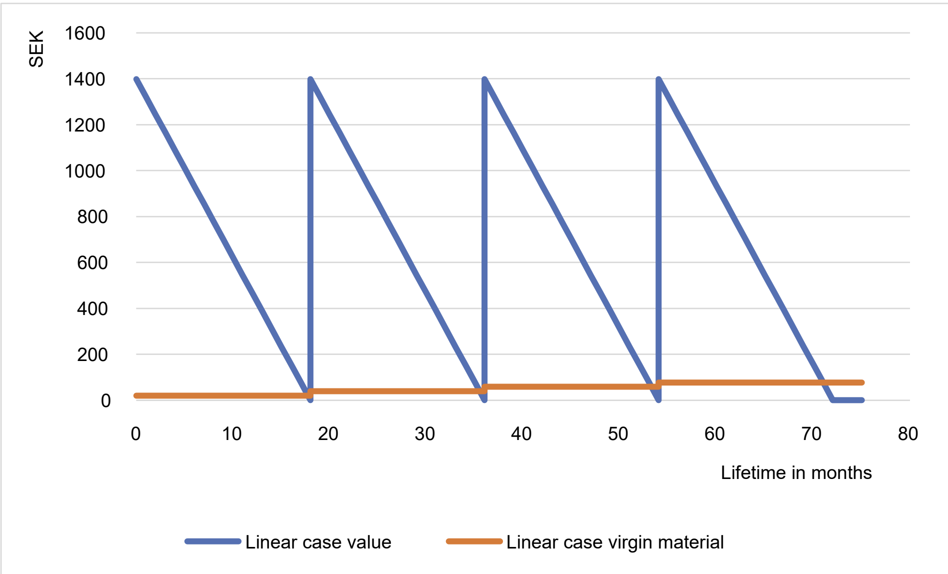

Figure 27: Circularity calculations of the linear sales model of a pair of jeans.

In the circular case, customers get a discount on new jeans when handing in their old jeans. This discount, 20 % of the sales price of 1 399 SEK, can be seen as a buy-back price. In line with the scenario description above, the pair of jeans is used by four different users, each for 1.5 years. The virgin material cost of producing the pair of jeans is equal to the linear case. The virgin material cost of repairing a pair of jeans is lower due to less materials needed and assumed to be 0.95 SEK (Figure 28).

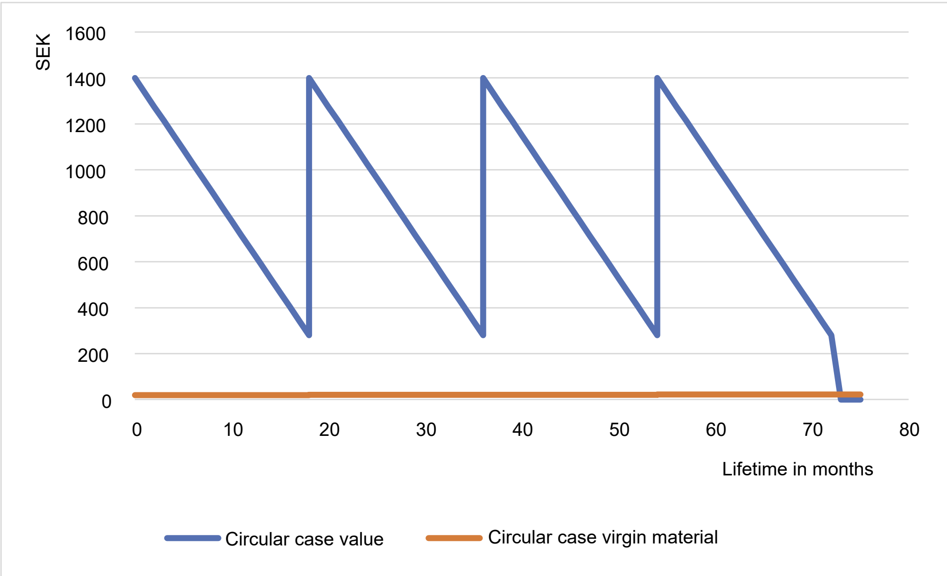

Figure 28: Circularity calculations of circular model of a pair of jeans.

The LFR gives a value of 54 in the linear case and a value of 227 in the circular case, which means that the circular case where jeans are used 4 times instead of one gives an improvement of 318 %, mainly due to the higher end-of-life value of the jeans in the circular case and the much lower virgin material costs (22 SEK in the circular case versus a total of 78 SEK to manufacture 4 new jeans in the linear case).

ENVIRONMENTAL ASSESSMENT

Figure 29 shows the contribution analysis for GWP and the change in impact depending on the number of reuses. The GWP is representative for all impact categories, which all show the same trend. With no reuse most of the impact derives from the production of fabric and the jeans. This impact is divided between each of the reuses and so this impact is reduced from each reuse. As can be seen from the figure, the largest reductions occur in the first 1–3 reuses and the impact of repair is almost negligible. The use phase remains steady as this is the impact of washing, and there is an assumed impact from transport to the repair facility and of materials.

Table 9: Environmental impact of one pair of Nudie Jeans used for one year (based on Nellström and Saric, 2019).

Environmental impact category	Circular case	Linear case
GWP (kg CO2-eq)	1.9	4.7
AP (kg SO2-eq)	5.7e–3	1.4e–2
EP (kg Phosphate-eq)	2.4e–3	5.1e–3
Particulate matter (kg PM2.5-eq)	4.2e–4	1.1e–3
Ozone layer depletion potential (kg R11-eq)	1.3e–8	3e–8
POCP (kg Ethene-eq)	5.4e–4	1.6e–3
Ionizing radiation (kBq U234-eq)	8.7e–1	1.2
ADP elements (kg SB-eq)	3.4e–6	9.8e–6
Human Toxicity Potential (kg DCB-eq)	2.6e–1	6.9e–1
Terrestric Ecotoxicity Potential (kg DCB-eq)	6.9e–3	1.3e–2
Marine Aquatic Ecotoxicity Potential (kg DCB-eq)	6.3e2	1.2e3
Freshwater Aquatic Ecotoxicity Potential (kg DCB-eq)	6.2e–2	1.2e–1

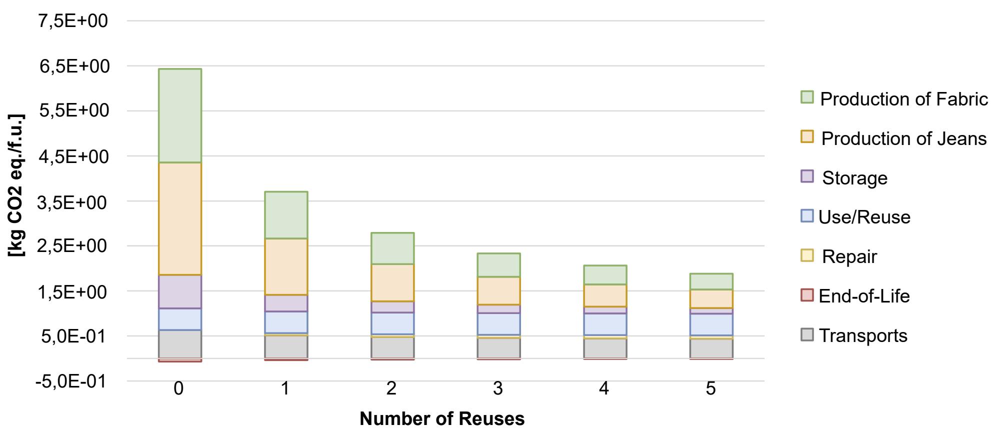

Figure 29: Contribution analysis for global warming potential, showing the change in impact depending of the number of reuses.

3.2.6 Kitchens

This case describes the renovation of kitchens for renting apartments. The customers of the kitchen manufacturer are mainly housing corporations including municipalities and private real estate owners. The company focuses on apartments that were part of the 1-million program in the 60ties. In many cases, they still have a kitchen from then which needs renovation or replacement. At the same time, the owners do usually not have enough money to renovate the whole building and even if they could renovate, placing a new kitchen in the apartment would increase the rent by 60 % which is above the price many tenants can afford. A business model is therefore created that reuses as much as possible in the kitchen while still giving it a fresh look at low costs. The frames and shelves are kept to a large extent and repainted to give it a fresh look. The worktop, doors, handles, and hinges are replaced with new ones. The sink is kept if possible, because of the high environmental footprint. Tiles are kept as well when possible, to reduce costs. Tenants only pay 200 SEK a month more after the installation of this kitchen.

Housing corporations buy the kitchen from the manufacturer who are then getting paid back by the tenants via increased rent. However, the possibility of the manufacturer leasing kitchens to the housing corporations is discussed. In such case, the lease should be focused on durability and quality, helping poor people with affordable good-quality kitchens, not tenants that want to change the kitchen because they would like a new colour.

Each kitchen is different in design, but a 'standard' kitchen used in the LCA calculations has 16 doors and 1.2-meter kitchen counter. The doors are made of wood (MDF or plywood), which is a renewable source. Yet this is treated as virgin in the circularity calculations.

LINEAR SCENARIO

In the linear scenario, a new kitchen is assumed to be used for 25 years. This is not a completely new kitchen, but has new doors, worktops, taps, sink, etc.

CIRCULAR SCENARIO

The kitchen is refurbished and used for 25 years after refurbishment. The refurbishment includes mainly new doors.

CIRCULAR SCENARIO 2

A new quality kitchen to be used for 30 years with some upgrading functions. For example, after 15 years the doors are repainted, and some parts might be changed if needed. The quality kitchen includes better quality MDF doors, other handles, both inside and outside of doors painted, LED lighting, etc.

ECONOMIC ASSESSMENT

In the linear scenario, customers pay 160 SEK a month for 10 years. In the circular scenario, customers pay an equal amount for 10 years, i.e., no changes are made to the total costs for the ones renting the apartment. The labour costs for maintenance and service are also estimated to be the same regardless of a new or refurbished kitchen is installed. However, a refurbished kitchen, mainly including new doors, is significantly cheaper than a completely new kitchen with new doors, worktops, taps, sinks, etc. A refurbished kitchen including installation costs, costs roughly 25 % of a new kitchen. The revenue for the manufacturer is higher for the linear business model, estimated to be roughly 3.6 times more than a refurbished kitchen.

In the second circular scenario, it is assumed that customers pay 260 SEK a month for 30 years as well as 500 SEK per visit to upgrade the kitchen. Due to the use of a high-quality kitchen and high service one wants to provide in this business model, the labour costs for maintenance and service are slightly higher (25 % more). However, this business model assumes one-time renovation after 15 years, which brings the total maintenance costs 4 times the maintenance costs of the linear model. The cost of the kitchen itself including installation is more expensive than the refurbished kitchen but cheaper than a completely new kitchen, i.e., 56 % of the costs of a new kitchen. Total revenues for the manufacturer coming from selling the kitchen as well as upgrades is estimated at 94 % of the revenue generated by selling a new kitchen.

Comparison of the costs, revenue, and profit for the manufacturer in the three scenarios shows that the third scenario, the circular high-quality kitchen with upgrades, leads to the highest profit (Figure 30). In this scenario, revenue is not only coming from selling kitchens, but also from the service agreement including upgrades, while the total costs including the upgrades are lower than manufacturing a new kitchen.

To challenge the conventional business model offering renovated kitchens, an additional circular 3 case was added. Here, the service is offered through a subscription payment model instead of a one-time transaction. The analysis shows that the circular 2 case results in a marginally higher profitability compared with the linear case. However, the circular 3 case shows a substantially higher profitability compared with all the other cases, as the revenues spread over time are resulting in a higher profit margin compared with the other cases.

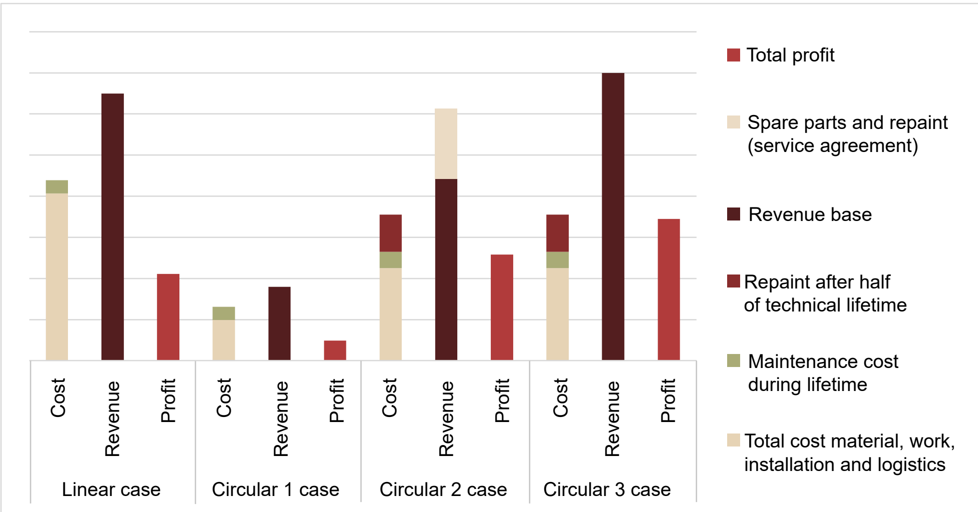

Figure 30: Financial analysis of the linear and circular scenarios.

The circular 3 scenario is generating a higher profit for the manufacturer, however, the total cost for the real estate developer or owner will be higher than for the other scenarios. The buyer will, however, only pay a fraction of the total cost per year, versus the other scenarios where the payment is done through traditional payment terms. This means that the buyer will "keep money in the bank" for a longer period compared with the other cases. The analysis shows that it takes about 5 years for the buyer to pay more than the second circular case would inquire (Figure 31). In other words, the buyer would be able to keep money in the bank for 5 years with an alternative cost.

Figure 31: Real estate owner cost in circular 3 case.

Table 10 shows the alternative return the buyer could expect with an estimated interest rate of 8 %. The yearly return is larger as the money kept in the bank is higher. For each year, the return is then based on what is kept in the bank after the yearly payment to the manufacturer and including the previous year's interest return.

Table 10: Alternative rate of return which could be expected with an estimated interest rate of 8 % when having money in the bank.

Alternative ROI real estate owner	8 %
0	4 104
1	3 632
2	3 123
3	2 573
4	1 979
5	1 337
6	644
7	−105
8	−913
9	−1 786
Total return	16 747

By adding another payment solution to the circular 2 scenario, the service provider could potentially generate more revenues and at the same time offer an enhanced service. When introducing a subscription-based payment model the risk of not getting the full payment might increase, as the invoicing plan towards customers is spread over a longer period. As the service of offering renovated premium kitchens is capital heavy, even a loss of payment from one customer can have a large impact on the service provider. Figure 32 shows the total profitability of the circular 3 case with and without risk factor, i.e., showing the profit if the manufacturer would only get 60 % of payments.

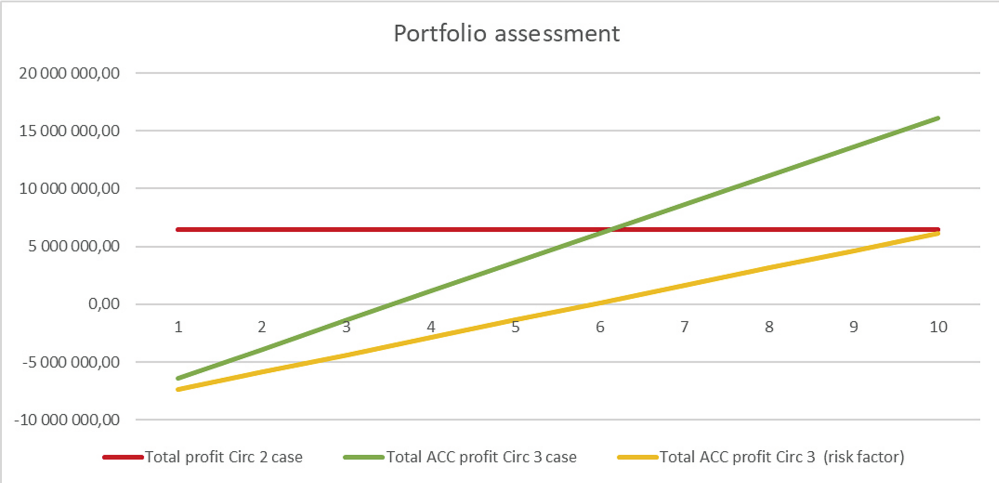

Figure 32: Analysis of payment risk factor, total profitability of the circular 3 case over 10 years.

In the longer run, a change of business model towards a subscription-based offer will have an impact on the organizational structure of the service provider. This type of offer raises questions regarding ownership, payments, insurances, customer service, daily operations, and other aspects of running the daily business and how it will be impacted. On one hand, the interface towards the user or customer needs to be seamless and clear, on the other hand, the structure of corporate governance needs to take the new organizational needs coming from offering the kitchen in a new way into consideration.

CIRCULARITY ASSESSMENT

The virgin material costs are determined based on the bill of materials with each material and weight specified and combined with commodity prices available on the internet. Comparing the first two scenarios, the amount of virgin material and hence virgin material costs are significantly lower in the circular scenario then in the linear scenario (Figure 35 and 36). On the other hand, the utility the kitchen provides to the tenants is similar. Hence, the circular offer where more utility is created per virgin material input can be considered more resource efficient (LFR of linear scenario is 28, while LFR of circular scenario is 184).

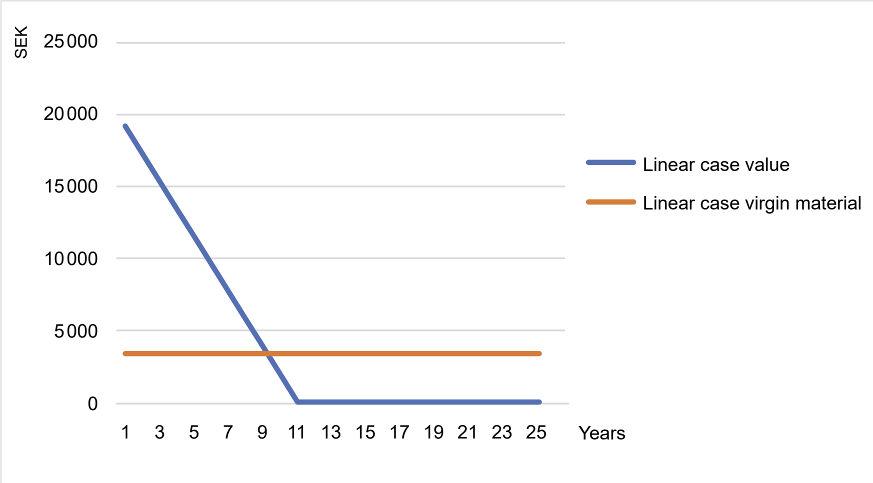

Figure 33: Circularity calculations of using a kitchen for 25 years – linear case.

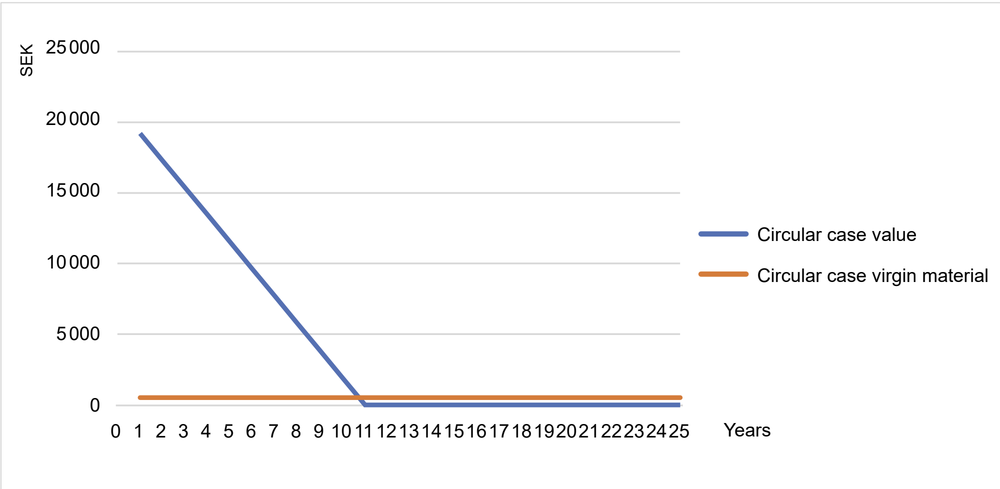

Figure 34: Circularity calculations of using a refurbished kitchen for 25 years.

ENVIRONMENTAL ASSESSMENT

Table 11: The main assumptions of the scenarios for the kitchen.

Scenario	Description
Scenario 1 (linear)	New kitchen (Modexa made) is used for 30 years.
Scenario 2 (circular)	New kitchen (Modexa made) is used 30 years, then refurbished and used for 30 more years.
Scenario 3a (circular)	New kitchen (with high quality wooden frames) is used 30 years, refurbished, used 30 more years, refurbished, and used 30 more years.
Scenario 3b (circular)	New kitchen (with high quality wooden frames) is used 50 years, refurbished, used 30 more years, refurbished, and used 30 more years.

The circular scenarios 2, 3a and 3b, have a reduction of 35 %, 42 % and 53 % in GWP impact compared to the linear, respectively Figure 35). The weight of materials is considerably less in the circular kitchen with a new kitchen requiring 617 kg of materials, whilst the refurbishment only requires 145 kg. Much of the reduction is due to the reduction in production impacts.

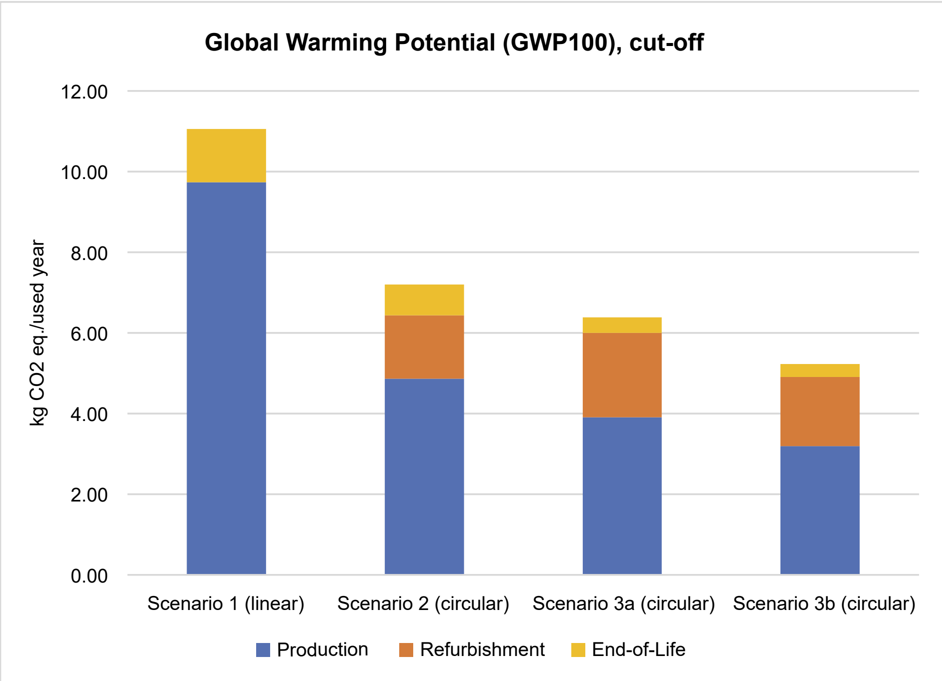

Figure 35: Global warming potential for renovating kitchens.

3.2.7 Leisure boats

This case compares linear and circular versions of a 10 metre recreational boat. Over 70 % of boats this size are constructed from glass reinforced polyester (GRP), a thermoset polymer composite. It has a high strength to weight ratio and is a long living material, resistant to the marine environment. However, they are difficult to dismantle and recycle, particularly the GRP, which is typically incinerated. Almost all motorboats are fossil fuelled driven, although electrified boats are emerging. Many boats are long lived (over 40 years) and therefore a major impact occurs during the use phase, due to fuel use and use of anti-fouling paints.

LINEAR SCENARIO

The linear case looks at a standard 10 metre boat with a diesel engine and a 30 year operational lifetime. The boat is manufactured in Sweden using modern manufacturing methods in a factory producing 53 of these boats per year on average (in addition to boats of other sizes). An average of 126 operation hours per year is assumed, with an average speed of 10 knots and a fuel consumption of 15 litre/hour. For maintenance it is assumed that the engine is replaced once and the battery twice during the boat's lifetime. At the end of life, the components are recycled whilst the GRP hull is incinerated.

CIRCULAR SCENARIO

The circular scenario is a so-called "prolonged lifespan" scenario where the expected lifetime is 50 years instead of 30 years. Another difference is that recycled components are used during maintenance.

ECONOMIC ASSESSMENT

The sales price of a brand-new boat is estimated 2 500 000 SEK for both the linear versus prolonged lifespan scenario. During use, maintenance is needed in both scenarios. The assumption is that the diesel engine is replaced once and the battery twice during the lifetime of the boat in the linear case. In the prolonged lifespan scenario, the battery is replaced four times and the engine three times. The cost of a new battery is estimated on 362 000 SEK while an engine is estimated on 200 000 SEK. Hence, the TCO in the linear scenario (ignoring any costs customers might have to finance the purchase and ignoring time value of money) equals 3 424 000 SEK for 30 years of use, and 4 548 000 SEK in the prolonged lifespan scenario for 50 years of use. Because the expected lifespan of the prolonged lifespan boat is longer, the total costs for consumers is calculated per year. The linear case results in 114 133 SEK per year, while the prolonged scenario results in 90 960 SEK.

CIRCULARITY ASSESSMENT

Virgin material input: the virgin material costs is calculated by extracting the weights and materials from the bill of materials used in the LCA and multiplied with commodity prices. Only the manufacturing of the boat and main components replaced are included in the calculations, while the assumption is that smaller maintenance and fuel is similar on yearly basis in both cases and can be ignored. As explained above, more components are replaced in the prolonged lifetime scenario, but components are replaced by recycled ones, hence having no virgin material costs during use.

Calculating economic value: the sales prices for the new boat and the main components are included in the economic value calculations. The assumption is made that engines and batteries are replaced after equal amounts of time, e.g., in the linear case the engine is replaced once, halfway the lifetime of the boat, in this case replaced after 15 years. The end-of-life value of the boat equals the material value of mainly steel (Figure 36 and 37).

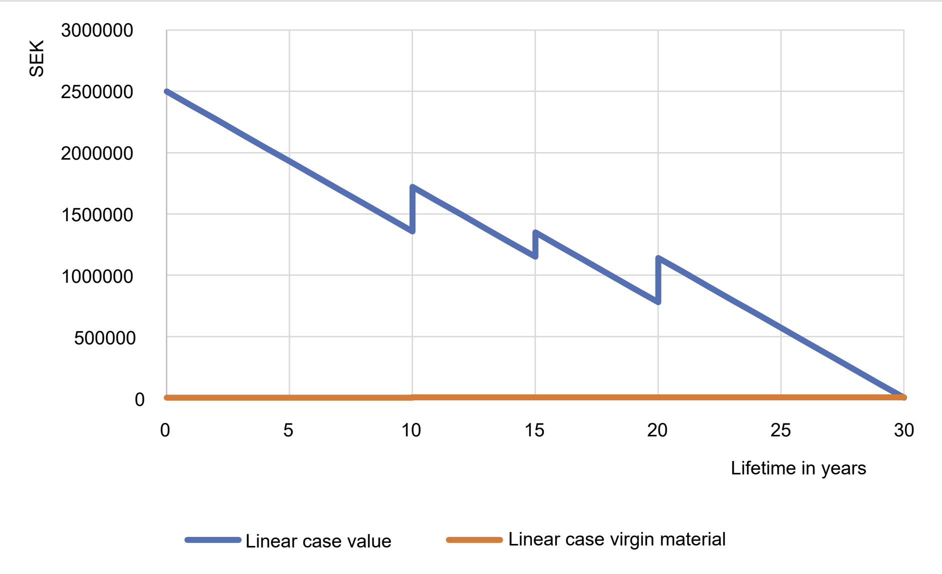

Figure 36: Circularity calculations of a boat.

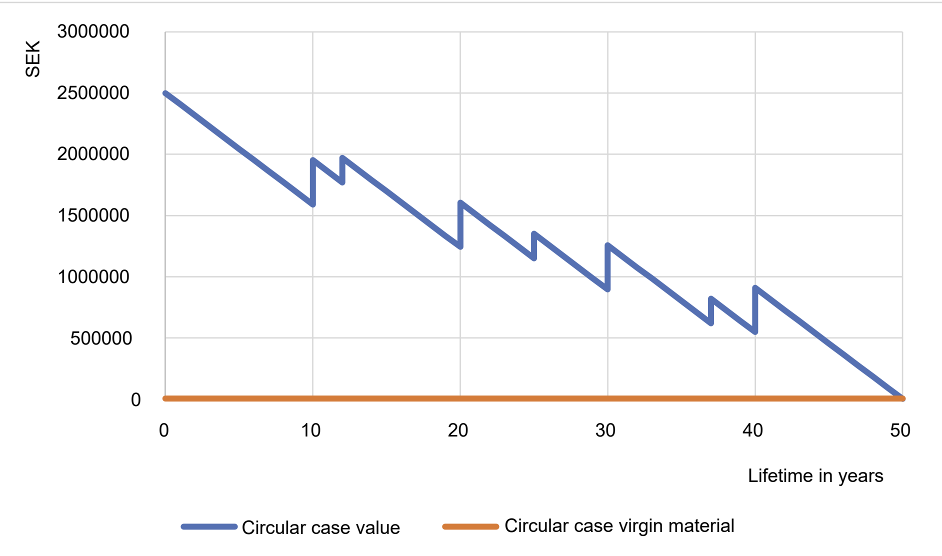

Figure 37: Circularity calculations of a boat with prolonged lifetime.

The LFR results in 7 712 for the linear scenario and 16 229 for the prolonged lifetime scenario, a significant improvement mainly due to less use of virgin material. The economic value of the linear versus prolonged lifetime scenario is almost equal.

ENVIRONMENTAL ASSESSMENT

Two additional scenarios on electric boats and company leasing were developed and compared for the environmental assessment. For electric boats, the diesel engine is replaced with an electric motor and a battery pack. The scenario includes changing electric components for maintenance. The example uses Swedish electricity, which has one of the lowest carbon intensities in the world (with therefore low GWP impacts). For the company leasing scenario, the boat is owned by a company and leased to five separate customers, thereby reducing the number of boats required, but increasing the number of boating operating hours per year to 630. Recycled batteries and engines are assumed to be used for maintenance.

A comparison of the four scenarios shows that there is a small reduction in GWP for prolonging the lifespan, which is reduced further in the company leasing business case (Figure 38). The impact from raw materials and manufacturing is reduced considerable in the company leasing compared to the base case. However, because the main impact is derived from the use of diesel as fuel the overall reduction is only 17 %. A much more dramatic reduction is obtained by switching the technology to electrical driven boats, resulting in a life cycle reduction of 82 % for GWP. If the use of electric boats would be combined with the company leasing model, there would be further reductions. In addition, company leasing reduces other impacts considerably because of an overall reduction in boats required. This would reduce material extraction impacts but also toxicity impacts derived from anti-fouling paint in the use phase, with one boat in the water, instead of five.

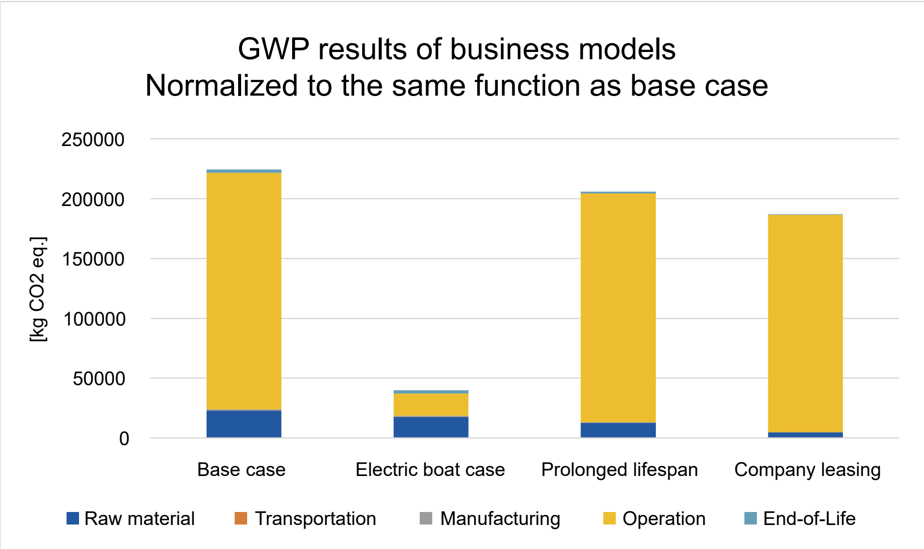

Figure 38: Comparison of the GWP for the three business models and the linear base case.

3.2.8 Lights

This case describes the provision of lights as a service. The main customers are municipal classrooms with changing needs over time which require a continuous dialogue with the customer to provide the right solution and services. The company offers improvements and upgrades of the lights when needed due to e.g., changing regulations and standards, for example colour rendering index (CRI), and incorporating more energy efficient technologies. (This case is also published as master thesis part of the LinCS project, Longnell, 2019).

LINEAR SCENARIO

A comparison scenario (provided by competitors, not the company) will be 50 years of using lights by customers. Customers in a linear scenario would need to buy several lights to cover this period. For a fair comparison, the lights should provide the same type of function/service and represent the upgrades done by the customer in the circular scenario. In other words, it covers the lights a customer would have bought in the 50 years' time period if they would not have subscribed to the service (Table 12).

Table 12: Simplified overview of circular and linear case (Longnell, 2019).

Year	Upgrades	Circular case	
0		New lighting fixture	New lighting fixture
5	Light quality	Upgrade LED chip	New lighting fixture
10	Internet of Things	Upgrade controller	New lighting fixture
15			
20	Energy-efficiency	Upgrade driver	New lighting fixture
25	Maintenance	New LED chip	
30	Internet of Things/Light quality	Upgrade software	New lighting fixture
35			
40			
45			New lighting fixture
50	Maintenance	New driver	

CIRCULAR SCENARIO

In the circular scenario, lights will have an approximate lifespan of 50 years with four upgrades for light quality, Internet of Things, energy-efficiency, and software. In addition, maintenance is conducted twice on average to change the LED-chip and the driver. Lights and parts of lights that are taken back are checked and reused. 100 % of the lights are returned to the company and 100 % is refurbished where only small parts are replaced. Components have different lifespans, for example a driver will live on average for 15 years, LCD 20 years, back plate 50 years, and fixtures keep on living on. Reuse, via refurbishment, is therefore possible for a long time period by replacing the broken parts.

Customers pay for a certain service. In first instance they get a standard basic package. Upgrades are discussed thereafter. There is no price difference depending on the age of the light, customers pay for a certain service.

ECONOMIC ASSESSMENT

In the circular case, customers pay a fixed leasing fee per month per square meter. The leasing fee stays the same regardless of the age of the product. In the circular case, the leasing fee is set at 340 SEK a year for one fixture. In the linear case, the sales price of a comparative fixture (i.e., 2 500 SEK) is assumed. The lighting is used for 8.3 years on average, giving a total of 6 new lighting fixtures to cover the same usage period of 50 years. In this case, the TCO of leasing the light fixtures instead of buying them leads to a slight increase in costs. If the customers have a 2 % discount rate, the total cost of buying lights would be 12 163 SEK for a 50 years period while leasing results in a total cost of 16 331 SEK for 50 years.

CIRCULARITY ASSESSMENT

The *virgin material costs* of the product and its upgrades are calculated based on the weight of each material in the product and during upgrades and commodity prices of each material. The assumption is made that the end-of-life value is the virgin material costs added to the product minus the virgin material that is discarded somewhere in the process. The virgin material costs in the linear case are estimated at 835.33 SEK per fixture. In the circular case, the virgin material input of producing the fixture is estimated at 597.95 SEK which is lower than in the linear case due to the reuse of old components during the manufacturing process of the light. The upgrades during the 50 years lifespan lead to an additional virgin material input that equals 589 SEK.

The *economic value* of the circular model can be calculated based on the leasing fee of 340 SEK a year for one fixture. While the light as a service contracts are flexible and can be cancelled by the customer, we assume that customers will plan to use the service for several years. Assuming decision periods of five years, the starting point is 340 SEK times 5, i.e., 1 700 SEK. The fixtures retain value and can be kept in use after a small check. We assume a value of 330 SEK for this check after which the value of the fixture is back on the original level. After all, the customer pays the same fee regardless of age (Figure 40). In the linear case, the sales price of 2 500 SEK is assumed for all fixtures (Figure 39).

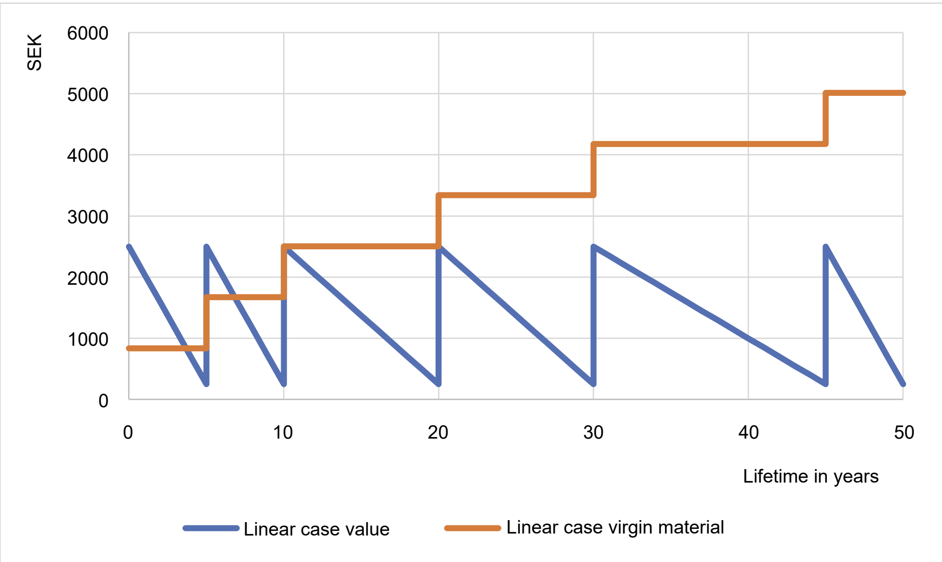

Figure 39: Circularity calculations of linear case: 6 new fixtures.

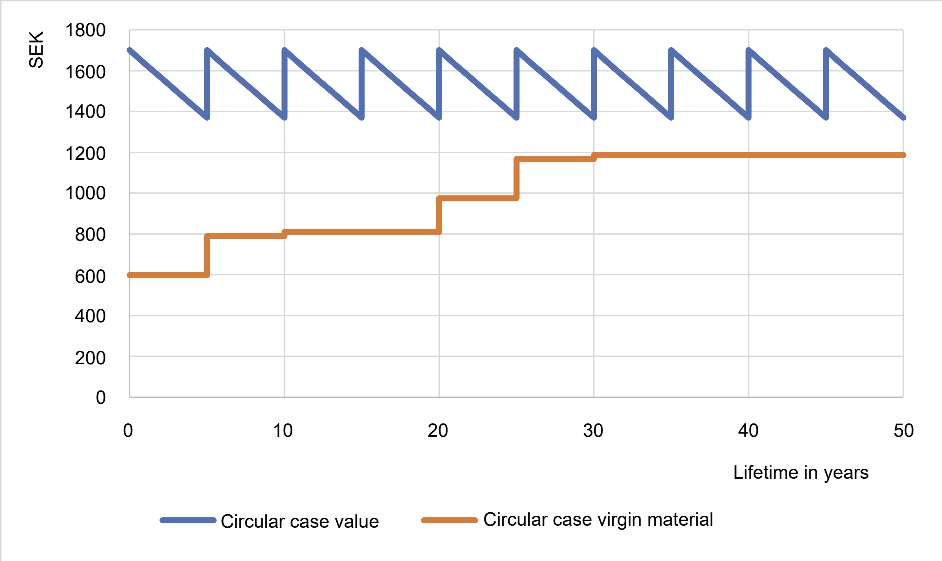

Figure 40: Circularity calculations of circular case: light as a service.

The circularity degree of the linear scenario is 14, while the circular scenario results in 65. This is reached through the slightly higher utility for the customer, but moreover by the much lower virgin material costs. Due to maintaining and upgrading the fixture during its life, much less materials are needed to provide the same function.

ENVIRONMENTAL ASSESSMENT

There is a reduction of impact for all impact categories for the circular case, ranging from 34 % for GWP to 53 % for abiotic depletion potential (ADP) (Table 13).

Table 13: Environmental impact of circular and linear scenarios for different impact categories (adapted from Longnell, 2019).

Environmental impact category	Linear case	Circular case	% Change
GWP (kg CO2-eq)	4840	3190	–34 %
AP (kg SO2-eq)	22.4	13.6	–39 %
EP (kg Phosphate-eq)	24.10	12.30	–49 %
POCP (kg Ethene-eq)	2.32	1.45	–38 %
ADP elements (kg SB-eq)	0.66	0.31	–53 %
ADP fossils (MJ)	48200	26340	–45 %

The major impact comes from the manufacturing phase, followed by the use phase Figure 41. This helps explains the large reduction of impacts from the circular case study by retaining the materials and components and avoiding further manufacturing. The impact categories with the largest reductions are those associated with materials that are used to manufacture the product. Packaging, transport and end-of-life have relatively negligible impact.

The results are sensitive to the number of replacements assumed with the linear system. For example, if replacement over the 50-year period is reduced from 6 to 4 replacements the reduction in GWP is 23 % (instead of 34 %). Therefore, the benefits depend on several factors including the life length of the linear alternative, but in addition how other benefits of the circular system are exploited such as the ability for Wi-fi integration and transmission.

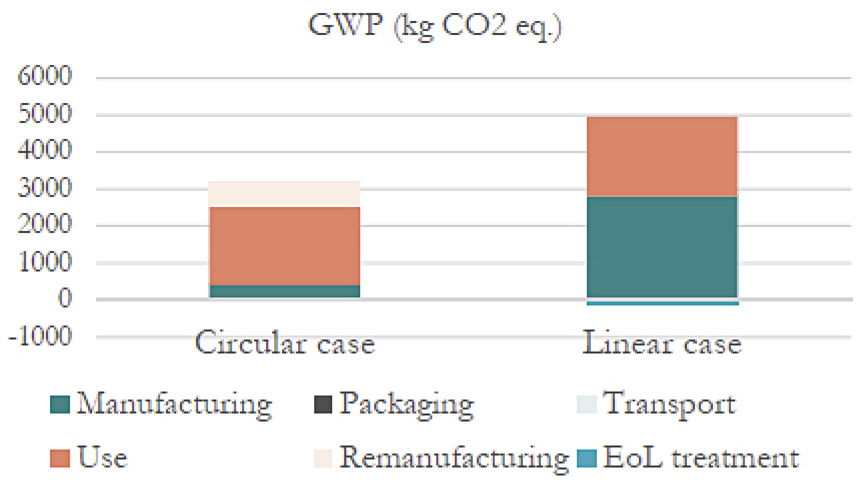

Figure 41: Contribution analysis of the lifecycle stages for the circular versus linear for GWP for the light case study.

3.2.9 Signs

This case describes the manufacturing of signs. Most of the customers are commercial property owners such as company hotels, and malls as well as trustees of public spaces. Signs are bound to change when a company changes name or location. At that point in time, most signs are scrapped. However, the company has started working with a circular sign concept to increase reuse.

LINEAR SCENARIO

The company offers a linear counteroffer where recycled material is more in focus. In this case, signs are made in aluminium and acrylic in a concatenated structure. The sign is sold and used for 4 years and is then scrapped. The concatenated structure makes it hard to change individual components, instead quite a lot of the sign must be changed at the same time.

CIRCULAR SCENARIO

The circular product is a modular sign where parts can be changed independently. Since this type of signs are currently out for first use and none have returned yet, the lifespan and average usage duration of the signs is unknown.

However, assumptions are made around when to change components in the sign as well as the number of times a sign can be reused. A reusable glass sign with exchangeable foil is assumed to be sold and used 6 times with different foils over a period of 25 years. The foil is changed every four years at the manufacturer's facility. LEDs are exchanged after 8 and 16 years at the customers location. A new coating of paint is applied before 5th use (i.e. after 16 years, also done at the customers location). The sign is scrapped after 25 years.

ECONOMIC ASSESSMENT

In the linear scenario, the sales price is 16 500 SEK. For the circular scenario, several discussions have been held about a fair price for the signs. Should customers pay the same price for signs in the first, second, or third life since they get the same function, or should customers pay less when signs become older. There is no definitive answer yet on what the price will be for second or third life signs. First, the assumption is made that remanufactured signs are offered at 70 % of the newly manufactured sign, following available literature on average prices of remanufactured versus new products. The sales price of the new sign is equal to the linear counteroffer, i.e., 16 500 SEK. Subsequent sales prices of the sign (2nd, 3rd, 4th, 5th, and 6th time) are 70 % of 16 500 SEK, i.e., 11 550 SEK. Hence, the TCO over a time period of 25 years equals 103 125 SEK for the linear case (where a new sign is bought every four years), and 74 250 SEK if customers would buy a new modular sign and use it for 25 years with changes every four years (Figure 42).

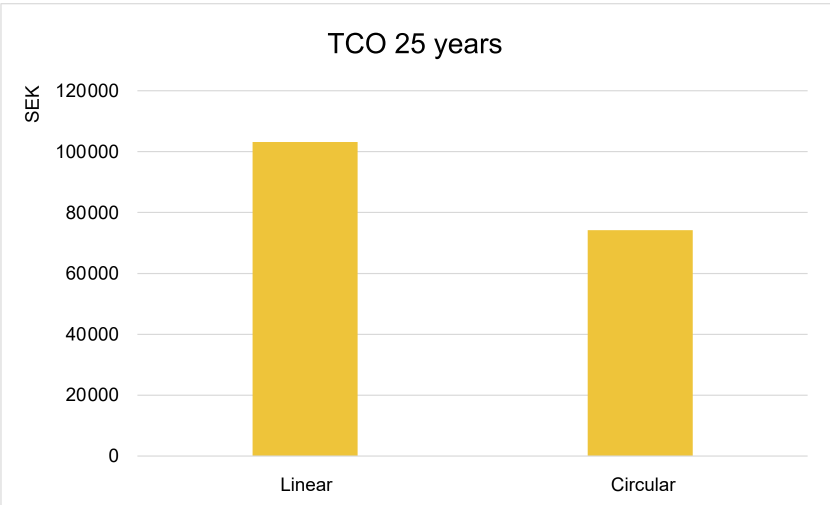

Figure 42: Total costs for customers buying signs for 25 years of use.

Data is collected and assumptions are made on the manufacturing costs for new signs for both the linear and modular sign, the transportation costs from factory to the customer, return transport from customer to the manufacturer's facility, costs for service and maintenance at customer location, costs for exchanging foils, and costs for recycling the signs at the end of life. The data is masked to protect confidentiality, but the relative results of the costs, revenue, and profit of the linear and circular business model is presented in Figure 43.

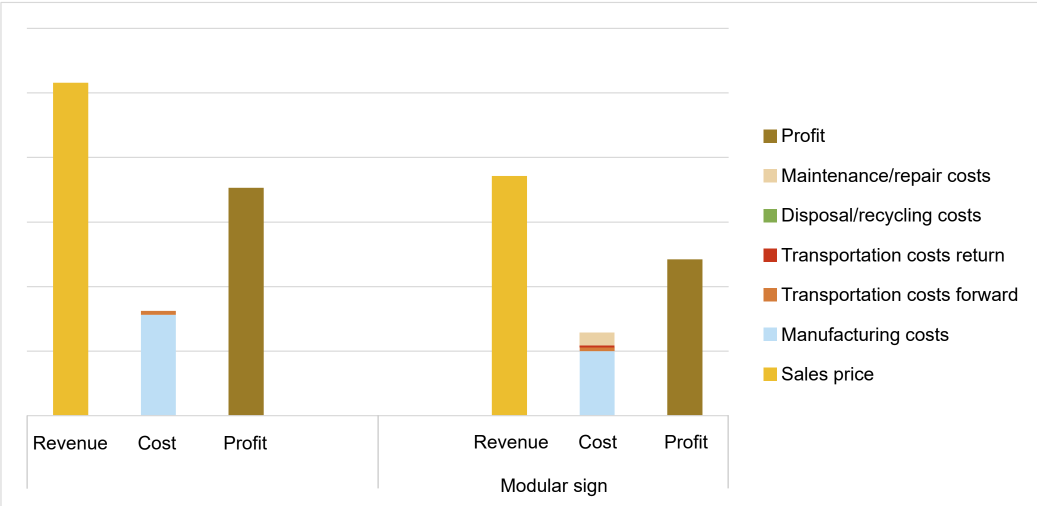

Figure 43: Revenue, costs, and profit of selling new and modular signs over 25 years.

The circular modular sign results in less revenue due to lower sales prices in the second to sixth time. The costs are also somewhat lower, mainly due to less manufacturing costs (only one sign is manufactured compared to six in the linear case). However, higher costs for return transport, service, maintenance and repair costs, and recycling costs exist in the circular model. This results in lower profits for the manufacturer than in the linear case.

CIRCULARITY ASSESSMENT

In the linear scenario, the end-of-life value is estimated at 35 SEK, while the virgin material cost is calculated at 4 500 SEK (Figure 44). In the circular scenario, at the end of the use phase, the signs are bought back against an assumed price of 5 000 SEK (Figure 45). The end-of-life value is equal to the linear scenario, i.e., 35 SEK. The virgin material cost is slightly higher than in the linear case, totalling 6 000 SEK including production and maintenance.

Figure 44: Circularity calculations of linear model: selling signs.

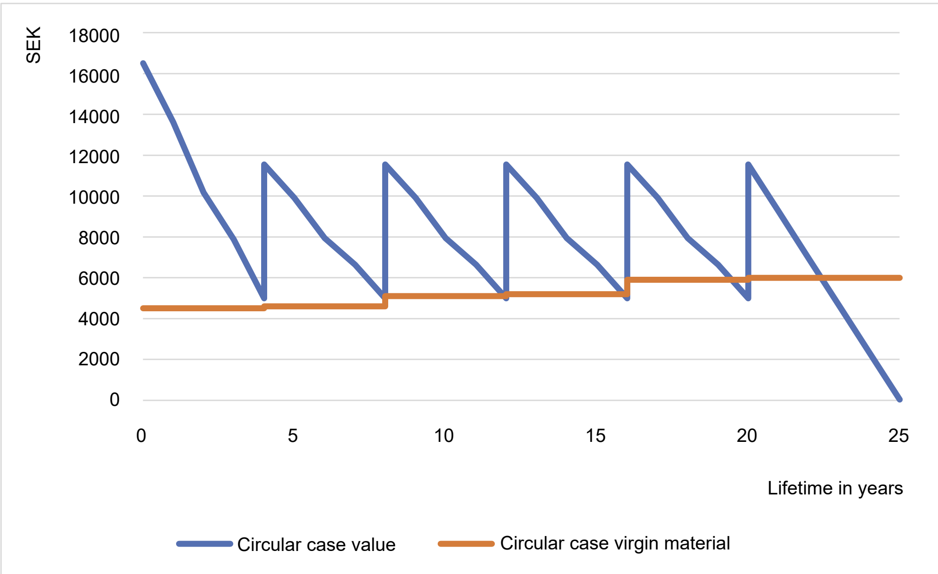

Figure 45: Circularity calculations of modular signs.

The LFR of the linear scenario is seven while the circular scenario (with lower prices for remanufactured signs than new signs) is 34. This is mainly due to the lower virgin material use in the circular modular case compared to the linear case of manufacturing new signs every four years.

ENVIRONMENTAL ASSESSMENT

The LCA study looked at six different scenarios (Table 14), which essentially looks at using different core materials for the linear and circular product versions.

Table 14: Overview of scenarios for LCA.

Scenario definitions	
Scenario 1 (linear, glass front sign)	Glass front sign is used for 4 years.
Scenario 2 (linear, aluminium front sign)	Aluminium front sign is used for 4 years.
Scenario 3 (linear, acrylic front sign)	Acrylic front sign is used for 4 years.
Scenario 4 (circular, glass front sign)	Glass front sign is used for in total 25 years and is refurbished every 4th year.
Scenario 5 (circular, aluminium front sign)	Aluminium front sign is used for in total 25 years and is refurbished every 4th year (hypothetical scenario).
Scenario 6 (circular, acrylic front sign)	Acrylic front sign is used for in total 25 years and is refurbished every 4th year.

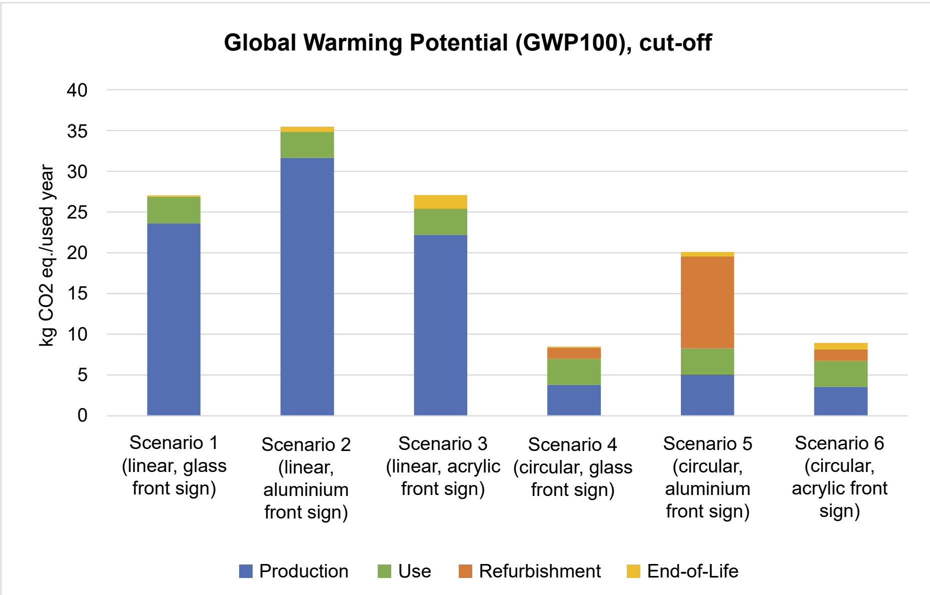

Figure 46: GWP for the linear and circular sign product versions for different materials.

For all of the materials, the circular versions have a much lower impact for GWP (Figure 46). The corresponding reduction in impact for the glass, aluminium and acrylic is 68.6 %, 43.3 % and 66.9 % respectively.

3.2.10 Woollen sweaters

Clothing manufacturers have begun developing approaches to become more circular through recycling, reuse, and repurposing of textile. In this case, wool waste from raw material production is upcycled into new woollen sweaters. Wool, despite its importance as a textile fibre, has little value in Sweden. In several recent studies, it was concluded that only 8 % of Swedish wool is used for textile production, with over 75 % of wool produced ending up as a waste product (Olofsson et al., 2010; Svenska Fåravelsförbundet, 2017). This is due to the current restrictions on the use of agricultural by-products, classifying wool as a waste product with no economic incentives to valorise the wool beyond disposal (Olofsson et al., 2010). Sweden also imports large shares of wool from neighbouring countries, in addition to a substantial share of wool being imported from abroad for its large clothing sector (Olofsson et al., 2010; Behaderovic and Zalkat, 2018). As a meat producing farm, shearing of the sheep is mandatory several times a year. In Sweden, the wool has no economic benefit for the sheep farmers and incurs costs for shearing and disposing of the sheared greasy wool. As such, the greasy wool is typically incinerated or composted on the farms. As such, it is essential to further develop the market for this product and understand how to sustainably manage it in new supply chains, providing added value to sheep farmers and clothing manufacturers.

LINEAR SCENARIO

The functional unit is one mid-weight sweater produced from wool. For the comparative linear case, wool is sheared and scoured in Sweden, after which it enters the same supply chain as described below.

CIRCULAR SCENARIO

The waste wool, also called greasy wool, is collected from a sheep farm nearby. In this new value chain, after shearing, the greasy wool is manually collected and sorted at the farm. Thereafter, it is shipped for scouring. In the scouring process, the greasy wool is washed and sorted. The process requires machinery to separate, wash the wool, heat for the liquid baths, and to separate the fat (i.e., lanolin), and requires detergents for washing. At the moment, no lanolin is captured at the company. However, two different scouring paths scenarios were assessed; the current system, where the wool is scoured on Gotland, and the planned future scenario, where the wool will be scoured in Belgium, which allows for lanolin capture and a higher quality wool yarn. From the scouring process, the wool is shipped to Lithuania, where it is spun into yarn. Furthermore, the yarn is produced with no dying or bleaching of the wool yarn to preserve the natural colour. This yarn is then used to produce different weaves in Lithuania. From the weaving process, the woven fabric is cut and assembled in the garment assembly plant in Estonia. The final midweight sweater of roughly 600 g wool is then shipped back to Sweden for retail.

ECONOMIC ASSESSMENT

The relative costs for producing a sweater in the conventional supply chain is shown in Figure 47. The largest cost component is the production process of the sweater itself. The purchase of wool is a minor contribution to the total costs of producing one sweater, roughly 5 % of the total costs.

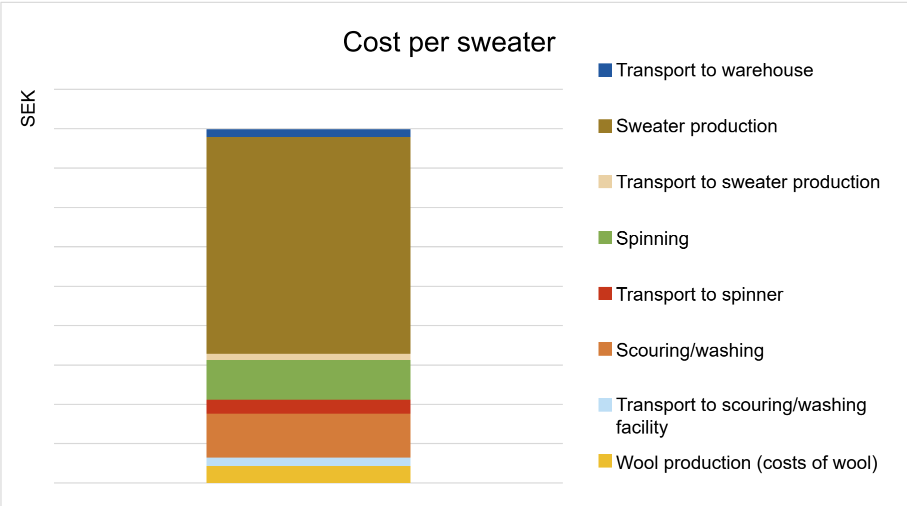

Figure 47: Costs of manufacturing one sweater. Only relative data is shown to protect confidentiality.

CIRCULARITY ASSESSMENT

The assumption is made that the use of greasy wool does not affect how the consumer values the products, hence the utility of the linear and circular sweater is assumed to be equal. The virgin material input costs are, however, significant lower if greasy wool is used. Wool, due to their relative high commodity price, represents the largest virgin material costs for the sweater. No end-of-life value is assumed for sweaters (Figure 48 and 49).

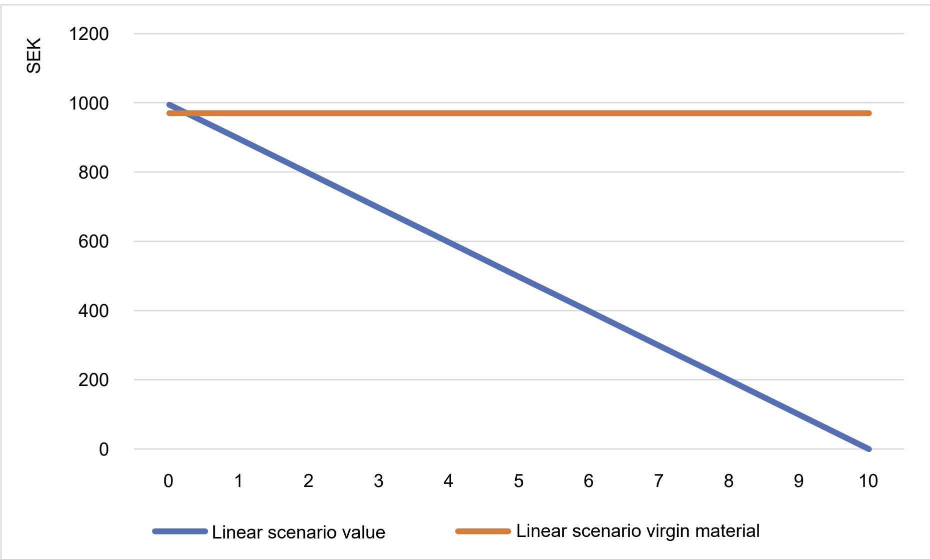

Figure 48: Circularity calculations of conventional woollen sweater.

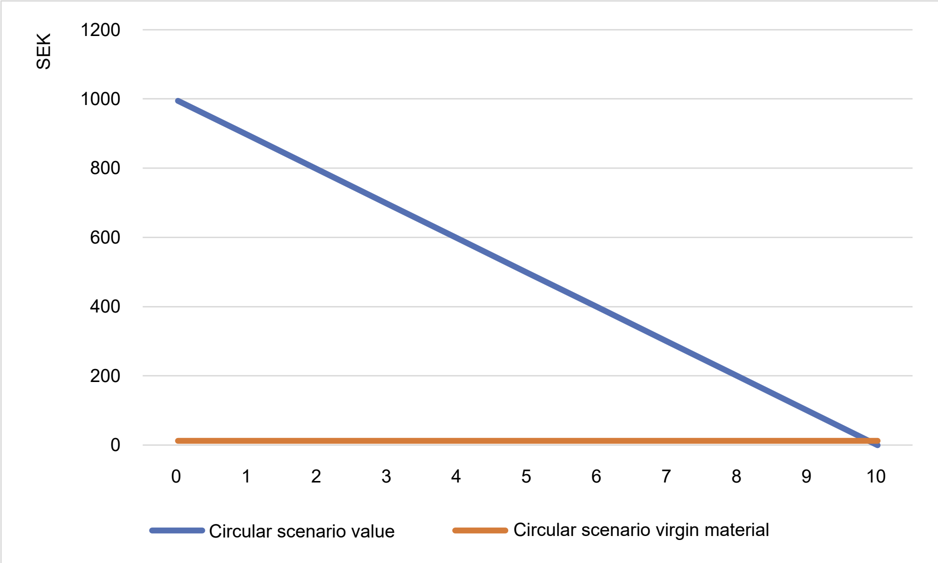

Figure 49: Circularity calculations of woollen sweater made of greasy wool.

The circularity calculation shows an improvement of more than 8 000 % by replacing conventional wool with greasy wool. The linear case results in a LFR of five while the circular scenario results in a LFR of 416. Since the value of the sweater is considered the same in both scenarios, this is solely due to the much lower virgin material costs when greasy wool is used.

ENVIRONMENTAL ASSESSMENT

The environmental assessment was conducted to provide an assessment of the environmental performance of valorising waste wool for producing garments to promote more sustainable decision making along the supply chain. This includes assessing the implications along the new supply chain and comparing it with conventional supply chains for wool and the manufacturing of garments, providing a novel contribution as few previous studies of wool systems go beyond the farm gate. The functional unit for the assessment is one mid-weight sweater produced from waste wool. The study includes a cradle-to-gate perspective, including the acquisition of the waste wool, all processing of the wool to produce yarn, knitting, final assembly, and final availability at the suppliers' warehouse and web shop, only available as an exclusive product through the web shop. Impacts from retail, washing, and end-of-life are not included in the study.

Table 15: Impacts per sweater for the different supply chains. SE-EE: Swedish wool, sweater production in Baltics, AU-EE: Australian wool, sweater production in Baltics (including upstream wool impacts), SE-BE-EE: Swedish wool, Belgian scouring, sweater production.

	GHG Emissions ($kg\ CO_2$-eq)	Acidification (Mole H+ eq.)	Freshwater eutrophication (g P eq.)	Resource depletion – mineral, fossils and renewables (g Sb eq.)	Resource depletion – water (m^3)
SE-EE	6.3	0.03	5.0	0.07	0.02
SE-BE-EE	6.2	0.02	4.0	0.04	0.21
AU-EE	14	0.25	8.0	0.26	0.03

The valorised wool process (i.e., the SE-EE and SE-BE-EE supply chains) have GHG impacts of roughly 6 kg CO_2-eq per sweater from a cradle-to-gate perspective, which are not significantly different between the European supply chains (Table 15). However, the conventional AU-EE supply chain, nearly doubles the GHG emissions per sweater. The SE-EE and SE-BE-EE supply chains have lower environmental impacts in nearly all categories. However, the water resource depletion in the SE-BE-EE supply chain is much larger than other supply chains, primarily due to the choice of the electricity system for process energy in the Belgian scouring and spinning process.

The results suggest that, compared to conventional supply chains for wool to produce sweaters, the use of the waste wool contributes to a CE, and goals and targets for more sustainable production in the clothing industry.

3.3 Conclusions

This chapter assessed the environmental and economic impact of ten case study products and quantified the circularity degree of each study.

3.3.1 Economic impact of circular products

Almost all cases showed a lower TCO in the circular scenario compared to the linear scenario. Customers will have to pay less to get the same functionality. This is in line with literature which reports a general discount for consumers when using reused, remanufactured products instead of new (Jakowczyk et al. 2017; Pang et al. 2015). It is argued that this price discount is needed to attract customers to recovered products (Abbey et al., 2015b; Souza, 2013). However, previous research has focused on buying items and research is lacking on the willingness-to-pay for recovered products offered in leasing or sharing business models where the customer is not responsible for any faults (van Loon and Van Wassenhove, 2020). More knowledge is needed to help companies setting the right price that can make their circular offer profitable and economical attractive and perhaps prevent rebound effects in consumption.

Companies offering customers a product or service through leasing or sharing business models do not meet the customers in person and setting the right price is complex. It is reasonable to assume that digital platforms when using the service are of great importance, and the type of added value offered through the platform will be key to secure customer relationships and future revenue. Getting to know each specific user through data analysis will be important to segment the relationship strategies. The role of customer service is also highly impacted, as traditional customer service opening hours (reflected by the open times of offices/stores) are being challenged by e-commerce shoppers and users of shared business models, which might need help during evening time if something urgent occurs. The experience of the contact with customer service could be the difference of customer retention or not in a market where there are many actors offering similar types of sharing and leasing services. In order to establish profitable and secure customer loyalty, more knowledge is needed in what type of added services there are, how and if it motivates higher prices, what service customers require and how these requirements impact the costs of operating a circular business model.

The case studies showed that profitability is an issue for some manufacturers. Even though the costs in the circular model are often estimated lower than in the linear model due to the manufacturing of significant less items to fulfil the same demand, the profit is also in many cases lower due to the lower revenue. This flags an important issue; companies seem to struggle with understanding customers' willingness to pay for circular models and might think, rather than know, that large discounts are needed to attract customers. This lower price has a large impact on the profitability of the circular business model. Knowledge about feasible prices may help companies in developing attractive circular offers.

3.3.2 Environmental impact of circular products

The case studies show that the circular offer significantly reduced the GHG impacts, in all but one case. In many cases, the GHG impacts were reduced by 50 to 60 %. By recovering the materials and components of used products and enabling reuse, refurbishment, or remanufacturing, the production of a new product and its environmental impact can be prevented. Thus, the recovery process or business model that enables life extension is usually less material- and energy-intensive.

The exception in our case studies is the chainsaw example, where the increased amount of transport between customers and rent locations for each use resulted in an increase in GHG emissions. This highlights one limitation of the LCA work, the analysis of the circular offer relies on several assumptions. Although this provides a small level of uncertainty, with the expected reduction of carbon intensity for the global transportation systems (e.g. due to the Paris Agreement and related targets), the performance of circular offers is likely to improve. However, an expected reduction in the carbon intensity of the underlying production systems will improve the carbon footprint of many linear products. That is not to say that linear products will match circular products, but highlights that we need to consider other environmental impacts. As the problems of GHG emissions are reduced, the material intensity becomes ever more central, with the associated impacts of extraction and mining processes and impacts on biodiversity. In summary, it is likely that the superior performance of circular products will become even more apparent in the future.

3.3.3 Circularity and environmental impact

When comparing the environmental results with the circularity assessment (Table 16), one can see that the circularity metric does not necessarily show the same improvement when transitioning to a circular product as the LCAs show.

Table 16: Summary of environmental and circularity performance of circular compared to linear product case studies. A minus percentage for GWP indicates a reduction in GWP when moving from linear to circular. A minus percentage for circularity indicates a worse performance for the circular product than the linear counterpart.

Product	GWP	Circularity
Bearings	–60 %	–25 %
Beer kegs	–210 %	10378 %
Chainsaws	+54 %	1765 %
Chairs	–25 %	–6 %
Jeans	–60 %	318 %
Kitchens	–35 %	549 %
Leisure boats	–17 %	110 %
Lights	–34 %	372 %
Signs	–69 %	363 %
Woollen sweaters	–55 %	8014 %

For bearings and chairs, the circular product has lower impacts in terms of GHG emissions but scores worse on circularity. In both cases, the circular product has lower virgin material costs, but due to the significant lower price of the recirculated product, the circular product has a lower circularity score. The lower price for customers allows additional spending on other products leading to a possible rebound effect (see the next chapter).

In the chainsaw example, the circular offer scores better on the circularity metric but worse in terms of GHG emissions. However, the environmental impact related to the production of chainsaws (e.g., mineral resource scarcity) is decreased when moving from the linear to circular offer because more consumers can use the same chainsaw and hence less chainsaws need to be manufactured to fulfil a certain demand. Because of use of less materials to generate a certain utility, the circular offer scores better on the circularity metric.

4 Linking the product (micro) level to the national (macro) level

This chapter presents the work on linking the system levels and understanding the macro level effects (Swedish national level) of circular improvements made at the micro (product) level. It examines how indicators, assessments and monitoring at these levels can be linked. The subsequent aim is therefore to suggest key indicators and a framework to facilitate the transition to CE. This includes consideration of any rebound effects caused by improvements in efficiency or changes in product use and customer behaviour. The objectives were to identify:

1. appropriate macro-level indicators that are complementary to micro-level indicators;
2. models and frameworks that help understand the link between product level changes and macro system level impacts that may occur.

This is achieved through a comprehensive literature review, a modelling exercise of macro-level effects caused by micro level improvements, and development of a potential framework to link the micro and macro levels. The methodology is explained in the next section before the results are presented and then discussed. Finally, recommendations for a framework to aid the assessment and monitoring of the transition to CE are made.

4.1 Methodology

The methodology consists of a literature review, modelling exercise (that models micro level effects at the macro scale) and investigation of CE of the inner loops. These are outlined in the following sections.

4.1.1 Literature review

In order to provide a foundation for the modelling, a literature review was conducted that focused on indicators and environmental assessment of CE products (Harris et al., 2021). Specific search terms targeted the three system levels, *micro, meso*, and *macro* and were limited to the period 2010–19. The search terms combined “circular economy” with other terms including environmental and sustainability assessment, life cycle assessment, quantification or measurement. The review focused on consumer products and therefore did not include construction, forestry or agriculture, as these are regarded as requiring specific approaches and policies that differ from consumer products. In addition, cities were not included at the macro level as an initial review of associated search terms identified that the literature on CE in cities is mainly related to solid waste management and water management, which does not align with the focus on consumer products.

The search terms yielded over 508 articles which were screened to less than 200. Articles were classified based on the analysis framework (table below). A separate related review of grey literature started with known reports from agencies and country governments (EU, Netherlands, China) such as *Indicators for a circular economy* by EASAC (2016) and reports from organisations like Ellen Macarthur Foundation and continued searching with search term 'circular economy' coupled with country names (e.g. circular economy; United States and/or EPA). A selection of grey literature reviewed is in the Appendix.

The articles were reviewed with a focus on both evaluating how (or if) studies compare circularity indicators with environmental performance or link the circularity indicators between society levels (e.g. the micro and macro-levels).

4.1.2 Multi-Regional Input-Output Modelling

The main aim of the modelling was to assess the implications at the macro level of the product changes at the micro level (associated with the LCA findings of Section 3) and increase the knowledge on which indicators can be used to monitor the levels. Scenarios are developed based on the LCA results to question "what if" similar circular improvements to products were implemented at the macro-level. This is not intended to be an accurate projection of a future state, but assess potential macro effects, including rebound and help understand what indicators or assessment might be required to monitor CE. The research considered the latest methods for environmental assessment of CE at different levels. At the macro level the following were considered:

1. Economic-based approach: Environmentally extended multi-regional input-output analysis (EE-MRIO)– e.g. EXIOBASE.
2. Mass-based approach: Joint Research Centre (JRC) Life Cycle Indicators – where material flow analysis from trade data is combined with a database of 500 representative products (LCA models). (Corrado et al., 2020.)

It was clear that the most appropriate method was MRIO as this is increasingly applied at the macro level to assess, cities, countries and the global impacts. In Sweden, it was the foundation of the PRINCE project (www.prince-project.se) to assess the footprint of consumption at the Swedish national level. In addition, the mass-based approach developed by the JRC has not reached a level of development that enables easy usage.

The literature review identified that a potentially useful framework to link the micro and macro levels of society is that of the societal needs or functions (Alaerts et al., 2019; de Wit et al., 2018). This framework categorises the products and services required by society into seven societal functions (SF's): Housing and Infrastructure, Nutrition, Mobility, Consumables, Services, Healthcare and Communications.

Therefore, the method utilised Exiobase which is a EE-MRIO-database to explore the potential implications of macro-level changes for key products (from Chapter 3) from micro-level improvements. The objectives are to:

- Determine the current impacts of the functions.
- Determine the contribution that circular improvements for the product group(s) (from the LCA) can make if applied at the functional level.
- Investigate potential rebound effects due to changes in expenditure.
- Test the SF framework to help monitor the macro and micro level changes induced by CE.

Exiobase is a global MRIO database that captures a significant proportion of the global economy in a database and links it to environmental impact coefficients (or vectors). It consists of 200 product groups, 163 industries and 48 countries. The calculation of a consumption footprint for a region in Exiobase, essentially (in simplified form) involves the multiplication of three matrices (Figure 50). The production coefficient table (consisting of 200 by 200 product groups) describes the production recipe, which is how much of the inputs in the rows are required to produce one unit of the products in any given column. The environmental extension matrix provides the emissions of resources used to produce one unit of the product or service. The final demand relates to how much of the products and services are consumed by a country, region or city.

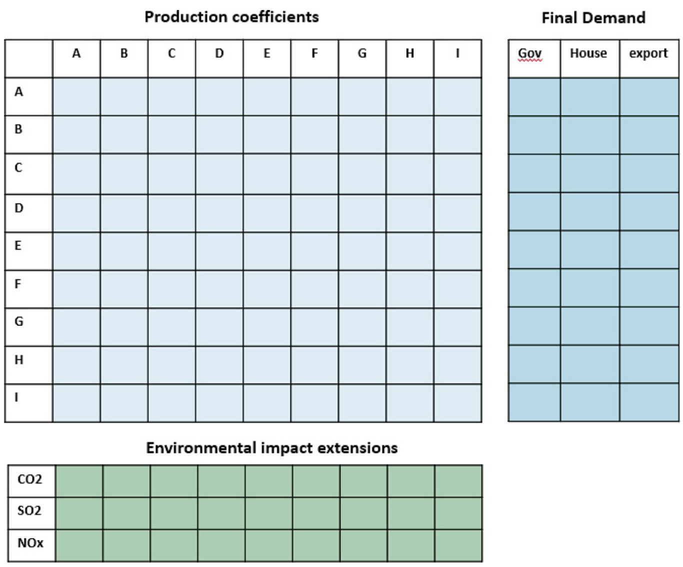

Figure 50: Basic matrices of Exiobase needed to calculate a consumption footprint

MRIO MODELLING

The 200 product groups of EXIOBASE were categorised into seven societal functions following de Wit et al. (2018) and consideration of Schmidt et al. (2019) (who place the product groups into similar categories but do not define them as societal functions). Each of the products that were modelled in Task 2 using LCA is placed into one of the seven societal functions as follows:

1. Housing – chair, kitchen, light.
2. Nutrition – none.
3. Mobility – bearing and boat.
4. Consumables – beer keg, jeans, signs, woollen sweater and chainsaw.
5. Services – none.
6. Healthcare – none.
7. Communications – smartphone.

Additionally, due to the challenges in assigning some product groups to societal functions, we added two further categories: "materials" and "others" (see Appendix 2 for a list of how product groups were aligned into the societal functions). EXIOBASE was divided into four regions Sweden, EU, Asia and Rest of the World (RoW), to facilitate changes to the intermediate products and production system. However only final demand was adjusted in the modelling, as all of the circular product versions (apart from boats) were related to life extension (LE). The modelling sought to scale up the effects of the LCA circular changes observed at the micro level (the LCA's in Chapter 3), to the macro-level for the associated product groups.

Hence, the resultant changes from the LCA analysis were assigned to the societal functions by mapping and modelling similar changes from the linear to the circular product. The conversion of impact reductions or increases from the LCA studies is challenging to convert into relevant changes within the final demand categories of Exiobase. This was therefore kept relatively simple, also to enable transparency as detailed in Table 17. Nearly all of the changes relate to LE and an increase in related services to facilitate activities such as repair and refurbishment. For example, for the chair LCA study, the lifecycle was extended by either 10 or 20 years, leading to a reduction of 6 % and 25 %. In the MRIO modelling, this life extension is assumed to reduce expenditure by 50 %. Similarly, for kitchens, which exist in the same societal function, the material-use is reduced from 617 kg to 145 kg in the refurbished kitchen and results in a reduction of 53 % in GWP. The move to a circular business model for lights also results in reductions of 60 % for all impact categories. Therefore, as can be seen in Table 17, changes were made to relevant product groups within Exiobase based on the LCA results.

Table 17: The changes assigned to the product groups within EXIOBASE based on the LCA product results, which were implemented on the four societal functions.

Societal function	Products	Type of circular change*	Exiobase (No.) and product description	LCA impact categories findings	Changes made to final consumption expenditure	
					Decrease	Increase
Housing	Chairs	LE	(125) Furniture, other manu goods	–6–25 % GWP	– 50 %: 125 Furniture 154 Wholesale trade 155 Retail trade services	+ 10 %: 172 Other business services +1 %: 163 Support. & aux transport
	Kitchens	LE	(125) Furniture, other manu goods	–53 % GWP		
	Lights	LE & increase in electronic components	(125) Furniture, other manu goods	–60 % all Impacts Categories		
Mobility	Bearings	LE and service increase	(124) Other transport equipment	58 %–65 %. reduction in emissions of CO2, NOx and SO2 60 % less materials and 62 % less waste	–50 % spending	+5 %: 152 Sale and maintenance
	Boats	Electric, sharing, higher use intensity	(124) Other transport equipment	74 % GWP reduction with biodiesel 78 % GWP reduction with electric motor	–40 % spending on new boats & cars	
Consumables	Beer kegs	LE	(154) Wholesale trade and commission trade ser	–50 % for GWP	– 50 % 154 Wholesale trade	+10 %: 163 supporting and aux transport
	Signs	LE	(154) Wholesale trade and commission trade ser	43 to 69 % reduction (depending on materials)		
	Jeans and wool sweaters	LE	(56) Wearing apparel: furs	54 % less impact over most IC	–60 %	+ 10 %: 63 Paper (bags)
	Chainsaws	Increased quality, service increase	(118) Machinery and equip. n.e.c.	35 % higher GWP – (transport dependent) 40 % less mineral resources	–50 % 8	+10 %: 169 – renting services
Communications	Smart-phone	LE	(121) Radio, TV and commun. Equip.	62 % and 36 % GWP reduction for – circular business models cloud offloading and modularity, respectively	–40 % 121	+5 %: 164 Post and tele services +10 %: 170 Computer and related services (cloud) + 10 %: 119 Office mach. & comp. (cloud)

*LE = Life extension

The study focuses on households as the products studied apply mainly to households, but also because this final demand category accounts for a major portion of impact (Ivanova et al., 2016). Direct emissions were not included as only as a total figure within Exiobase for national households and there is no method to discern to which SF's they are attributed to. In addition, most of the products above (boats being the exception) do not result in direct emissions. Therefore, we assume that the direct emissions remain relatively stable within our model.

MODELLING POTENTIAL REBOUND EFFECTS

The rebound effects are modelled by reassigning the savings in expenditure due to the modelled changes, to other product and services based on three scenarios. The total decrease in expenditure due to life extension was small at 2.48 %, but this still allows for modelling of potential rebounds. The following three scenarios were chosen to represent worst case (increased flying) and other lifestyle choices that could occur where spending is either spent on leisure or investment:

1. Flying rebound – assigns the difference in expenditure to extra vacation.
2. Culture rebound – assigns the difference on recreational services and some extra commuting as well as restaurant and hotel services.
3. Financial rebound – assigns the difference in expenditure to financial intermediation services, insurance and pensions and auxiliary financial intermediation.

In the Flying rebound, the difference is allocated to different products associated with an overseas vacation using an air travel. The Culture rebound allocates, the difference to products related to increased spending on cultural and recreational activities. In the Financial Rebound, the allocation is made to products associated with financial services, pension funds and investmentand auxiliary services connected to these financial services. This is intended to represent and model personal investments in stocks, shares and other savings.

4.1.3 Investigation of the economy of the inner loops

Currently, the extent and size of the existing circular economy is largely unknown apart from statistics on waste and recycling quantities. Even this does not accurately describe circularity because some recycling materials are eventually incinerated. However, there is already a significant base of reuse, repair and remanufacturing in Sweden, which consists of second-hand markets and for example sales of spare parts. Therefore, in this project we wanted to review the available information on this part of the economy. The purpose is to perform a review of which statistics are available for these inner loops of the economy(including spare parts and the second-hand market). This attempts to identify the current value and mass flows of the maintenance, repair, reuse and remanufacturing economies.

The approach was to search the statistics on imports and exports of Sweden using data from Sweden Statistics (SCB). This analysed data on imports, exports and production in the following KN levels: 4, 6 and 8 (where 8 is the most detailed level). A simple analysis was performed that searched KN numbers using the following search terms: "Reparation", "Delar", "Delar till" and "Tillbehör".

4.2 Literature review

The review provided an overview of indicators and assessment methods suitable to track progress towards CE and provided guidance for linking system levels.

4.2.1 Circularity indicators and environmental assessment of system levels

As stated earlier, a more thorough review can be read in Harris et al (2020). Here, lessons are separated in terms of the three system levels of micro (referring to products), meso (industrial symbiosis) and macro (national or city level). Starting with the micro-level, there are several environmental assessment methods used in the CE context at the product-level including footprint based methodologies (carbon, water, material and ecological), energy/exergy based analysis, material/substance/chemical based analysis, indicator analysis (sustainable process index, dissipation Area Index, Sustainable Environmental Performance Indicator) but LCA is the most predominant (Elia et al., 2017; Saidani et al., 2019; Tanzer and Rechberger, 2019; Tecchio et al., 2018). Studies focused on the measure of circularity revealed over 70 indicators and tools for use at the product and other levels (meso, macro) which cover a broad range of CE elements (Table 18).

Table 18: CE elements assessed by reviewed circularity indicators by life cycle stage. Source: adapted from (Parchomenko et al., 2019).

Extraction (inputs)	Production	Use	After use/recovery	Disposal (emissions/ impacts)
➢ Supply risk and scarcity of resources ➢ Energy consideration ➢ Stock availability or concentration ➢ Recycled material value	➢ Sharing of infrastructure/ utilisation of resource streams ➢ Additional process inputs ➢ Primary vs. secondary materials, parts and products	➢ Embedded stocks or distinct lifetimes ➢ Longevity or residence time ➢ Value change or production use	➢ Downcycling and quality loss ➢ Materials mixing ➢ Product, part, material retention ➢ Cascading use of resources ➢ Potential for recycling or remanufacturing ➢ Recycling, remanufacturing, recycling complexity ➢ Recycling efficiency	➢ Waste disposal

Others not classified by life cycle stage	
➢ Resource productivity or process efficiency	➢ Modelling of materials cycles
➢ Spatial dimension	➢ System stability
➢ Destination of flows	➢ Toxicity and clean material cycles

Boyer et al (2020) suggest three dimensions for inclusion in the measurement of circularity, which relates to slowing material throughput (maintenance) recirculation of materials and utilization rate (Figure 51). There are a number of indicators to address these dimensions, but many have limitations. Some tools are time-intensive and/or may require immense amounts of data (e.g. the PCI, (Linder et al., 2017)). Others have limited application and have only been applied to specific sectors, e.g. waste quality and treatment options (e.g. the CEPI, (Huysman et al., 2017)). In addition, with the abundance of indicators and tools, there is a risk that organisations will pick and choose indicators that provide results that fit to their own needs and brand (Pauliuk, 2018). Finally, while CE strategies such as circular business models are promoted, actual environmental impact outcome is often uncertain (Kjaer et al., 2018; Tukker, 2015; Tukker and Tischner, 2006).

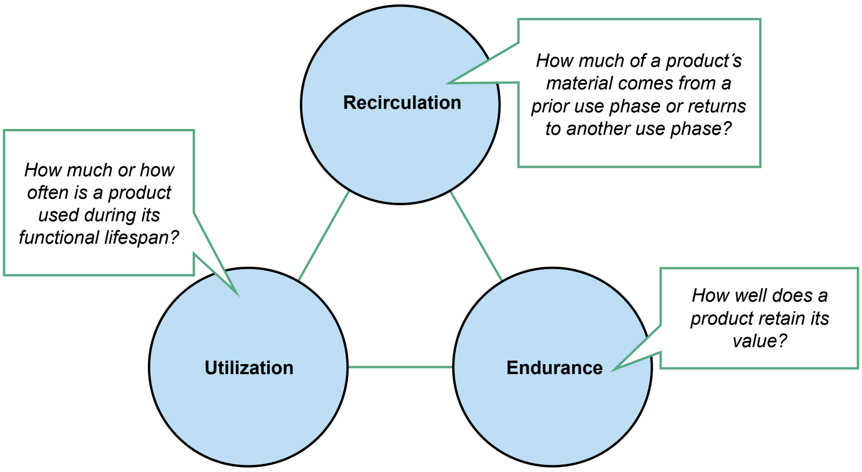

Figure 51: three dimensions of circularity (Boyer et al 2020)

Few studies compare the correlation between circularity indicators or tools and environmental implications e.g. using LCA. One exception is Lonca et al. (2018) who show some correlation (Table 19) but approaches such as extending product lifetime sometimes yield less-than-beneficial results. In fact, in a review of environmental assessments of circular solutions, van Loon et al. (2021) found that not all lead to environmental impact reductions. The outcome was found to depend on the characteristics of product use, frequency of related product innovation and the methods and assumptions of the assessment (van Loon et al., 2021). Rebound effect is also noted as a potential issues but is challenging to assess due to the wide system boundaries of circular solutions (Zink and Geyer, 2017).

Table 19: Level of alignment of environmental assessment methodologies with the five CE requirements. Methodologies provide either direct or indirect quantification, and this is noted at the relevant level. Source: adapted from Lonca et al., (2018).

Level of alignment (increasing going down)	Environmental Assessment Methodologies
1. Reducing inputs and the use of natural resources	*Indirect:* EDP – Ecosystem damage (indirect); *Direct:* ExA – Exergy Analysis; EmA – Emergy Analysis; EE – Embodied Energy; CED – Cumultative Energy Demand; EF – Ecological Footprint; MIPS – Material Inputs Per unit of Service
2. Increasing the share of renewable and recyclable resources	*Indirect:* SPI – Sustainable Process Index; DAI – Dissipation Area Index; *Direct:* EPSM – Environmental Performance Strategy Map; SEPI – Sustainable Environmental Performance Indicator; CF – Carbon footprint
3. Reducing emissions levels	*Direct:* WF– Water Footprint; MFA – Material Flow Analysis
4. Reducing valuable materials losses	*Indirect:* SFA – Substance Flow Analysis; LCA
5. Increasing the value durability of products	*None addressed increasing the durability of products*

Finally, it is acknowledged that combining methods and indicators will give a more nuanced assessment of a circular solution. A few studies complement LCA with other types of analyses to incorporate other aspects of relevance to CE. For example, studies have combined LCA with cost-benefit analysis (Landi et al. (2018)), the Material Reutilization Score and the MCI (Niero and Kalbar (2019), and the MCI with life cycle sustainability framework (Niero and Hauschild (2017), Lonca et al (2018). Each of these studies note some divergence between the assessment methodologies and emphasise the importance of complementing singular circularity tools with other analyses.

There is less literature that addresses the environmental implications of the CE at the meso-level. Again, the most commonly used environmental assessment method is LCA, together with other life-cycle based methods (e.g. carbon footprints) and MFA. Emergy and energy analyses, resource efficiency indicators and combinations of these methods are also utilised (Figure 52). Notably, the meso-level studies were similar to micro-level with a focus on both environmental impacts and circulation of materials (as opposed to macro-level which were predominantly focused on circulation of materials).

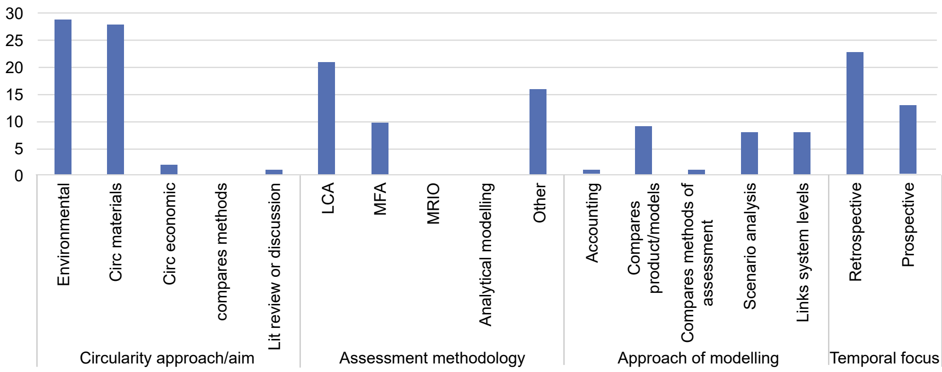

Figure 52: Number of publications at the meso-level that cover each of the inclusion criteria of the literature based on the approaches and methodologies (Harris et al 2021)

Studies at the meso-level address a range of direct environmental impacts on the meso-level and more notably (e.g. associated with industrial symbiosis), several articles have also assessed the indirect impacts of meso-level changes on other system levels (such as implications for the impacts of products, see e.g. (Mattila et al., 2012; Røyne et al., 2015)). In addition, while many of the meso-level studies focus on industrial symbiosis (IS) networks as the object of analyses, some studies have assessed the broader sector-level implications of resource efficiency and environmental performance benefits from IS networks (see e.g. (Geng et al., 2012; Mattila et al., 2012; van Ewijk et al., 2018)). Nonetheless the need for further investigation into sectoral implications to track the progress towards CE is noted. For example, van Ewijk et al. (2018) suggest an approach to link sectoral level circularity indicators to progress towards CE. Finally, there are examples of monitoring industrial parks or regions in China (Geng et al., 2012; Mattila et al., 2012) related to the national programs to monitor the implications of circular approaches, such as industrial symbiosis.

A review of macro-level literature revealed the most room for improvement. First, aggregated indicators are used to assess material circularity and resource productivity, but this approach fails to address environmental impacts. In addition, national indicators do not cover the stocks or the use phase and there is therefore the current level of the CE is largely unknown, because the level of repair, maintenance, remanufacturing and second-hand market is not quantified (Harris et al., 2020). Several papers echo this point and suggest new indicators including: stocks (Aguilar-Hernandez et al., 2019; Graedel, 2019), longevity (Franklin-Johnson et al., 2016), in-use stock growth and useful service lifetime of materials (Pauliuk, 2018). Moreover, better accounting of the inner-loops (e.g. reuse, repair, refurbishment and remanufacturing) is needed. For instance, the EC estimated that reuse and recycling activities are associated with 3.9 million jobs, but those related to renting, leasing or spare parts and repair industries are not included (European Commission, 2018b). Indicators are largely focused on material flows related to: production and consumption, waste management, secondary raw materials and competitiveness and innovation (European Commission, 2019). These are similar in scope and approach to those of China (Geng et al., 2012). Additional limitations of current European material-based indicators include: (1) that the data may not be available, (2) weight does not reflect environmental impacts, and (3) they do not measure reduction or prevention (EASAC, 2016; Geng et al., 2012).

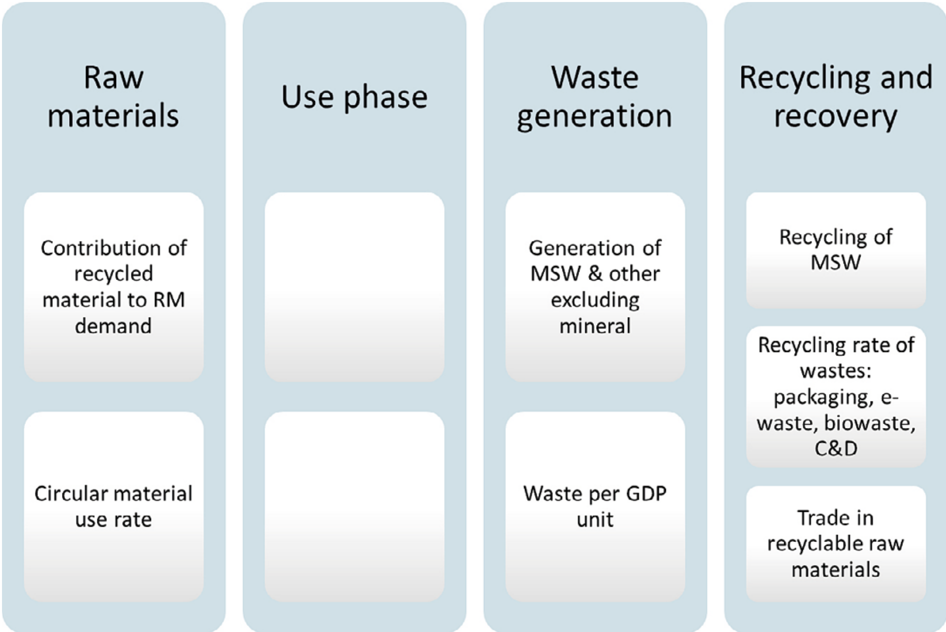

Figure 53: A life cycle view of the EU's CE indicators showing a void for use phase (Source: Harris et al. 2021)

In summary, besides a gap in metrics in the use phase, there are few articles that discuss or examine the link of CE between the system levels, particularly in terms of environmental impacts. These limitations highlight the need to connect circularity to environmental impact, monitor CE at all system levels (beyond product and firm level), and determine a which aspects need to be measured. The challenges identified for this work are something that the international standards organisation (ISO) has identified and is addressing. Among others, technical committee 323 (TC 323) has ongoing work about how to standardise CE principles[5].

[5] https://www.iso.org/committee/7203984.html

4.3 Modelling Results

4.3.1 Current status of household consumption

The results of the footprint impact analysis for the SF's are shown in Figure 54 and Figure 55. housing and infrastructure accounts for most of the GWP impact (30 %), with nutrition (21 %), mobility (19 %) and consumables (14 %) also making high contributions. For the material footprint housing and infrastructure and nutrition together account for a major part of the impact with 29 % and 28 % respectively.

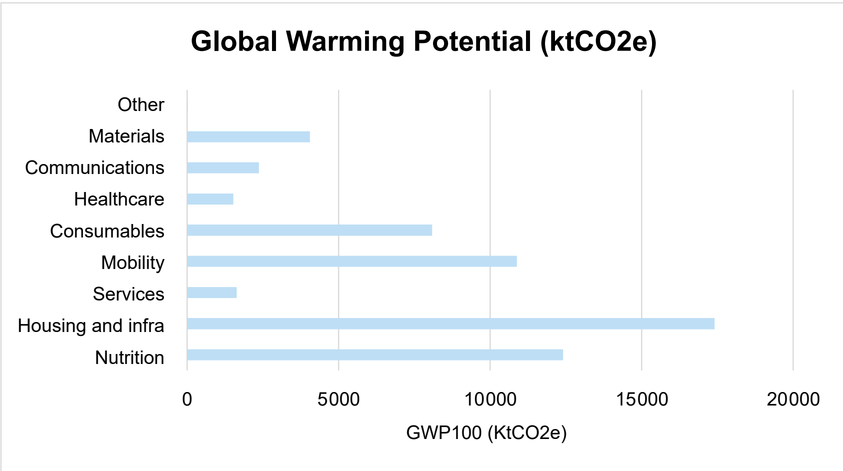

Figure 54: Global Warming Potential footprint of Swedish household consumption, year 2011, by Societal Function

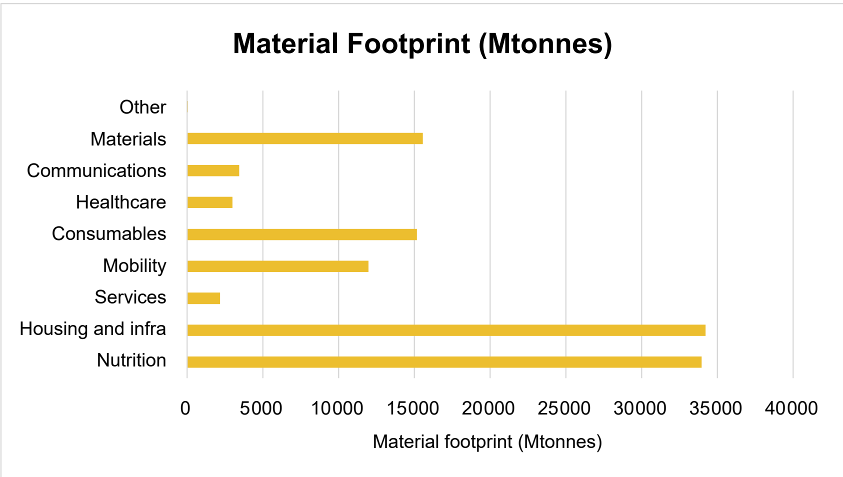

Figure 55: Material footprint of Swedish household consumption, year 2011, by Societal Function

A closer look at the Housing and Infrastructure SF in Figure 56 shows that the largest contributions come from “steam and hot water services” and “real estate services”.

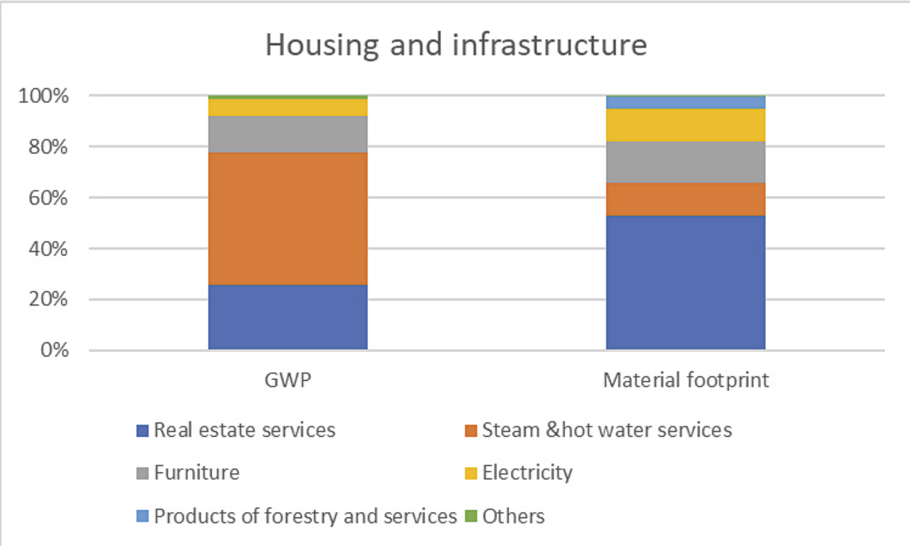

Figure 56: Contribution of main product groups of Housing and Infrastructure to GWP and material footprint

Mobility is dominated by motor transport on land as shown in Figure 57, and the use of fuel with motor gasoline and gas/diesel oil together accounting for 35 % of GWP and 41 % of the material footprint.

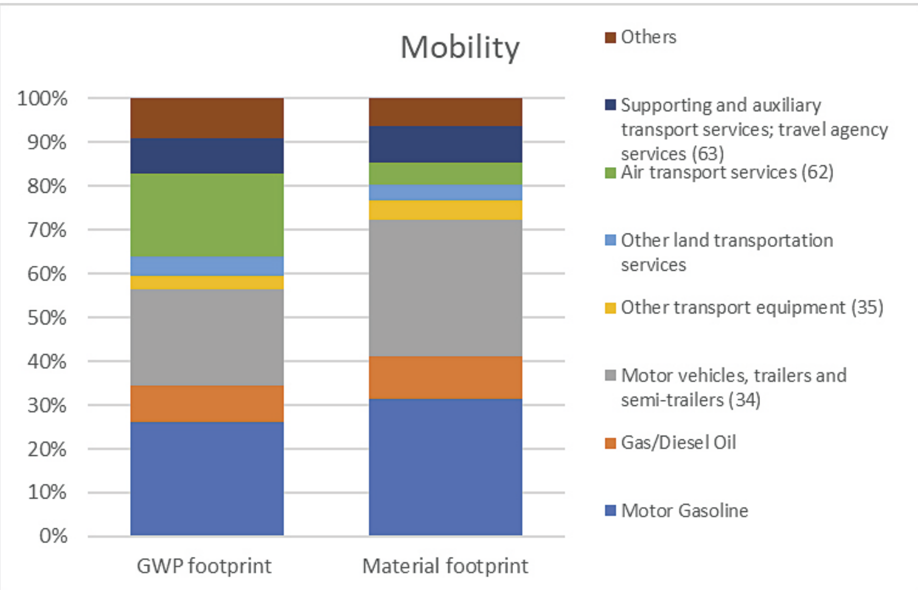

Figure 57: Contribution of main product groups to Mobility to GWP and material footprint

Consumables (Figure 58) on the other hand is dominated by hotels and restaurant services for GWP (30.8 %) and a similar picture is observed for material footprint (27.4 %). Wearing apparel and textiles are also strong contributors with 15–16 % of the impact for both GWP and material.

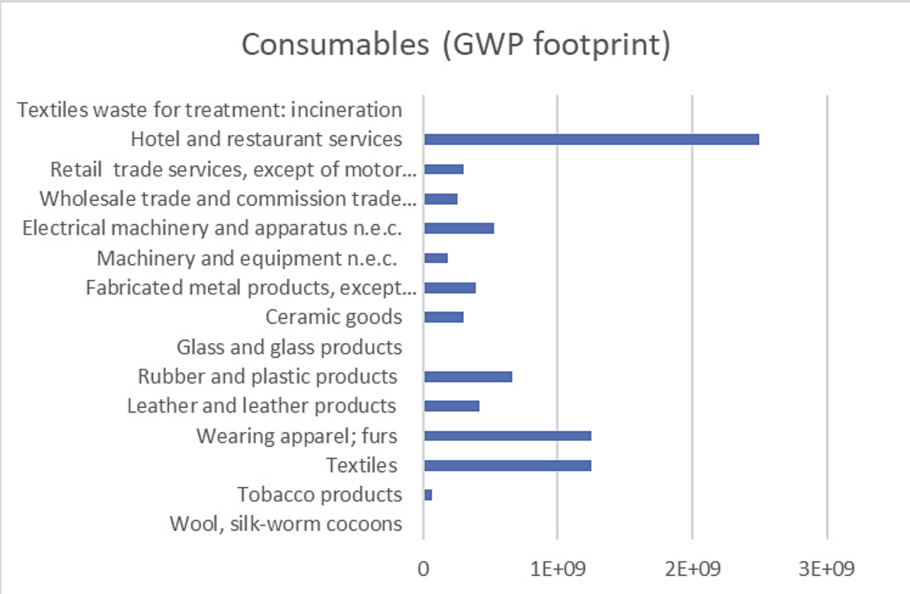

Figure 58: Contribution of the main product groups to Consumables for GWP

The Communications SF is dominated by "Radio, television and communication equipment" for both GWP and Material footprint with 40 % and 47 % respectively, which primarily relates to electrical and electronic equipment.

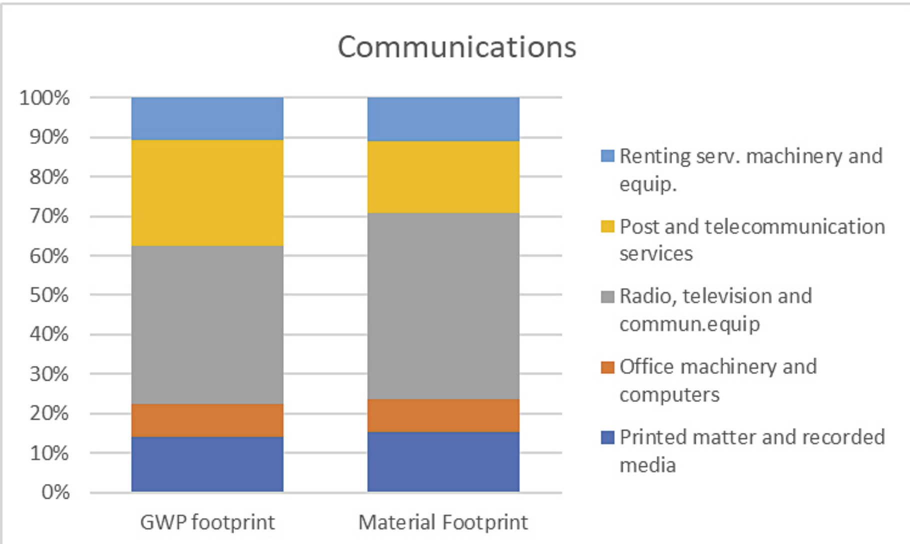

Figure 59: Contribution of main product groups to Mobility to GWP and material footprint

4.3.2 Potential of CE and/or the rebound effect scenarios

IMPLICATIONS OF CE CHANGES

Table 20 shows an overview of the decrease in environmental impacts due to the product LEs. The largest reductions show to be in GWP100 and Material Use, both of which are over 4 %. This is mostly since the products included are material and production heavy.

Table 20. Overview of difference in Environmental impacts due to product LEs

	GWP100	Land Use	Material Use	Water Use
Original	5.84E+10	1.65E+05	1.20E+05	1.43E+03
LE Adjusted	5.58E+10	1.62E+05	1.14E+05	1.39E+03
% Difference	4.40 %	2.08 %	4.19 %	2.67 %

Further examination of the results reveals that the largest decrease of impacts originates from Housing and Infrastructure and Consumables. The decrease in the first category is mostly due to lower demand for furniture, which includes chairs and kitchens, while the decrease in the latter category is mainly due to a combination of lower demand for clothing, communication equipment, and a lower demand for trade services. Figure 60 and Figure 61 below show an overview of the reductions per category.

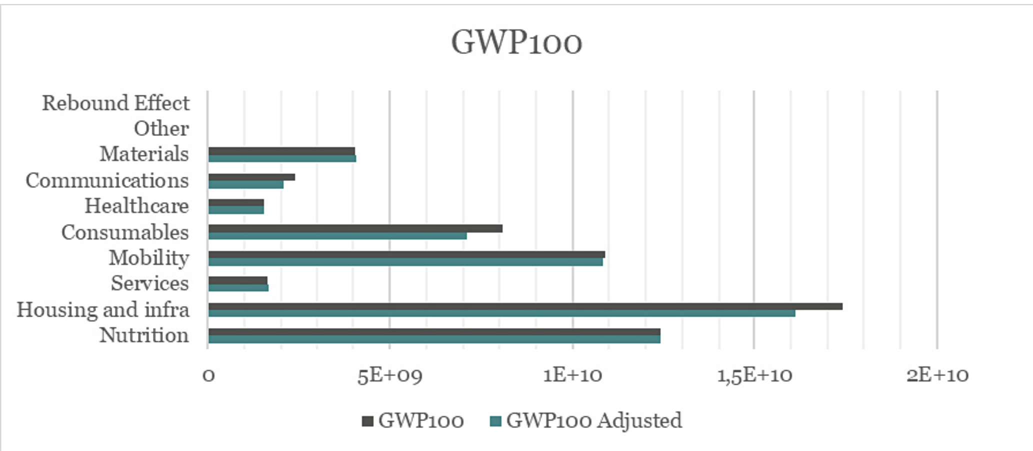

Figure 60: Reduction of GWP due to LE per Societal Function.

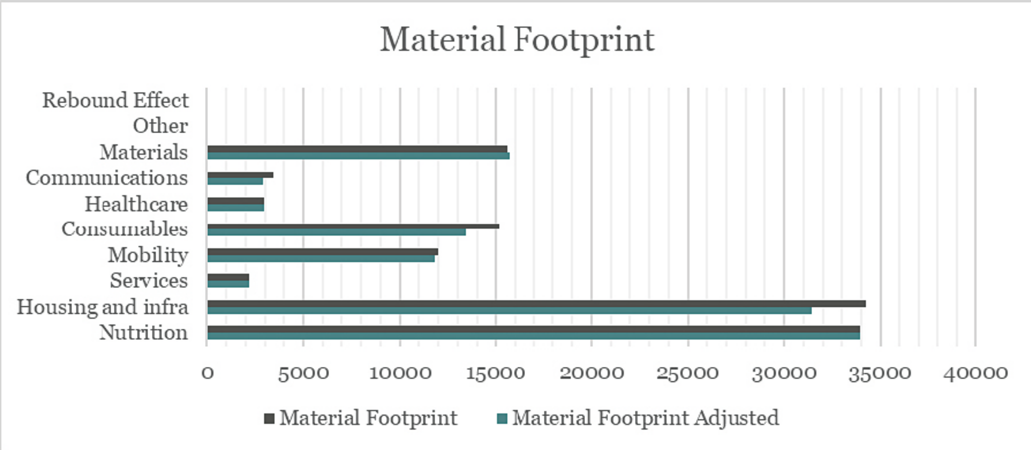

Figure 61: Reduction of Material Footprint due to LE per Societal Function.

The increase in services associated with the move to circular business models needed for LE, also has an associated impact. However, this is not included as a specific rebound effect in Figure 60 and Figure 61, but instead they are coupled with the associated products and services. This is because they are considered necessary system changes to implement the business model. The results show that these changes account for less than 1 % of the total impact of the adjusted demand, as shown in Table 21.

Table 21: Footprint impacts of the services associated with circular business models for life extension.

	GWP	Land Use	Material Use	Water Use
Service "rebound effects"	2.58E+08	9.00E+02	4.27E+02	2.57E+00
Percentage of Total Impact	0.46 %	0.56 %	0.37 %	0.19 %

IMPLICATIONS OF THE POTENTIAL REBOUND EFFECTS

A wide range of Exiobase products are utilised in the three scenarios. Motor Gasoline and "recreational, cultural and sporting services" are present in both the Flying Rebound and the Cultural Rebound, but all other products are different in the scenarios. Total expenditure for each scenario is the same as the original final demand. Figure 62 compares the impacts for GWP and Material Use for the original demand, the demand after LE, and each scenario. Note that the demand after LE ("After LE") results show the impacts without the savings being assigned to any other categories, and therefore represent no rebound effect.

The results show that none of the scenarios match or overtake the original demand in terms of total impact in GWP or Material Use. While the Flying rebound has the largest impact of all scenarios in GWP, the Culture scenario has the largest impact for Material use. The Finance scenario performs best of the three scenarios in both impact categories.

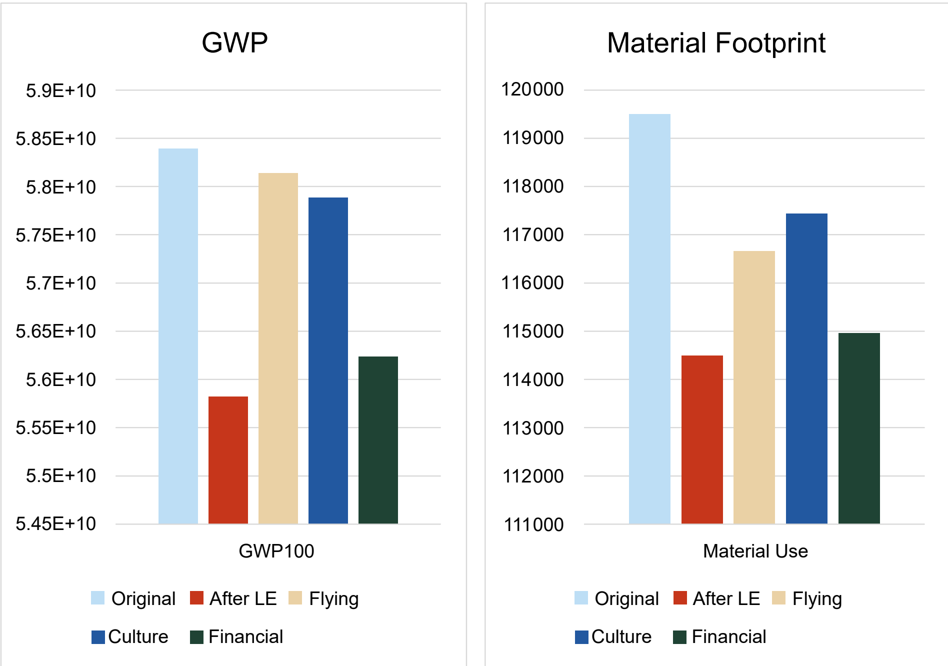

Figure 62: Comparison of the GWP and material footprint of the original, after LE are applied, and the scenarios.

In Figure 63 and Figure 64 it can be seen that the motor gasoline is a the major source of the rebound effect for the Cultural scenario and also a major contribution to the Flying scenario. Hotel and restaurant services also demonstrate high rebound effect for both GWP and material footprint. The principal component for the Financial scenario is the "Insurance and pension funding service", but the total impact of this scenario is less than the consumption of motor gasoline in the other scenarios.

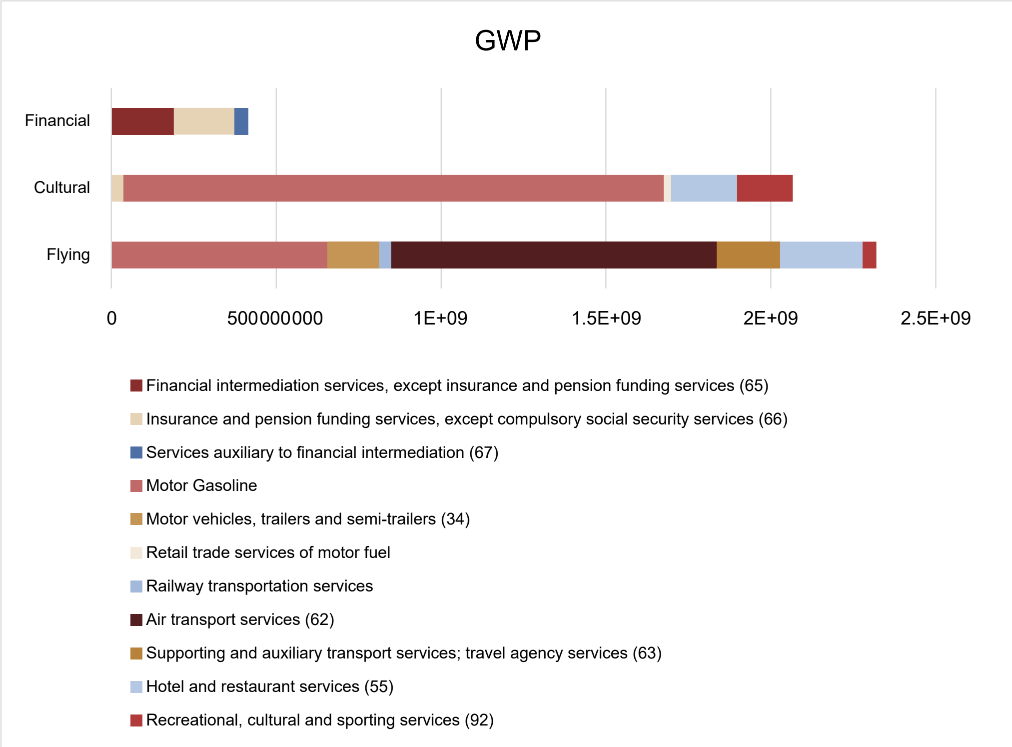

Figure 63: Comparison of GWP for the scenarios and the contribution of product groups to GWP.

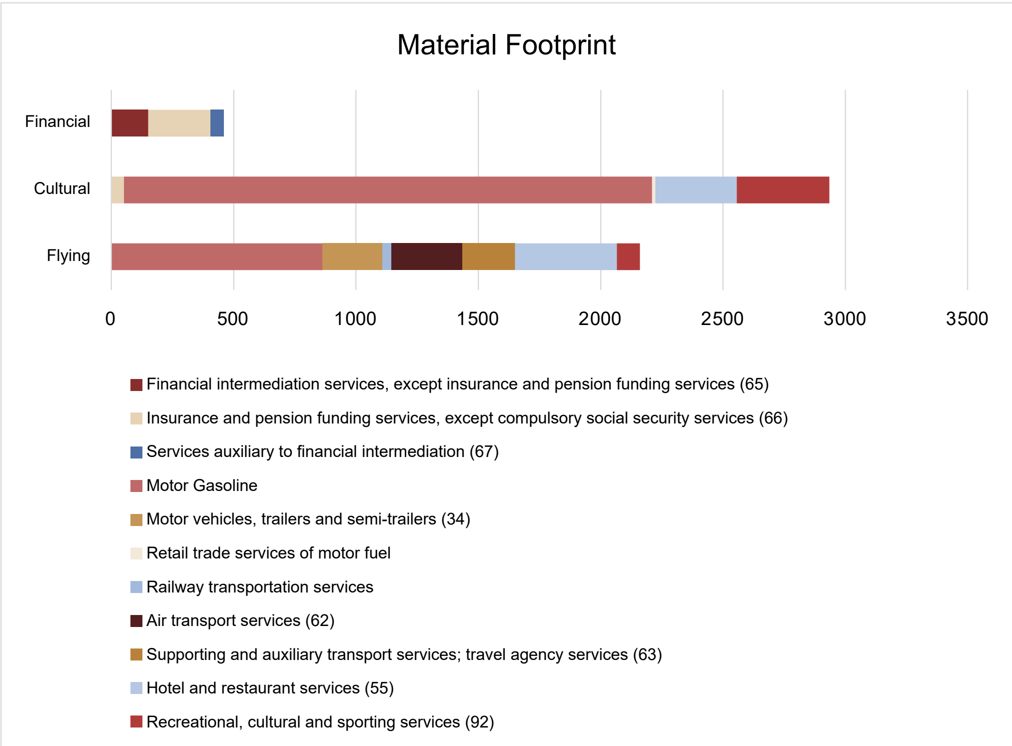

Figure 64: Comparison of MF for the scenarios and the contribution of product groups to GWP.

4.3.3 Economy of the inner loops

This part of the study sought to identify which statistics and data are available in Sweden on the extent and size of the existing circular economy, which consists of activities that include reuse, repair, remanufacturing, second-hand markets and sales of spare parts. Unfortunately, despite an extensive search there is currently very limited data or information available on these activities.

However, the search of the KN levels of SCB statistics on imports and exports identified 208 numbers of relevance to spare parts and the inner loops of repair. The results of the search of SCB statistics are shown in Table 22. This shows the total weight and value for imports and exports (relevant to repair and spare parts). In addition, the table shows the statistics available on industrial production of spare parts, although it should be noted that there are large gaps in this data due to confidentiality within the SCB database.

However, this initial data screening shows that the mass and value of spare parts has a notable significance on the economy. Additionally, the underlying data showed that approximately 60 % of the total imports for spare parts was related to machines and vehicles. About 60 % of the total export of spare parts is for machines, vehicles, aircraft and electronics. The most prominent sub-category based on value for electronics was for telephone apparatus related to wireless networks. In addition, about 60 % of the total production of spare parts is for vehicles.

Table 22: Mass of value of imports, exports and industrial production related of spare parts, repair and accessories.

Activity	Quantity (tonnes)	% of Swedish imports by mass	Value (tkr)	% of Swedish imports by value
Imports	2.69E+06	3.1 %	2.09E+08	14.6 %
Exports	1.80E+06	2.0 %	1.98E+08	13.5 %
Industrial production mass	3.66E+04	0.01 %*	1.60E+08	28.6 %*

*Inconsistent data and some classified categories result in incongruities.

A proposed equation to calculate the inner loop economy is as follows:

Inner loop economy = Spare parts imported + spare parts manufactured in Sweden – (Products with imported parts) – (products parts made in Sweden)

However, there is insufficient data, particularly on production. In addition, it is not possible to distinguish between components that are produced for repair and components that are produced as components for a new product. Furthermore, some categories were excluded because they are too aggregated and contain both products and product parts. Therefore, the numbers within the above table remain indicative only. A recommendation, therefore, would be to update the statistical classification system in order to provide definition and distinction to product parts used within the inner-loops (i.e. for repair and maintenance etc).

4.4 Discussion

4.4.1 Literature review findings

This section provides literature findings with guidance for monitoring transition to CE. Naturally, the choice of indicators for monitoring progress towards a circular economy should represent and promote increased *circularity* but perhaps more importantly, the desired ends, a more sustainable economy with less environmental impact. The concept of *circularity* in the CE context suggests at least three dimensions, circulation, intensity of use and longevity (Boyer et al 2020). While two of these dimensions have to do with products and materials delivering utility in place, it is noted that national frameworks commonly address flows and circulation. Some studies suggest complementary indicators including: stocks (Aguilar-Hernandez et al., 2019; Graedel, 2019), longevity (Franklin-Johnson et al., 2016), in-use stock growth and useful service lifetime of materials (Pauliuk, 2018).

Regarding the desired ends of CE, circularity should lead to reduced environmental impact. However, correlation between circularity and environmental impact is not thoroughly established. A few assessments at the product level exist (Niero & Kalbar, 2019; Walker et al., 2018), but similar research looking at meso and macro-levels is near non-existent. This is notable since several mass flow indicators are proposed as circular economy indicators despite the lack of research related to direct correlation between such indicators and environmental impact.

Finally, at the macro-level, the focus is on improving material circularity and resource productivity, based on aggregated indicators, but the approach fails to address environmental impacts.

Beyond basic correlation between CE indicators and environmental impacts per se, considerations to broader system outcomes is also important. Namely, the choice of indicator and assessment is critical to monitor progress without contributing to burden-shifting in the system and with consideration to what an assessment may miss, such as rebound effects resulting from resource efficiency (Franklin-Johnson et al., 2016; Zink & Geyer, 2017). Reduced mass flow does not necessarily result in reduced environmental impact. For example, reducing product mass may demand more energy intensive materials or materials with increased toxicity. Moreover, some so-called circular outcomes such as reuse simply do not replace production. As one example, smartphone reuse was estimated to result in nearly 100 % rebound (Makov & Vivanco, 2018). Availability of used smartphones was assessed to mostly just allow more device ownership, which means that smartphone reuse may do little to reduce environmental impact at the system level.

Another challenge is limitations to scientific understanding of the how pressures link to consequences. Most environmental assessments including LCA and footprint methods and MRIO models measure pressures on the environment (midpoint), not actual consequences (endpoint. Based on this limitation, it has been noted that more research is needed to attempt to incorporate environmental consequences and thresholds (such as consumption limits) into environmental assessment methodology to help define actions in a transition to a CE (Alaerts et al., 2019; Helander et al., 2019; Verones et al., 2017). Despite these limitations, some studies have concluded that resource footprints (energy, water, land and materials) are good proxies for environmental damage (Steinmann et al., 2017). In particular, six indicators (climate change, ozone depletion, the combined effects of acidification and eutrophication, terrestrial ecotoxicity, marine ecotoxicity, and land use) have been determined to largely cover estimated environmental consequences (Steinmann et al., 2016). Based on this foundation, resource footprints have been suggested to be part of a 'dashboard of indicators' for CE monitoring (EC, 2011). The limitation of these indicators is that they are measured and represent relative environmental impact, and absolute limits for products, regions, sector or nations are largely underdeveloped.

Establishing thresholds based on macro-level targets could provide more constructive targets for monitoring lower-level units and entities. There are a couple methodological approaches worth considering. While a tendency exists to account for system-wide environmental impacts in more comprehensive consequential life cycle assessment (bottom-up), coupling these with top-down approaches are necessary as absolute "limits" of environmental impact are "experienced" at economy (global)-level, not at the product or micro-level. One approach is the Safe Operating Space developed from the perspective of Planetary Boundaries (PB), which determines processes that are essential for maintaining the earth system in its current Holocene like state (Rockström et al. (2009) and Steffen et al. (2015)). Based on these processes, thresholds are defined. Linking the planetary boundaries to methodologies such as LCA presents several challenges (Clift et al., 2017; Ryberg et al., 2016). Several studies have nonetheless demonstrated the potential of combining LCA with the Planetary Boundaries (Anders et al., 2020; Sala et al., 2016; Sala and Goralczyk, 2013; Sandin et al., 2015).

The EU's Joint Research Centre (JRC) provides a mass-based alternative (to economic-based MRIO models) that can offer a complementary approach to PB. The approach aims to couple trade data (in terms of estimated mass flow) in the European economy to data about representative products from LCA databases (Benini et al., 2014; Corrado et al., 2020).

Regardless of whether one utilises bottom-up (from micro-level) or top-down (from macro-level) approaches (or both), there still exists a need to somehow understand dependencies and relationships between measures at different system levels, namely between the micro and macro levels *(Arnsperger and Bourg, 2016; Saidani et al., 2017)*. The meso-level – often represented in studies of industrial symbiosis – is one established unit of analysis that could be helpful in such a pursuit. However, very few studies examine the connections between meso-level systems, such as industrial symbiosis parks, and micro and macro level units of analysis. A couple exceptions examine using meso-level indicators for monitoring of progress at both meso and macro-levels toward the CE in China (Geng et al., 2012; Su et al., 2013), examine utilization of sectoral circularity to measure progress (van Ewijk et al., 2018) and assess the life cycle performance improvements of products resulting from industrial symbiosis (Martin (2015); Martin (2020a); Martin and Harris (2018)).

An alternative non-spatial meso-level unit of analysis, the *societal function,* shows promise as the bridging unit of analysis (de Wit et al., 2018; OECD, 2018; UNEP, 2002). One such framework divides products and services into seven societal needs for CE purposes: housing, nutrition, mobility, consumables, services, healthcare, and communication (Alaerts et al. (2019) and de Wit et al. (2018)). Products are categorized into these functions, creating a analytical connection between micro and macro-levels. Ultimately, such a framework could be used along with thresholds to allot environmental impact to societal functions. One benefit of this approach is that focus on societal needs and functions aligns with the aim of circular business models and reflects the cross-sectoral nature of consumption (Alaerts et al., 2019).

4.4.2 Modelling using Multi-Regional Input-Output

IMPACTS OF THE SOCIETAL FUNCTIONS

The use of MRIO has shown the potential to monitor the environmental impacts of consumption within the framework of the societal functions, which is supported by previous research that investigated the impact of Swedish consumption using MRIO (Fauré et al., 2019; Palm et al., 2019; Schmidt et al., 2019).

The SF framework was able to show that currently, housing and infrastructure is the highest impacting category for both GWP and material footprint. This is closely followed by nutrition, and together these two societal functions represent 51 % the Swedish GWP and 57 % of the material footprint. This aligns with Fauré et al. (2019) who (using slightly different categorisation) found that construction and food products and direct emissions from households were the most important product groups. Similarly, research at the EU level has found food, particularly meat and dairy products, to be a key contributor of impacts (Beylot et al., 2019).

This finding alone has important ramifications for circularity as these two societal functions require distinct approaches to reduce impact, which may not best be approached with a focus on "circularity". Housing and infrastructure through its use of bulk materials would generally be considered as having a high potential for reducing its material footprint through recycling of end of life construction materials. However, within the Exiobase SF model, the major contributions to the impacts within housing and infrastructure are "steam and hot water services" and "real estate services", which suggests that the focus should be on energy and heating. For nutrition, the major impacts derive from meat, dairy and "food products n.e.c." which again are unlikely to be addressed with circularity, but are more effectively reduced through changes in demand (e.g. diet), and reduced food waste. This suggests that there is a limit to what can be achieved with circularity and that more traditional reductions in energy and improvements in resource efficiency are still required.

The next most significant SF's are mobility (19 % of GWP and 10 % material footprint) and consumables (14 % of GWP and 13 % material footprint). Again, a large percentage of the impacts for mobility are related to energy, in this case "motor gasoline" and "gas/diesel oil", which together account for 35 % of GWP and 41 % of the material footprint. The highest single material footprint, however, comes from "motor vehicles, trailers etc" (with 31 %) which has the highest potential for circularity improvements within this SF.

The Consumables SF is dominated by "hotel and restaurant services" which is the result of the high impact of food and beverage products as well as other associated services. In the Communications SF Radio, television and communication equipment", which accounts for 47 % of the material footprint and has strong potential for improving circularity.

The remaining SF's are "Healthcare" and "Services". Healthcare is dominated by "recreational, cultural and sporting services (43.5 % of GWP and 49.7 % of MF), whereas "medical, precision and optional instruments" together with "health and social work services "account for the remaining impacts. Therefore, it appears that recreation and medical services have similar shares of impact. For the Services SF, "financial intermediation services etc" and "insurance and pension funding dominate" due to high final demand rather than a high impact.

Within this present assessment, we developed two further categories (other and materials), as some final demand could not easily be assigned to SF's. Materials is dominated by "chemical n.e.c." (71 % and 55 % for GWP and MF respectively), with "paper and paper product" and "wood and products of wood" also above 10 % of impacts. We were not able to calculate the distribution but it seems reasonable to assume that these are evenly distributed amongst the SF's, as they are commonly used in manufacturing and packaging.

Finally, the MF and GWP are closely correlated in terms of proportional impact, for most product groups, but there are some notable exceptions. These include product groups where GWP is higher than the MF such as: those that use fossil fuels, for example "air transport services" (mobility), and energy "steam and hot water supply services" (housing and infrastructure), "financial intermediation services" (services) and also "dairy products" (also for other animal products, but most pronounced for dairy). In contrast other groups (although few in number) have a higher MF than GWP such as "real estate services" (housing and infrastructure), ceramics (consumables). This is an important consideration in the development of circularity.

MODELLING THE POTENTIAL REBOUND

The modelling of potential rebounds focussed on the redistribution of financial savings to alternative product groups (i.e. instead of saving the money). Applying all circular changes from the LCA's to similar product groups in the SF's resulted in a reduction of only 4 % for GWP and the MF. This is despite some significant reductions for some product groups of up to 50 %. To enable this transition to longer life products we assumed an increase in the need for associated services which resulted in less than 0.6 % increase in GWP and the MF.

All of the scenarios for the redistribution of spending resulted in lower impacts than the original, with the financial services scenario showing the smallest impact. The culture scenario showed the highest rebound effect due to an increase in the consumption of "motor gasoline".

Overall, the scenarios showed that the types of products and services where the savings are redistributed has a significant effect on the potential rebound and the next benefit of the circular product changes. However, none of the tested rebounds resulted in an overall increase in impacts, compared to the current scenario.

An alternative scenario which we did not test, is where the money is saved instead of re-spending. One could argue that savings could be used by banks for large investments or money saved would eventually go towards large, perhaps impacting products such as house, cars or holidays. However, in a study on Chinese households Wei and Wang (2020) showed that this indirect rebound effect was trivial in the short term at the national level, but still considerable at the household level. They argue that considering only the household level rebound could be misleading for national policy makers by overestimating the total rebound effect.

USING MRIO AND SOCIETAL FUNCTIONS FOR MONITORING THE TRANSITION TO CE

As discussed above the use of MRIO and societal functions provides a valuable platform to assess the impacts of consumption and therefore help monitor the transition to a CE. This will be discussed in the next section. However, there are some challenges due to the aggregation provided by the 200 product groups provided in Exiobase. This may however, be manipulated to some degree, or future aggregation (or choice of the 200 product groups) could be more appropriately focused to function as representative products within the SF's.

This is also evident in using MRIO to model future scenarios, for which it is a somewhat crude method. For example, construction work must be used for both offices and housing, even though we have very different choices to reduce the impact of each. For instance, office sharing has been suggested to greatly reduce the impacts of offices by 52–76 % and could potentially reduce the required office space by up to 70 % leading to reduced construction requirements (Harris et al., forthcoming). Housing is not so adaptable to sharing though.

Nonetheless, the MRIO modelling was able to demonstrate how reductions applied at the micro level would results in macro level impact reduction, although small in our modelling. It was also able to demonstrate that potential rebound effects are an important consideration for policy, and that MRIO may help model such potential effects.

Future work using following this research should focus on integrating the additional categories that were created (material and others) into the societal function's framework.

4.4.3 Moving towards an indicator framework

The literature review has shown that both circularity and environmental indicators are required to monitor the transition to CE. Circularity indicators based on value and mass have their value in helping to understand improvements in resource productivity in the quest to serve societal needs using fewer materials. However, there is a clear need to support this with knowledge on the environmental impacts, especially for example, where there are changes in material types and system changes.

As discussed above, it is evident from the literature review that there is a need to link the assessment of the different system levels, and to environmental implications to monitor the transition to CE. Further, there appear to be adequate methods to enable this. Table 23 provides an overview of the types of indicators required for each level and the assessment methods, which include LCA at the micro and MRIO at the meso and macro levels. One drawback of using MRIO is the time delay for databases. For example, EXIOBASE uses old data (currently 2007, then 2011 in the updated version) as a basis. However, the PRINCE project (Fauré et al., 2019; Palm et al., 2019) has demonstrated that it is possible to create a hybrid model and integrate more up to date data for the Swedish production coefficient table.

Therefore, having the SF analysis at the meso-level provides both a link and a timelier basis to track and introduce relevant policy. With further development there is potential for the mass-based method developed by the *EU's Joint Research Centre (JRC)* to supplement or even replace the MRIO modelling. In t*he* work of JRC the trade data of the mass flow in the European economy is linked to LCA databases of representative products (Benini et al., 2014; Corrado et al., 2020). This is based on the mass of products and consumption impacts, thereby being a potential physical, mass-based alternative to the economic-based MRIO models. It therefore combines material flow analysis with LCA and has been used to assess the hotspots of urban consumption (Lavers Westin et al., 2019).

Table 23: Indicator and assessment method framework for monitoring the transition to CE and link the system levels

	Circularity indicator	Environmental indicator	Goal
Micro	Material Value	LCA indicators depending on product type.	Linking to scaled thresholds based on high level limits: • Global ecological health/Gaia system • Impact of biodiversity • Planetary Boundaries
Meso	Material circulation Value of inner loops	Footprints by S.F (e.g. using MRIO)	
Macro	Tracking main bulk materials and key materials Value of inner loops Flows from stocks	National consumption footprint (e.g. using MRIO)	

The specific type of indicators that can be used at each level are elaborated Table 24 (although these require refinement, or more detail for actual implementation). This also shows how the micro-level, links to the societal function and the macro level total impact at the national level. Alaerts et al. (2019) suggest that the focus of monitoring should be on representative products and services associated with the major portion of material demand, effects and impacts per system monitored, as it is not possible to provide exhaustive monitoring. Therefore, at the micro and societal functions level, the monitoring should focus on key representative products, services, and product groups within each of the societal functions. But also the total impact of providing that function to society is crucial information, so that it can be monitored and reduced.

At the micro-level the indicators should monitor the range of key product and service performance, which could form the basis of regulation and policy thresholds (e.g. which already exist for energy standards for electrical and emissions for cars). Micro-level assessments of products using LCA are required, but in some cases, circularity indicators can supplement this information and be used as a proxy where LCA type knowledge is already available for the product.

Monitoring at the SF function level then monitors the meso-macro effects of micro-level changes and the total impact of providing that function to society/the nation. The sum of the SF of course provides the total impact of consumption for a given year of the country. Targets (based on thresholds) for each SF also require development, to enable policy to target the reduction of the impacts associated with the provision of each SF to society and stay within the nations portion of limits, e.g. those calculated from the Planetary Boundaries (Steffen et al., 2015).

To supplement this, it would be helpful to monitor the economy of the inner loops and the informal economy (e.g. second-hand shops and markets), maintenance and repairs, and spare parts. Since these are critical for a CE, this is required to understand the size and potentially, the impact of these sectors. However, improvements in categorisation of product groups and data is required to enable this.

The literature also points to the importance of understanding stocks of materials and products etc, which could facilitate the management of these resources, and aid the retention of these and the slowing of loops. Moraga et al. (2021) suggests the use of two indicators: in-use occupation ratio (UOR) and final retention in society (FRS). They argue that a distinction between supply, in-use, and hibernation phases is essential for CE.

Table 24: Examples of linking indicators of products and functions across system levels. The table shows only the major representative Exiobase products at associated at the Meso level – therefore the percentages of their contribution to the Societal Function (% of SF GWP) do not add up to a total 100 %.

Societal Function	Product	Micro level indicators	Meso – societal function level			Macro – national level indicators
			Major/relevant representative groups from Exiobase (No.)	**% of SF GWP**	**SF level indicators**	
Mobility	Car	GHG per km MF per car LCA impact categories	(67) Motor gasoline (123) Motor vehicles (162) Air transport services	26.1 21.9 18.7	Mobility Total: GHG/MF of cars/public transport etc per year GHG/MF of fuels per year In use stock indicators	Total GHG & MF of mobility per year Total material use (by key types) per year Total material stock* (by key types) Swedish Environmental Objectives
	Bus	GHG per km MF per bus LCA impact categories				
	Train	GHG per km by train Material use per train LCA impact categories				
Housing & infra.	Houses	GHG per m^2 MF per m^2 LCA impact categories	(125) Furniture; other manuf. goods n.e.c. (148) Steam and hot water 8 services	14.7 52.0	Housing and infrastructure Total: GHG/MF use of housing/offices/ new construction and maintenance per year In use stock indicators	Total GHG & MF of housing and infrastructure per year Total material use (by key types) per year Total material stock (by key types) Swedish Environmental Objectives
	Offices					
	Roads	GHG per km Material use per km LCA impact categories				
Consumables	Fridge	GHG in use per year MF per fridge LCA impact categories	156) Hotel and restaurant services (55) Textiles (56) Wearing apparel; furs	30.8 15.4 15.4	Consumables Total: GHG/MF use of fridge/textiles/paints per year In use stock indicators	Total GHG & material use of consumables Total material use (by key types) per year Total material stock (by key types) Swedish Environmental Objectives
	Textiles	GHG per kg textile MF per kg textile LCA impact categories				
	Paints	GHG per km by car MF per car LCA impact categories				

Linking micro and macro

*Material stock refers to the materials that exist and are stored within society (outside of those of the natural world), e.g. those contained in buildings, infrastructure and other products.

This framework also enables the tracking of interactions between the SF's. For example, working at home (teleworking) may reduce mobility impacts but could increase impacts from individual consumption of materials and energy (Nakanishi, 2015). Similarly, web-based movies remove the need to travel to DVD stores, but due to storage and network impacts, already account for 1 % of global GHG emissions (The Shift Project, 2019).

To enable CE consideration of hazardous chemicals is also needed so that circularity can occur without risk of toxic emissions or exposure. In research on measuring chemicals contained in national consumption of Sweden, Persson et al. (2019) suggested five indicators: use of hazardous chemical products, use of pesticides, use of antimicrobial veterinary medicines, emissions of hazardous substances, and of the potential toxicity of these emissions. However, hazardous chemical content of products is best monitored with specific regulation. Whereas a circularity monitoring framework should focus on the core task of circularity and related environmental implication. Nonetheless, a CE framework could be used to highlight products and components whose hazardous content is limiting circularity.

4.4.4 Summary – avoiding rebound effects

Taken together, the literature and modelling suggest that there are four main rebounds to consider for CE improvements:

1. Non-displacement – creation of additional markets, where new products are not displaced but there is a net increase in products sold, and the resultant impacts.
2. Direct rebounds – that occur from changes to the product or business model, such as an increase in services.
3. Spending shifts – where savings from the reduced expenditure on certain products or services may be diverted to more impacting categories such as air transport and to hotels.
4. Societal function shifts – where a reduction in certain types of products within one SF are replaced by increases in another SF due to change in the demand of product types (e.g. the shift from DVD's to online streaming of videos.

Two other rebound effects were noted by Gillingham et al. (2013) that apply at the national economy scale. Reductions in demand can drive down prices leading to a "macroeconomic price" effect. Increased efficiency could also lead to pockets of industrial growth resulting in a "macroeconomic growth" effect, e.g. where innovative materials developed in one sector are used in other sectors leading to growth. Shifts in the mode that consumption is made, such as whether it is online, could also be an important consideration (Frick and Matthies, 2020).

The main aim of monitoring the transition to CE is therefore to help assess and understand the changing impact of product, services and the SF's, to enable policy to reduce the potential for rebound effects to occur. The framework described in the section above has the potential to enable this by:

- Providing a timelier monitoring of the impacts of consumption.
- Increasing the links between the systems levels and helping to understand the shift of impacts between the SF's.
- Identifying which societal functions are the most critical and where reductions can be targeted by policy.

4.5 Conclusion

This chapter consisted of three parts: 1) a review of the literature on environmental assessment and indicators of CE; 2) a modelling exercise to assess the link between product level changes and macro system level impacts; 3) a potential framework to model the transition to CE.

The literature review highlighted that there is currently a focus on circularity indicators (measuring recirculation of material flows or value of a system) at both the micro and macro levels but these have not been linked effectively to the environmental impacts. The challenge to link the micro and macro levels remains, as does improving the understanding of how circularity can reduce environmental impact.

The modelling using MRIO (Exiobase) demonstrated the usefulness of both MRIO and the societal functions framework to help understand the link between product level changes and macro level impacts. The modelling showed that the largest impacting SF's were "housing and infrastructure" (30 % of GWP) and nutrition (21 % of GWP). The reduction of impacts within these SF's may best be achieved with a focus on non-circularity issues such as improvements in heating and reduced consumption of dairy products.

This suggests that there is a limit to what can be achieved with circularity and that more traditional reductions in energy and improvements in resource efficiency are still required. This is also true for the mobility (19 % of GWP and 10 % of MF) where "motor and gasoline" and "gas/diesel oil" together account for 35 % of GWP and 41 % of the MF. Nonetheless "motor vehicles, trailers etc" have 31 % of the GWP, which does lend itself to circularity.

The applied changes to the four SF's resulted in a 4 % reduction in GWP and MF. In the modelling of potential rebound effects, the financial savings from the life extension of products and the shift to services, three alternative spending scenarios were modelled. None of these resulted in higher impacts than the current situation. However, there was a clear difference in impact between the scenarios, with the Financial scenario having only 18 % of GWP of the Culture scenario (where spending was reassigned to recreation and cultural activities). This has important ramifications for policy that needs to consider how consumer savings will be redistributed.

Adequate assessment tools exist to assess and track CE at each level, with LCA being the leading method at the micro and MRIO models at the macro. The societal functions framework was shown to provide a useful perspective from which to examine the circularity of society. Crucially, the framework can act as a meso-level link between the micro and macro levels to monitor progress towards CE.

In terms of indicators, mass and economic value-based circularity indicators can provide a proxy but should not be relied on in the long term, without knowledge of environmental impact. CE assessments should therefore be linked to environmental consequences. Ultimately thresholds (e.g. Planetary Boundaries) should be developed for each SF's so that there are targets to limit the impact of each and limit the impact of national consumption.

Other research has placed the circularity of the economy as only 9 % (de Wit et al., 2018). However, this research noted the absence of statistics and assessments of the use phase, which includes stocks of materials, products and components, and the economy of the inner loops. There is a need to track the economy of the spare parts, repair and second-hand economy if the extent and impact of CE is to be measured and monitored. The initial screening of statistics related to KN numbers for repair and spare parts showed that they represent 2–3 % of imports and exports and approximately 28 % of the value of industrial production. This suggests that this sector of the economy has a significant bearing and more research and understanding is required to enable it to be tracked.

5 Policy and industry analysis

This chapter will discuss Swedish/EU policies which need to be introduced or altered to promote a sustainable CE and prevent the proliferation of the ones who are not. In Section 5.1, an overview of the current Swedish and European legislation related to CE is provided and a summary of the findings of earlier policy briefs is given (Section 5.2). In Section 5.3, insights and comments on policies from the manufacturing companies' part of the LinCS project are summarised.

5.1 European legislation related to CE and insights from earlier policy briefs

The recent communicated European Green Deal reinforces the agenda introduced by the CE package and action plan in 2015, identifying CE as a vital part in reaching the Green Deal goal of a climate-neutral EU by the year of 2050[6]. The European Green Deal consists of four main publications which create a roadmap for the changes needed in terms of policy and funding to achieve the EU vision of a just, competitive and climate neutral union by 2050. These documents include communication on the vision and an overview of what policy areas need to be revised, an investment plan, and a proposition of a Just Transition Fund.

Among the many legislation and policy revisions that are due according to the Green Deal, a new CE action plan will be implemented ("A new Circular Economy Action Plan for a Cleaner and More Competitive Europe" [7]), including a 'sustainable products' policy aiming to promote and encourage circular thinking in design of all products (promoting reuse and reduce above recycling), and to strengthen extended producer responsibility[8]. Tax reforms will enforce a "polluter pays"-principle[9], shifting tax from labour to pollution and efforts will be made to put in place extensive cooperation across value chains for a better resource use efficiency[10]. These legislative changes will be planned and decided upon on in the next five years, and early examples of such changes will most likely be seen in the plastic packaging industry[11]. One action already taken within the EU in May 2019 is the adoption of new rules regarding single-use plastics. The rules cover a ban on selected single-use products made of plastic, measures to reduce consumption, extended producer responsibility schemes and a collection target for plastic bottles[12].

[6] https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf
[7] https://ec.europa.eu/environment/circular-economy/
[8] https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf
[9] https://ec.europa.eu/commission/presscorner/detail/en/fs_20_48
[10] https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf
[11] Ibid
[12] https://ec.europa.eu/commission/presscorner/detail/en/IP_19_2631

The Ecodesign and Energy labelling framework
The legislative framework has a purpose of both helping consumers to choose energy efficient products through *Energy labelling* and ensuring that the best products from an energy efficiency perspective are being brought to the market through *Ecodesign*[13]. The product specific regulations in terms of energy efficiency are based on a life-cycle perspective. Resource efficiency and circularity performance is increasingly considered as well. Some examples are durability, recycling, and reparability. The framework aims to remove the worst performing products from the European market, by setting minimum requirements for products[14]. Energy consuming products that pass their specific eco-design requirements are rated and labelled based on their energy performance. A new framework for energy labelling is currently being developed, among other things in order to also incorporate factors of *resource* efficiency. A scoring system for repairability and upgradability, that can be incorporated either in eco-labelling or as an assessment tool for products incorporated by ecodesign requirements, is also being developed[15].

Below is a summary of EU different regulations and directives.

- The REACH regulation affect what products can be circulated and in what way, since this is the overall legislation on chemical use in the EU. It declares what chemicals are allowed in products. The use of chemicals in products and goods have an impact on the potential to incorporate them in circular loops [16].
- The RoHS directive aims to reduce the risk of negative impact on human health and on the environment by replacing or limiting the use of certain hazardous chemical substances in electrical and electronical equipment. The directive was adopted by the EU in 2011 and later adopted in Swedish law in 2012[17].
- Differentiated fee structure for plastic packages
  - Fee for plastic which is not recycled. The EU commission has in its proposal for the new 7-year financial framework included a tax on the amount of non-recycled plastic packaging waste in each member state, at a rate of 0.8 EUR per kilogram[18].

[13] https://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-eu/cirkular-ekonomi/Ecodesign-working-plan-2016-2019.pdf

[14] https://www.energimyndigheten.se/energieffektivisering/jag-ar-saljare-eller-tillverkare-av-produkter/ekodesign-energimarkning-och-ce-markning/ekodesign/ekodesigndirektivet/

[15] http://www.energimyndigheten.se/globalassets/energieffektivisering_/jag-ar-saljare-eller-tillverkare/dokument/produktgrupper/energimarkningsforordningen_2017-1369.pdf

[16] https://www.delegationcirkularekonomi.se/download/18.745dc19c170b0621a1f6
6b/1583757395107/1906 %20Kartl %C3 %A4ggning %20om %20design %20f %C3 %B6r %20
cirkularitet.pdf

[17] a) https://www.kemi.se/lagar-och-regler/ytterligare-eu-regler/elektrisk-och-elektronisk-utrustning-rohs; https://eur-lex.europa.eu/legal-content/SV/TXT/PDF/?uri=CELEX:02011L0065-20200501&from=EN
b) https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-2012861-om-farliga-amnen-i_sfs-2012-861

[18] https://zerowasteeurope.eu/wp-content/uploads/2018/09/PlasticsTax_FINAL.pdf

  - China, which historically imported large volumes of plastic waste from the EU, stopped the importing in 2018. This has led to that the EU has taken action on handling the waste within the union, and set a target of recycling all plastics packaging within the EU by 2030[19].
- Examples of European directives
  - **The European waste directive (2008/98/EG).** The aim of the directive is to reduce waste by giving instructions on how to prevent the disposal of goods, give clear definitions on what is considered as waste and not, explain the waste hierarchy and how to steer based on it, minimum requirements on producers and requirements on the administration of waste generated. In 2018, the European union decided on amendments on the directive with the aim of reducing waste and encouraging reuse, recycling and improved waste handling[20].
  - **The directive on packaging and packaging waste (94/62/EG).** The aim of the directive is to harmonise national directives on the handling of packaging and packaging waste and reduce the environmental impact from packaging and packaging waste. An amendment on the directive in 2018 made it include more actions to prevent packaging waste and to enhance reuse and materials recycling[21].
  - **The directive on landfill and waste (1999/31/EG).** The aim is to prevent or in the best possible way limit, the negative impact from landfills on surface water, ground water, land, air and human health[22].
  - **The directive on end of life vehicles (2000/53/EG).** The directive points out measures to take in order to limit waste from end of life vehicles and its components by securing reuse, materials recycling and recycling[23].
  - **The directive on batteries and accumulators and expired batteries and accumulators (2006/66/EG).** The aim is to reduce the negative environmental impact from batteries and accumulators both during usage and in the end of life phase[24].
  - **The directive on waste which contains electrical or electronic products (WEEE) (2012/19/EG).** The aim is in first hand to prevent the occurrence of WEEE and thereafter through reuse, materials recycling and recycling make sure to take care of all the valuable raw material included in the products and components with as low environmental impact as possible. Also, the directive aims to limit the need of extracting natural resources to produce new products and components[25] (ref).

[19] https://www.europaportalen.se/2018/01/eu-ska-ta-hand-om-sitt-eget-plastavfall
[20] https://eur-lex.europa.eu/legal-content/SV/TXT/PDF/?uri=CELEX:02008L0098-20180705&from=EN
[21] https://eur-lex.europa.eu/legal-content/SV/TXT/?uri=LEGISSUM %3AI21207
[22] https://eur-lex.europa.eu/legal-content/SV/TXT/?uri=LEGISSUM %3AI21208
[23] https://eur-lex.europa.eu/summary/SV/I21225
[24] https://eur-lex.europa.eu/legal-content/SV/TXT/?uri=CELEX %3A32006L0066
[25] https://eur-lex.europa.eu/legal-content/SV/TXT/?uri=CELEX %3A32012L0019

5.2 Swedish legislation related to CE and insights from earlier policy briefs

In July 2020, the Swedish government decided upon a national strategy for the transition to CE. The strategy was based on the work and recommendations from the delegation for CE which was initiated in 2018. The national strategy adopted by the government points out the direction for the work that needs to be done within four main categories: circular production and product design, consumption and business models, securing poison free circular material flows[26] and CE as an ambition for society and industry through innovation and incentives. The first focus area circular production and product design aims at creating transparency and clarity on product component composition, origin, environmental impact, and process for reuse or recycle in the end of life. Decisions that enhance long product lifetimes and circularity should be taken already in the design phase. Production processes should be designed to promote the reuse and recycling of non-hazardous material into new products. The second focus area of consumption and business models is about creating sustainable ways and habits of consumption. This should be done by improving the information to consumers and making it easy to for consumers to make sustainable and circular choices. Sharing platforms and new business models that promote reuse, remanufacturing and recycling is also an enabler. The third focus area of securing poison free circular loops is about promoting reuse first. Fossil based goods should also be replaced bio biobased and renewable sources in a way that respects and harmonises with the biodiversity and eco-systems. The Swedish recycling system should be developed and well prepared for handling the waste streams in Sweden and keeping the circular loops poison free. The fourth focus area is about creating incentives for the transition to CE in society. The incentives aim at creating circular business models, accelerating the supply and demand of reuse and remanufacturing and support research and innovation within the area.

Besides upcoming legislation with the purpose of accelerating CE, changes in legislation to promote a more sustainable future have also been developed and implemented in the past. Below, a short summary of some Swedish laws and frameworks promoting the transition to CE.

Waste legislations, the WEEE directive and others impacting behaviors towards increased circularity

The Swedish and European waste regulations steer the member countries on what can be considered waste, how to prohibit that waste occurs and how to handle waste. Furthermore, it gives directions on how trade of end-of-life resources can be done. The combination of directives and regulations steers and guides the European activities towards CE.

[26] https://www.regeringen.se/4a3baa/contentassets/619d1bb3588446deb6dac198f2fe4120/200814_ce_webb.pdf

Below is a summary of Swedish different regulations and the Swedish national climate goals.

- A Swedish governmental investigation in 2015 concluded a recommendation of introducing a tax on consumer goods that contained certain hazardous chemical substances. This resulted in that a new chemical tax for some electronical goods was introduced in July 2017. The main purpose of the tax is to restrict and limit the use, spread and exposure to flame retardants found in consumer goods. With the tax, the government aims to incentivise producers to introduce more environmentally friendly products to the market. The tax is weight based with a fixed maximum sum per product[27].
- The Swedish regulation on producers responsibility for electrical equipment aims to reduce the amount of waste, reduce the negative impact on the environment and human health, motivate producers to take responsibility of the problems with the waste and introduce prohibiting measures, make it easier as an owner of the equipment to return the waste, make sure that all waste is collected is handled according to the directive and to promote resource efficiency in order to reach the recycling targets in the directive[28].
- Differentiated fee structure for plastic packages
  - The fee on plastic packages aims to mirror the actual cost of materials recycling to motivate producers in designing for recycling. With the differentiated structure, it will cost producers more to introduce products which are difficult to recycle compared to those who are designed for recycling. The structure is divided in level one and two. Level one has the highest fee and concerns all packages produced in other materials stated under the lower fee level 2[29].
- Sweden's environmental objectives
  - The overall national climate objective in Sweden is to reach a net zero emission of GHG by the year 2045. This requires a reduction of GHG with 85 % in 2045 compared with the emissions in year 1990. The additional 15 % reduction is anticipated to be reached with alternative GHG reducing measures. From the year 2045 and onwards, the yearly emission should be negative[30].

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[27] a)https://skatteverket.se/foretagochorganisationer/skatter/punktskatter/kemikalieskatt/vemsomskabetalaskatt.4.5c1163881590be297b5175f2.html b)https://skatteverket.se/foretagochorganisationer/skatter/punktskatter/nyheterinompunktskatter/2019/nyheterinompunktskatter/andradeskattesatserforkemikalieskattfran1augusti2019.5.8bcb26d16a5646a148dda2.html c)https://www.regeringen.se/49bb0f/contentassets/4a79d2c36415435fb2c202dbf54b0bda/kemikalieskatt--skatt-pa-vissa-konsumentvaror-som-innehaller-kemikalier

[28] https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-20141075-om-producentansvar-for_sfs-2014-1075

[29] https://www.ftiab.se/3169.html

[30] https://www.regeringen.se/artiklar/2017/06/det-klimatpolitiska-ramverket/

- The Swedish GHG emission reduction of the domestic non-trading sector have milestone target for the year 2030 and 2040. For the year 2030, the emissions should be reduced with 63 % and with 75 % in year 2040, both compared with the year 1990. The emissions are those coming from transportation, machines, smaller industries, buildings and farming. The alternative GHG reducing measures, such as carbon capturing by forest farming or investments in climate projects internationally can stand for a maximum 8 percentage units in 2030 and 2 percentage units for the year 2040 respectively out of the total reduction in GHG emissions.
- The domestic GHG emissions from transportation, excluding the domestic flight operation, should reduce by 70 % within the year 2030 when comparing with the year 2010.

• Examples of Swedish legislation
  - **The Swedish environmental law (1998:808).** The aim of the regulation is to foster sustainable development which ensures current and future generation a healthy and good environment. Such development is built upon the foundation of the insight of that the environment has a protection value and that the humans right to develop and make changes in nature comes with a responsibility of taking care of the environment.
  - **Avfallsförordning (2020:614)[31].** Den svenska avfallslagstiftningen bygger till stor del på gemensam lagstiftning inom EU. Genom det så kallade avfallspaketet trädde nya bestämmelser ikraft den 1 augusti 2020. Målet med ändringarna är bland annat minskade avfallsmängder, ökad återanvändning av produkter, ökad återvinning samt en förbättrad avfallshantering.[32]

5.2.1 Previous findings, policy briefs – EU (international level of recommendations)

Previous policy briefs on CE have addressed a wide range of issues, some of them already covered, signalled to be of significance, or on its way of being implemented within the framework of the European Green Deal Directive. Below is a brief overview of a selection of policy recommendations. Listed is a variation of aspects that have been identified as important to be able to successfully transition to CE.

[31] https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/avfallsforordning-2020614_sfs-2020-614

[32] https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Avfall/Lagar-och-regler-om-avfall/

TAX REGULATION, FROM LABOUR TO POLLUTER

Tax reform is highlighted in several publications as a way of incentivising businesses to develop circular models[33]. Increasing tax burdens on pollution and resource extraction, while reducing tax on labour, is suggested to be an enabler for industry transitioning towards circularity. This shift would incentivise businesses to be more resource efficient. It would also to some extent compensate for the additional costs of the more labour-intensive process of refurbishment, repair, and remanufacturing, as compared to the often highly automated manufacturing of new products (van Loon and Wassenhove, 2018). Increased taxes on landfill and incineration, as well as on non-repairable products is also suggested as an enabler for CE[34].

DEFINITIONS AND LEGISLATION ON WASTE AND REMANUFACTURED GOODS

Furthermore, policy briefs have called for clarifications in the legislative framework on waste management. Circular businesses need functional definitions on the difference between waste, used- and remanufactured goods, as well as clear protocols regarding these in terms of international trade[35]. An example here is the WEEE Directive, where a clear definition of the "preparation for use" process is needed to remove uncertainties for businesses operating in the refurbishment and reuse sector[36].

Regions exporting scrap material should secure compliance with health protection standards during process and that exported goods are optimally prepared for recycling. Countries importing recyclable materials should prepare for and enable high-quality recycling and remanufacturing, safe for workers and the environment[37].

DATA COLLECTION AND MONITORING PLATFORMS

There is a need for accurate monitoring platforms at which the progress and effects of the transition to CE can be closely monitored and understood. A better collection and availability of timely data is also called for, to be able to monitor and assess the effects and impacts of CE-related processes and policies within the EU. It is also suggested that, to make relevant assessments of the economic benefits of CE and future costs of scarcity must be taken into consideration[38]. The European union recognises the importance of transparency and is considering an "electronic product passport" that contains information on the products' origin, repair and disassembly possibilities,

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[33] https://www.circle-economy.com/insights/policy-brief-on-circular-economy-and-climate, https://unctad.org/en/PublicationsLibrary/presspb2017d10_en.pdf, https://www.regeringen.se/49550d/contentassets/e9365a9801944aa2adce6ed3a85f0f38/fran-vardekejda-till-vardecykel-2017_22.pdf

[34] https://unctad.org/en/PublicationsLibrary/presspb2017d10_en.pdf

[35] Ibid

[36] https://www.eesc.europa.eu/sites/default/files/files/qe-03-19-510-en-n.pdf

[37] https://unctad.org/en/PublicationsLibrary/presspb2017d10_en.pdf

[38] https://circular-impacts.eu/sites/default/files/D6.3v2_Synthesis-Policy-Brief_FINAL.pdf

composition and materials used, and end-of-life recycling. The product passport was suggested within EU's Eco-innovation action plan and the European resource efficiency platform[39].

INSTRUMENTS FOR PROMOTING CIRCULARITY

There is a wide variation of instruments that could be used to further promote the implementation of CE. Suggestions given by UNCTAD (United Nations conference on trade and development) include extended legal warranties with the aim of promoting circular design in products, streamlined regulations for sharing and leasing businesses, promotion of access over ownership, and developing virtual platforms for asset sharing[40].

Public procurement is an important instrument in steering the transition. ”Incentives for green public and private procurement help create demand for circular products” (Hoogzaad & Bardout, 2018). The benefits of green public procurement (GPP) are further highlighted in the third edition of Buying green, a European union publication. By using their purchasing power, governments can choose goods and services with reduced environmental impact[41]. “GPP can be major driver of innovation, providing industry with real incentives for developing green product and services”[42]. Examples of green contracts are; energy efficient computers, office furniture from sustainable timber, low energy buildings, recycled paper, cleaning services using ecologically sound products, low emission vehicles, electricity from reusable sources[43].

Within the Nordics, potential industries where public procurement can be an enabler in the transition to a circular have been identified in a report published from the Nordic council of ministers. In construction and renovation of buildings, recycling could be enhanced through specifications in contracts. Savings in material and money can be made within the construction of road infrastructure, by looking at nearby construction projects and utilising their secondary material flow. Furthermore, waste water treatment, appliances, furniture and textiles are areas with potential[44].

EXTENDED PRODUCER RESPONSIBILITY

The extended producer responsibility is highlighted in the paper Policy brief on CE and Climate, where it is referred to as one of the three most efficient policies[45], together with GPP and the EU's Ecodesing Directive. However, there is also criticism towards the extended producers responsibility. The introduction of these type of policies do not give incentives for producers to incorporate

[39] https://ec.europa.eu/environment/ecoap/about-eco-innovation/policies-matters/eu/20130708_european-resource-efficiency-platform-pushes-for-product-passports_en

[40] https://unctad.org/en/PublicationsLibrary/presspb2017d10_en.pdf

[41] https://ec.europa.eu/environment/gpp/pdf/Buying-Green-Handbook-3rd-Edition.pdf

[42] Ibid

[43] https://ec.europa.eu/environment/gpp/pdf/Buying-Green-Handbook-3rd-Edition.pdf

[44] http://norden.diva-portal.org/smash/get/diva2:1092366/FULLTEXT01.pdf

[45] https://www.circle-economy.com/insights/policy-brief-on-circular-economy-and-climate

circular design before in the creation phase of a product. In a report assessing how the extended producer responsibility has affected producers, respondents agreed that the extended producer responsibility has yet not succeeded in its objective of changing their designs for easier recycling (Kunz, Mayers & Van Wassenhove, 2018).

RESOURCE EFFICIENCY

The importance of incorporating *material efficiency* as a factor in the EU Ecodesign Directive is also highlighted[46]. This as opposed to only focusing on the energy efficiency of energy-related products.

METABOLIC FLOW OF VIRGIN AND SECONDARY MATERIALS

Another suggestion is that there is a need for an international forum where different sectors such as governments, academia and non-state actors can collaborate in closing material cycles and making sure that the value of materials and products already in use is extended[47].

5.2.2 Previous findings, policy briefs – Sweden (national specific recommendations)

In 2018, a Delegation for CE was established by request of the Swedish government. Since then, several publications, mappings and policy briefs have been produced by the delegation aiming to investigate what opportunities and obstacles there are in the Swedish transition towards CE, and to advise the government on the matter of CE[48]. The *Delegationen för cirkulär ekonomi* in Sweden presented a policy brief in 2019 on the national strategy for CE, providing insights on missing links between national goals, legislation, available data and the industry. Using these insights, suggestions on what a national strategy for CE should incorporate were communicated. This work was the basis for the decision taken in July 2020, when the national strategy for the transition to CE was adopted by the Swedish government. Below presents a summary of findings from the delegations work:

- A clear vision with narratives and goals was seen needed from the Swedish government, where the intentions for the Swedish transition towards a circular, bio-based and resource efficient economy are clearly stated and communicated, as well as exactly what this transition is going to entail[49]. The vision to be communicated should place Sweden as a frontrunner for sustainability and CE. The delegation suggested that the national strategy should include a commitment by the govern-

[46] Ibid

[47] Ibid

[48] https://tillvaxtverket.se/download/18.40bbbaae16d1aacd58b7ddf4/1568816194484/Sweco %20 Kartläggning_design %20för %20cirkularitet_190627.pdf

[49] https://tillvaxtverket.se/download/18.2a70b79816f1ab4d8e37a72/1576747743736/Inspel %20 till %20Sveriges %20strategi %20för %20cirkulär %20ekonomi_final.pdf

ment to review laws and regulations to make sure that current legislation allow for an efficient transition process. A commitment to establish new models for public procurement was also suggested, where demands on resource efficiency and circularity is included in procurement guidelines, and where procurement of function or service (rather than products) and of innovation is made possible. Chemicals that limit circular processes should be identified and addressed, especially for plastics[50]. The national strategy should also call for producers to develop and enter voluntary agreements or statement of intents, to guarantee functionality of their services or products over a certain amount of time[51].

- Potentially conflicting goals of CE and resource efficiency were also highlighted, where some parts of recycling/remanufacturing activities might require a disproportionately heavy use of other resources to accomplish. According to the delegation, Swedish stakeholders have expressed a need for clear and explicit guidance on how to prioritise in these cases. If circularity is the tool with which optimal resource efficiency is to be achieved, attentiveness to, and guidance for, situations where this is not the case is needed. For CE to be free from hazardous chemicals, the delegation mentions that some older goods and materials might not be suitable to circulate as they are too hazardous.
- The delegation recommended making a national mapping of the metabolic flow of resources in Sweden. The purpose of this would be to identify the availability of resources, how they are used and what would be the most optimal way to use these resources[52]. Secondly, the delegation called for extended warranty on products. This could initially be achieved by businesses taking the initiative to adjust warranties of their products or services themselves, which in time might lead to changed legislation[53]. A third recommendation was to consider taking inspiration from the Dutch *Green Deals*-model as an enabler for innovation. The delegation stated that they intend to further investigate the possibilities of designing and adapting a Swedish version of the model. The key thought of *Green Deals* is to accelerate sustainable innovation by granting certain actors permission to temporarily be exempted from current legislation, during which they can test run specific ideas, business models or processes that are not possible within current legislation. If deemed successful, legislation can then be modified[54].

[50] Ibid.
[51] Ibid.
[52] https://tillvaxtverket.se/download/18.2a70b79816f1ab4d8e37a72/1576747743736/Inspel %20 till %20Sveriges %20strategi %20för %20cirkulär %20ekonomi_final.pdf
[53] Ibid.
[54] Ibid.

Furthermore, the Swedish organisation Svensk Handel have conducted a study with a number of Swedish businesses, saying that lack of transparency in material value chains is an issue for businesses trying to be circular. Sweden should therefore promote the implementation of transparency requirements of value chains, preferably global, but at least within the EU[55].

5.3 Industry insights CE policy

To collect further understanding on how industry is hampered and encouraged in their transition to CE, a questionnaire was sent out to the companies involved in the LinCS project. The questionnaire can be found in Appendix 4. The respondents were all Swedish manufacturers interested in or already working with circularity. The companies represent different industries and vary from small to midsize companies to large multinationals.

Challenges for CE identified by the respondents were normative notions on access and ownership, limits due to business size, economic viability of business models, supply chain's complexity due to lack of information on material, taxes, trade-offs between energy and resource efficiency, and finally missing links between policy and regulations.

ACCESS AND OWNERSHIP – CHALLENGING NORMATIVE CONSUMPTION

Several respondents mentioned that customers usually are inclined to buy an asset rather than buying access to a function. Most customers are set on simply buying the goods or products they need. Conveying the benefits of buying a service or function of something that is traditionally owned, is therefore one of the biggest challenges for these businesses. One respondent, selling modular signs designed for reuse, say that: *"It takes time for the market to change. Ownership is still the most used way to get use of a sign. Renting only suits a few"*. Another respondent expresses that meaningful comparisons between their service versus a linear one is difficult to do since the added value provided in their model is not comparable to the added value of a physical product. He says that the biggest obstacle is to: "*actually make the comparison and to keep it relevant, it often comes down to economics, which is fine, if (customers) calculate the real economics. But they do not"*.

Changing the norm from ownership to access is a challenge for businesses. A shift in perspective is needed, and this takes time to achieve. Three of the businesses studied which are all B2B expressed that it takes time to get a customer to sign up for a service contract, and to get acceptance from customers with not owning the material asset. This usually involves bigger contracts over a longer period, promising prime delivery of a specific function, while making sure that they will get their product back when it no

55 https://tillvaxtverket.se/download/18.40bbbaae16d1aacd58b7ddf4/1568816194484/Sweco %20 Kartläggning_design %20för %20cirkularitet_190627.pdf

longer serves its purpose for the client. Alternatively, the customers have the right to modify, repair or switch the product when needed. One respondent experience that sometimes this is connected to rules of conduct within private organisations and big corporations, where internal guidelines restrict or acts as a barrier for them from looking at alternatives to buying physical goods and products.

ECONOMY AND THE MARKET

Being a circular company in today's market context, one company says that: *"A lot of time has been spent on development, and many businesses have high priority in sustainability, but so far only few live up to this in reality. Still the price wins over sustainability and makes us vulnerable in procurements"*. Another company mentions both benefits and drawbacks to their business model: *"The drawbacks, and the gains, is that we have a massive investment in the installation. It is difficult to finance. On the other hand, you have a recurring, controllable income stream which benefit both us and customers. You avoid the fluctuations. You can with certainty say that this is how much we will gain from this client for the next year or 10 years, and it's the same for the client, this is how much it will cost"*.

SIZE OF BUSINESS, SCALE OF PRODUCTION, BUSINESS CAPACITY

Business scale was also addressed as an issue by several respondents, where ambitions of extended circularity through remanufacturing, refurbishing and redistribution, local repair and assembly sites and after-sales service have been proven difficult to achieve due to, among other, the combination of high manual cost and low production volumes. One company says that: *"The difficult part is that being a small company, also means that it makes everything harder to be completely circular considering high costs and capacity"*. Furthermore that: *"It is always a matter of higher costs and more work, as in putting it in relation to liquidity and capacity. This means it's much harder for a company like us driven by CE and sustainability to scale up"*.

CIRCULARITY CANNIBALISING LINEAR SALES IN THE SHORT TERM

An incentive to remanufacture their products, expressed by one of the companies, was that selling a service or function is part of their business strategy. Therefore, it is natural to use the products and materials in the loop for as long as possible for some of the products. However, they also expressed the issue that a transition to offering a service instead of a product could cannibalise their linear sales in the short term. The respondent said that: *"I even asked a sales director for Europe and Africa about, if we do more of this and it's more remanufacturing, don't you think it's cannibalising normal, linear sales? And the response was: "well, maybe a little bit, but if we don't do this our competitors will do it". So we have to, and we have to be best at this as well"*.

All the respondents perceived their company to have the competence and knowledge needed to transition to or sustain a circular business model. One of them added to this that time pressure often is a barrier. Some expressed that they are beginners since they have never done this kind of transition before, and that input from researchers is still appreciated. When asked about policies or legislation affecting the work with circularity at their company, either as enablers or obstacles, few respondents had specific answers. Most of them said that there are no external policy restrictions that affect their ability to be circular. One respondent said that: *"sometimes yes, if expanding circularity means (temporary) cost increases there are some challenges with the financial department"*. This can however be a matter of internal company focus areas. If the transition to CE is not within the company strategy, motivating higher costs connected with the transition can be challenge.

Several of the organisation expressed that they would like to see a change in prices of virgin materials and a shift in how virgin materials are valued today. One respondent expressed that*: "The reverse logistics of our products are hardly economical; there is only limited material value in the product. Secondly, reusing our second raw material after collecting and processing is less economical than buying virgin or other recycled material"*. Taxes on virgin materials to stimulate the collection and use of recycled materials would therefore help making circular businesses more economically viable.

Another suggestion was to have internal business strategies saying: "*that increases in material costs to a certain extent (+10 %) are accepted when switching from virgin material to recycled material or from fossil bases to bio-based materials"*. Another respondent reflected on why most businesses don't transition to circular models; *raw materials are really undervalued and really cheap, and in some cases subsidised, so why wouldn't they do it like they've always done?"*. Yet another one said that more focus should be put on resource efficiency, internally and externally promoted by national policies, as an addition to the more common focus on energy efficiency.

Furthermore, one company argues that there is a need to set hard goals and to work towards them. This is something they lack in today's national policy context. There are directional guidelines, but too few actual regulations pushing businesses towards sustainability and circularity. The respondents' experience is that this is also the case when it comes to guidelines for procurement: *"A lot of organisations are looking for policy makers to provide a carrot, and I'm a part of that too, but the stick is what makes it happen I think*".

When asked about already existing policies that benefit them, one company said that: *"Maybe policies that have turned into directives in the EU, that actually set demands and sometimes quite strict legislation on companies, helps us in some ways to produce and change products so that they can be maintained longer or recycled*". The same respondent also mentioned that: "*I think we've really started to become more active in the last three or four years. One of the absolute biggest strategic targets for EU is in material and resource use, so commissioners talking about circularity is affecting business of course. We have all the reasons to do more*".

CE TRADE-OFFS

One company, selling light as a service, mentioned that there is a trade-off between energy- and resource efficiency for their products. They explained that: "*One of the drawbacks, is to have a plastic guard in front of the light so that we can make sure that the precious components are never compromised in a volatile environment. That decreases our energy efficiency, but it prolongs the life of the raw material in the lamp exponentially. It's one of those compromises where we end up looking a little bit worse, because everyone is just looking at energy efficiency*". The quote illustrates that policies promoting energy efficiency in product design, might unintentionally have a negative effect on resource efficiency. While policy enforcing a specific goal, (e.g. in this case energy efficiency) can be beneficial for several reasons, paying attention to possible secondary effects is important (as also discussed above).

SUPPLY CHAIN AND MATERIAL CONTENT – TRACEABILITY

Traceability of circulated products and materials was another issue mentioned by the respondents. CE can be hampered by the challenges presented connected with traceability of remanufactured and/or recycled materials and products. During circulation, supply chain complexity can increase, resulting in a situation where it can be difficult or even impossible to provide a declaration of content for recycled products. This in turn might significantly affect the market advantages of circular businesses, as well as limit the possibility for their products reaching the market. One business said that: "D*eclaration of content when circulating products can be a problem*", and furthermore that, the more a product is circulated, the more difficult it is to: "*trace material content and source of raw materials*".

When asked about how supply chains are managed, another respondent reasoned that: "*We would probably know from where our steel suppliers are sourcing their material, and if it's coming from scrap or not. But regarding environmental risk and safety and so on in mining, we make sure that our supplier in turn have their own supplier quality audit in place and that they do what they say, but we wouldn't go to their supplier and check*".

PRODUCTION PROCESS (PHYSICAL/LOGISTICAL LIMITS TO CIRCULARITY)

One large business expressed that the design of the factory can be limiting in reaching full circularity. They try to reuse most materials and fluids needed in production, but that inflexibility of the production line means that if a specific product is produced but does not meet the specifications, it's not certain that they would put it back in the production line or of they would have to scrap it. Putting it back in to production would mean stopping and resetting the operating lines, which will increase the total cost, if not counted for already in the beginning. A small business, on the other hand, expressed that their manufacturing line is designed in such way that components can be fed into the manufacturing line, having flexibility to deal with returned components in an efficient way.

6 Conclusions

The transition from linear to CE is gaining increasing momentum and awareness in stakeholders, ranging from consumers to industry and policy makers. The recently adopted European green deal and the Swedish national strategy for CE are examples of this. Legislation historically (end-of-pipe) aimed at securing waste treatment and minimizing hazardous material in components brought to market, has in recent years been amended with wordings aimed at increase reuse, repairing and refurbishment of products. Designing for circularity is key. Traditional business models are being questioned and discussion about transparency in components and along supply chains are intensified. The digital development during the past decade has incurred many possibilities that align with and can act as an enabler of the transition to CE. The recent development and increased focus on CE is also highlighting organizations' very existence as a part of an ecosystem of actors, together operating within our planetary boundaries. With this comes the important shift of mindset of thinking of waste as resources.

The LinCS project has assessed the micro and macro level impact of transitioning to CE, through a systematic and comprehensive literature review, the assessment of the environmental, economic, and circularity impacts of changing ten different products into circular products, and through an assessment of rebound effects on macroeconomic level.

The literature review showed a clear need for knowledge on the environmental impact of circular products. Especially the impact of circular product design and circular business models on consumer behaviour and consequent environmental impact is unknown. Hence, the majority of the case studies selected for this research included circular product design and circular business model aspects. It was found that most case studies achieved a reduction in environmental impact of up to 60 % for most impact categories (in particular for global warming potential /greenhouse gas emissions). This is primarily the result of product life extension, implied by the move to repair, remanufacturing or a service-based business model. Reuse, refurbishment, or remanufacturing operations are usually less energy intensive than manufacturing a product and hence save on GHG emissions if it means that the product can be used for a longer period of time. Especially for passive products such as signs, jeans, chairs, bearings, and kitchens, life extension is beneficial because the major environmental impacts occur in the production phase. However, for more active products such as boats and cars, the impact occurs in the use phase through the use of chemicals and fossil fuels. With the planned transition to renewable energy, these use phase impacts will however change, and the focus might shift to e.g. material intensity. Policy needs to apply a mix of instruments that categorises products appropriately and targets specific products with specific actions.

In some cases, circular business models increase transport. Sharing requires movement of the product between users which can, with the current consumer travel behaviour and car fleet, lead to an increase in GHG emissions when changing to the circular business model. Also here the expected reduction in the carbon intensity of the underlying production systems will reduce the use phase (including travel) impacts and the focus might shift to other environmental impact categories in the future. Not much knowledge exists on the environmental impact of circular versus linear products in the longer term, including decarbonized energy. Naturally, there are some limitations to LCA modelling and case studies require several assumptions. The main assumptions and uncertainties are largely related to consumer behaviour, which include usage patterns, transport to facilities (such as hiring location or repair facilities) and spending e.g., of savings. For example, until large quantities of consumers are involved in the new business models, it is difficult to draw conclusions on average transport emissions related to sharing, or know if economic savings from repair are spent on other more environmentally impacting activities such as air travel. In addition, collective savings controlled by banks can be directed to investment in construction or infrastructure, which may result in large impacts. To foster CE without inducing overall rebound effects it is necessary to understand and monitor the macro effects of consumption of circular products with the user of appropriate circularity indicators. Hence, the conclusion is that circular products can greatly reduce environmental impact, but promotion of CE does not necessarily lead to overall environmental improvement if its application is not carefully implemented as there is potential for rebound effects.

The literature review highlighted the risk of fostering “circularity for circularity’s sake” due to the proliferation of circularity indicators and tools, without demonstrated correlation to environmental impact. There is currently a risk that organisations can cherry pick from a suite of indicators to suit their own interests, demonstrating apparent circularity but with little correlation to environmental improvements. There is also not enough knowledge about possible rebound effects and the link between product improvements on the micro scale and the consequences at the macro (national) level. The reviewed literature noted the lack of links between the system levels, particularly in terms of indicators and monitoring. Macro scale monitoring is embryonic with much focusing on material mass flows with no link to environmental implications. The use phase is largely missing in national indicators accounts, for example it is not currently covered in the EU’s CE indicators. In other words, there is poor knowledge on the stocks and flows in and out of the economy, to increase knowledge on when certain material streams might enter the recycling or waste flows. In addition, there is a large hidden CE which is currently not tracked such as repair and spare parts (e.g., for cars) and second-hand economy. The circularity of nations and the globe has been assessed as around 9 % in recent research (de Witt et al 2020; Aguilar-Hernandez, 2018) but this has only accounted for recycled mass flows and not the “inner-loops” which is widely regarded as the desired application of CE.

Adequate tools and indicators already exist to monitor and link the micro and macro levels. At the micro level LCA is most effective, whilst at the macro multi-regional input output modelling is improving and can help to monitor the macro level implications of consumption. A framework known as the societal needs or societal functions that divides the needs of society into seven functions, can potentially provide a bridge between the micro and macro level to aid monitoring. To accelerate the transition to CE from policy making perspective, the societal functions framework can track, monitor and develop targeted policy instruments for each societal function: housing and infrastructure; nutrition, mobility, consumables, services, healthcare, and communication. Based on the societal function, indicators can be developed to track each system level so there is knowledge on sub-elements of each function (e.g. GHG emissions of transport) and the individual societal functions. Over time this can provide tracking of how the footprint of societal functions is changing or how impacts are shifting between function – e.g. impact of DVD's and transport to rent has shifted to online energy impacts (i.e. online videos now account for over 1 % of GHG emissions). This will provide knowledge on the total national footprint of consumption and the individual functions. Specific policy instruments can then be based on which functions and sub-elements should be targeted for reduction.

Another area of potential is to improve the knowledge on the current use phase of CE by developing statistics on the use of repair facilities and spare parts, as well as second-hand reuse economy. The contribution of this sector needs to be understood and assessed, to understand if it aids the lowering of consumption impacts or creates additional markets. This can be tracked using mass and economic information initially. Ultimately, this framework can be linked to environmental implications, such as impacts on biodiversity and other planetary boundaries to help achieve the SEO's and minimise national societal impacts.

The companies that participated in this study are of different sizes and acting within different industries. Some act in environments where a signed contract between parties mean long term heavy capital investment, while others have customer relationships which occurs on demand and are customer initiated. For example, contracts within the railway industry versus the commerce of apparel. Their experience of challenges and opportunities with external policies affecting their own operations and capabilities are hence also a result of the nature of their business and its relationships. However, no matter if small or large, organizations dedication to circularity is like most decisions affected by the strategic direction of the organization. If decisions and direction towards circularity are not anchored within organizations, extra costs incurred because of external policy could results in a reactive response not aligned with the strategic direction. A proactive culture with a clear direction towards circularity will benefit when decisions of new investments and short-term costs are taken due to external policy.

In the investment phase and design phase of new operation facilities, potentials in circular flows should be considered and included in the design phase of production, so that the implementation of these do not disrupt and increase production cost as in the case where a fully efficient linear flow has been developed. The circular flows can come from both own operations or from another partner within or outside the value chain. Incentives and guidelines supporting actors to incorporate this perspective should be created, along with incentives for designing products for circularity that lower the impact on the environment.

Further work on investigating how to benefit of those products which are recycled is recommended as virgin material cost versus recycled material costs can sometimes be too competitive. An initial phase could target those material with largest planetary impact and highest turnover. Further research is also needed towards how innovation is affected in CE and what its role can be for sustainable circular products. Knowledge is currently lacking on customer behaviour in CE, for example when it comes to changes in design (such as design for upgradeability, modularity), circular business models such as sharing. More research towards the impact of circular products and business models on consumption levels is needed.

Increasing emphasis should be put on supply chains and the activities alongside it. Traceability of products and components is identified as an important step in enabling circularity of materials. The understanding of where and how a component have been produced and where it has been applied in previous cycles would give credibility to using them in new potential cycles. As supplier revision might be done on first or second tier, ambition to audit and cooperate with lower tier suppliers can often be low. This is often by the actor in power closest to end customer seen as the responsibility of the partners further upstream in the supply chain. Transparency can in those cases enable cooperation.

Within an historic context, economic theories such as economies of scale have been focusing on efficient supply to meet a demand. The larger volume of production, the lower will be the margin cost of producing that extra component or product, and the higher will be the profit per product. As CE practices aim to decouple the volume need from the economic development, there is a need for economic theories incentivising profitability with less products producing. This area could be of interest for further research, to find the new economic theories supporting the decoupling.

On a societal level, the importance of legislators and policy makers to speak about CE as a method of reaching our climate goals is of importance. The communication itself holds a strong signal value and creates awareness on the importance of enabling the transition.

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Appendix 1: Selection of grey papers on CE monitoring and indicators

Type of initiative	Level of initiative	Title	Description
Macro	European Union	New Circular Economy Action Plan (2020)	Addresses recycling and reuse and includes a special focus on resource intensive sectors that have high potential for circularity including building and construction; electronics and ICT; batteries and vehicles; and packaging.
		EU Monitoring Framework for the Circular Economy (2018)	10 indicators grouped according to the four stages of circular economy: production and consumption, waste management, secondary raw materials and competitiveness and innovation. It shows progress towards circular economy in the EU and its Member States.
		EU Resource Efficiency Scoreboard (2013)	Set of resource efficiency indicators including a lead indicator on resources, dashboard indicators on materials, land, water and carbon, and theme-specific indicators. It shows progress towards resource efficiency in the EU and its Member States.
		Raw Materials Scoreboard (2016)	Set of indicators linked to the European Innovation Partnership (EIP) on Raw Materials, which provides EU quantitative data on the EIP's general objectives and on the raw materials in the context of EU policy.
		EASAC – indicators for a circular economy (2016)	Promotes the CE principle at three levels: individual firm level, the ecoindustrial park level and the macro- or eco-city/ecoprovince level, with indicators in four categories.
	National	A Deep Demonstration of a Circular, Regenerative and Low-Carbon Economy in Slovenia (2020)	Slovenian parliament has passed a motion to adopt an EIT Climate-KIC-led circular economy proposal. Centres around driving circularity in five main areas: forestry; built environment; manufacturing; food; and three pillars: mobility: smart and circular communities; circular green development; circular policy design and science
		Government of Canada (2020)	Focused on net-zero emissions, land and ocean conservation, tree planting, and single-use plastic ban.

Type of initiative	Level of initiative	Title	Description
		Scotland Circular Economy Bill (2019)	Proposed legislation in the Circular Economy Bill includes measures to cut litter and waste and forms part of wider plans for a new approach to reducing, reusing and recycling materials to help drive Scotland's circular economy.
		Strategy for Circular Economy, Denmark (2018)	Budget for 15 initatives linked with circular economy.
		France key indicators for monitoring the Circular Economy (2017)	10 indicators monitoring the circularity of France economy, covering the seven pillars of the circular economy. It includes EU comparison.
		Netherlands Circular Economy Monitoring System (2018)	This report (Dutch only) proposes 21 indicators to measure circularity in the Netherlands. It includes EU comparison.
		Indicators used in Japan 3rd Fundamental Plan for Establishing a Sound Material-Cycle Society (2013)	Indicators based on dimensions of material flow in the economy (input, circulation and output) with a focus on stock of materials. Also measures indicators of societal effort towards a circular economy, including the size of the market for rental and leasing of goods, results of surveys of consumer awareness and actions related to circularity, while other general indicators include per capita generation of municipal waste for consumers.
		Germany Resource Efficiency Programme (ProgRess II) (2016)	German initiative started in 2012 to support the sustainable use and conservation of natural resources. Since 2016 uses total raw material productivity as a headline indicator.
	City/Regional	The Amsterdam City Doughnut: A Tool for Transformative Action (2020)	Assessment and plan for happy, healthy livable cities – focused on air, water, land quality - based on doughnut economics by Kate Raworth.
		OneNYC2050	A Liveable Climate: Initative 20 of 30.
		South Holland, NL (2019)	Focused on port of Rotterdam and plastics (petrochemicals).
		Flevoland, NL (2019)	Aiming to become a raw material supplier for the circular economy, with a focus on green raw materials and used materials, processing waste flows in the region into circular raw materials, in particular by facilitating chain formation and stimulating local processing.

Type of initiative	Level of initiative	Title	Description
		Metropolitan Region of Amsterdam (2019)	Priority is to reuse raw materials in a high-quality way, since its highly urbanized setting features a large stock of materials in the built environment. Primary indicators provide insight in the raw material use of a region; Dashboard indicators cover issues such as recycling, energy and biodiversity; Transition indicators reflect the degree of institutional renewal of this system.
		Victoria, Australia (2019)	Recycling Victoria: A new economy is the Victorian Government's 10-year circular economy policy and action plan to fundamentally transform the state's recycling sector, reduce waste, create thousands of jobs and set Victoria up for a more sustainable future.
		NSW (New South Wales), Australia (2019)	Focused on waste and recovery of resources.
		Ontario, Canada (2017)	Sets targets and a plan for waste reduction.
	Private	Dutch Association of Investors for Sustainable Development (VBDO)	Ranking for Dutch companies based on qualitative close ended assessment questions grouped into 4 categories.
		Cotec Evaluation of Circular Economy in Spain (2017)	20 indicators to assess circularity. Framework applied to Spain compared to other countries.
		Circularity Gap Report (2018)	Global Circularity Metric based on the percentage of cyclical use of materials is proposed as a single measure of circular economy.
	Private	Circulytics (2019)	New measurement indicators from Ellen MacArthur Foundation.
		KPN (2017)	Report the process of this transition based on indicators that measure the percentage of equipment and material, which is reused or recycled.
		Philips (2017)	Measure and report their "Circular Revenue": the revenue from products and services that meet specific Circular Economy requirements defined by Philips themselves (e.g. refurbished products or performance based business models).
		Ellen MacArthur Foundation Circularity Indicators (2015)	Business activities and product tools developed for measuring circularity. Focuses on material circularity as a main indicator.

Type of initiative	Level of initiative	Title	Description
		University of Cambridge Circular Economy Toolkit	Product focused online self-assessment tool for businesses provides guidance based on qualitative surveys.
		Circle Economy Circle Assessment (2017)	Online tool for businesses, focuses on seven elements to improve organisational activities, and support the implementation of circular economy strategies at the company level.
		Cradle to Cradle Certification (2012)	Product focused certification system utilising Life Cycle Analysis (LCA) by an accredited independent body.
Other		Circular economy standard BS 8001:2017	New guidelines for implementation of circular economy principles for organizations.
		Indicators for a Circular Economy	A report from 2017 detailing indicators for CE by the CE Research Center – https://ce-center.vlaanderen-circulair.be/en

Appendix 2: Product groups relations to societal functions

	EXIOBASE product group	Code	Societal Function
1	Paddy rice	p01.a	Nutrition
2	Wheat	p01.b	Nutrition
3	Cereal grains nec	p01.c	Nutrition
4	Vegetables	p01.d	Nutrition
5	Oil seeds	p01.e	Nutrition
6	Sugar cane	p01.f	Nutrition
7	Plant-based fibers	p01.g	Other
8	Crops nec	p01.h	Nutrition
9	Cattle	p01.i	Nutrition
10	Pigs	p01.j	Nutrition
11	Poultry	p01.k	Nutrition
12	Meat animals nec	p01.l	Nutrition
13	Animal products nec	p01.m	Nutrition
14	Raw milk	p01.n	Nutrition
15	Wool	p01.o	Consumables
16	Manure (conventional treatment)	p01.w.1	Other
17	Manure (biogas treatment)	p01.w.2	Other
18	Products of forestry	p02	Housing and infra
19	Fish and other fishing products; services incidental of fishing (05)	p05	Nutrition
20	Anthracite	p10.a	Other
21	Coking Coal	p10.b	Other
22	Other Bituminous Coal	p10.c	Other
23	Sub-Bituminous Coal	p10.d	Other
24	Patent Fuel	p10.e	Other
25	Lignite/Brown Coal	p10.f	Other
26	BKB/Peat Briquettes	p10.g	Housing and infra
27	Peat	p10.h	Other
28	Crude petroleum and services related to crude oil extraction	p11.a	Other
29	Natural gas and services related to natural gas extraction	p11.b	Other
30	Natural Gas Liquids	p11.b.1	Other
31	Other Hydrocarbons	p11.c	Other
32	Uranium and thorium ores (12)	p12	Other
33	Iron ores	p13.1	Materials
34	Copper ores and concentrates	p13.20.11	Materials
35	Nickel ores and concentrates	p13.20.12	Materials
36	Aluminium ores and concentrates	p13.20.13	Materials
37	Precious metal ores and concentrates	p13.20.14	Materials
38	Lead	p13.20.15	Materials
39	Other non-ferrous metal ores and concentrates	p13.20.16	Materials

	EXIOBASE product group	Code	Societal Function
40	Stone	p14.1	Materials
41	Sand and clay	p14.2	Materials
42	Chemical and fertilizer minerals	p14.3	Materials
43	Products of meat cattle	p15.a	Nutrition
44	Products of meat pigs	p15.b	Nutrition
45	Products of meat poultry	p15.c	Nutrition
46	Meat products nec	p15.d	Nutrition
47	Products of Vegetable oils and fats	p15.e	Nutrition
48	Dairy products	p15.f	Nutrition
49	Processed rice	p15.g	Nutrition
50	Sugar	p15.h	Nutrition
51	Food products nec	p15.i	Nutrition
52	Beverages	p15.j	Nutrition
53	Fish products	p15.k	Nutrition
54	Tobacco products (16)	p16	Consumables
55	Textiles (17)	p17	Consumables
56	Wearing apparel; furs (18)	p18	Consumables
57	Leather and leather products (19)	p19	Consumables
58	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	p20	Materials
59	Wood material for treatment	p20.w	Materials
60	Pulp	p21.1	Materials
61	Secondary paper for treatment	p21.w.1	Materials
62	Paper and paper products	p21.2	Materials
63	Printed matter and recorded media (22)	p22	Communications
64	Coke Oven Coke	p23.1.a	Other
65	Gas Coke	p23.1.b	Other
66	Coal Tar	p23.1.c	Other
67	Motor Gasoline	p23.20.a	Mobility
68	Aviation Gasoline	p23.20.b	Mobility
69	Gasoline Type Jet Fuel	p23.20.c	Mobility
70	Kerosene Type Jet Fuel	p23.20.d	Mobility
71	Kerosene	p23.20.e	Mobility
72	Gas/Diesel Oil	p23.20.f	Mobility
73	Heavy Fuel Oil	p23.20.g	Mobility
74	Refinery Gas	p23.20.h	Other
75	Liquefied Petroleum Gases (LPG)	p23.20.i	Mobility
76	Refinery Feedstocks	p23.20.j	Other
77	Ethane	p23.20.k	Other
78	Naphtha	p23.20.l	Other
79	White Spirit & SBP	p23.20.m	Materials
80	Lubricants	p23.20.n	Materials
81	Bitumen	p23.20.o	Materials
82	Paraffin Waxes	p23.20.p	Materials
83	Petroleum Coke	p23.20.q	Other
84	Non-specified Petroleum Products	p23.20.r	Other
85	Nuclear fuel	p23.3	Other

	EXIOBASE product group	**Code**	**Societal Function**
86	Plastics	p24.a	Materials
87	Secondary plastic for treatment	p24.a.w	Other
88	N-fertiliser	p24.b	Materials
89	P- and other fertiliser	p24.c	Materials
90	Chemicals nec	p24.d	Materials
91	Charcoal	p24.e	Housing and infra
92	Additives/Blending Components	p24.f	Other
93	Biogasoline	p24.g	Mobility
94	Biodiesels	p24.h	Mobility
95	Other Liquid Biofuels	p24.i	Housing and infra
96	Rubber and plastic products (25)	p25	Consumables
97	Glass and glass products	p26.a	Consumables
98	Secondary glass for treatment	p26.a.w	Other
99	Ceramic goods	p26.b	Consumables
100	Bricks	p26.c	Housing and infra
101	Cement	p26.d	Housing and infra
102	Ash for treatment	p26.d.w	Materials
103	Other non-metallic mineral products	p26.e	Materials
104	Basic iron and steel and of ferro-alloys and first products thereof	p27.a	Materials
105	Secondary steel for treatment	p27.a.w	Materials
106	Precious metals	p27.41	Materials
107	Secondary preciuos metals for treatment	p27.41.w	Materials
108	Aluminium and aluminium products	p27.42	Materials
109	Secondary aluminium for treatment	p27.42.w	Materials
110	Lead	p27.43	Materials
111	Secondary lead for treatment	p27.43.w	Materials
112	Copper products	p27.44	Materials
113	Secondary copper for treatment	p27.44.w	Materials
114	Other non-ferrous metal products	p27.45	Materials
115	Secondary other non-ferrous metals for treatment	p27.45.w	Materials
116	Foundry work services	p27.5	Services
117	Fabricated metal products	p28	Consumables
118	Machinery and equipment n.e.c. (29)	p29	Consumables
119	Office machinery and computers (30)	p30	Communications
120	Electrical machinery and apparatus n.e.c. (31)	p31	Consumables
121	Radio	p32	Communications
122	Medical	p33	Healthcare
123	Motor vehicles	p34	Mobility
124	Other transport equipment (35)	p35	Mobility
125	Furniture; other manufactured goods n.e.c. (36)	p36	Housing and infra
126	Secondary raw materials	p37	Materials
127	Bottles for treatment	p37.w.1	Materials
128	Electricity by coal	p40.11.a	Housing and infra
129	Electricity by gas	p40.11.b	Housing and infra
130	Electricity by nuclear	p40.11.c	Housing and infra
131	Electricity by hydro	p40.11.d	Housing and infra
132	Electricity by wind	p40.11.e	Housing and infra

	EXIOBASE product group	**Code**	**Societal Function**
133	Electricity by petroleum and other oil derivatives	p40.11.f	Housing and infra
134	Electricity by biomass and waste	p40.11.g	Housing and infra
135	Electricity by solar photovoltaic	p40.11.h	Housing and infra
136	Electricity by solar thermal	p40.11.i	Housing and infra
137	Electricity by tide	p40.11.j	Housing and infra
138	Electricity by Geothermal	p40.11.k	Housing and infra
139	Electricity nec	p40.11.l	Housing and infra
140	Transmission services of electricity	p40.12	Housing and infra
141	Distribution and trade services of electricity	p40.13	Housing and infra
142	Coke oven gas	p40.2.a	Other
143	Blast Furnace Gas	p40.2.b	Other
144	Oxygen Steel Furnace Gas	p40.2.c	Other
145	Gas Works Gas	p40.2.d	Other
146	Biogas	p40.2.e	Housing and infra
147	Distribution services of gaseous fuels through mains	p40.2.1	Housing and infra
148	Steam and hot water supply services	p40.3	Housing and infra
149	Collected and purified water	p41	Housing and infra
150	Construction work (45)	p45	Housing and infra
151	Secondary construction material for treatment	p45.w	Housing and infra
152	Sale maintenance repair of motor vehices	p50.a	Mobility
153	Retail trade services of motor fuel	p50.b	Mobility
154	Wholesale trade and commission trade services	p51	Consumables
155	Retail trade services	p52	Consumables
156	Hotel and restaurant services (55)	p55	Consumables
157	Railway transportation services	p60.1	Mobility
158	Other land transportation services	p60.2	Mobility
159	Transportation services via pipelines	p60.3	Housing and infra
160	Sea and coastal water transportation services	p61.1	Mobility
161	Inland water transportation services	p61.2	Mobility
162	Air transport services (62)	p62	Mobility
163	Supporting and auxiliary transport services; travel agency services (63)	p63	Mobility
164	Post and telecommunication services (64)	p64	Communications
165	Financial intermediation services	p65	Services
166	Insurance and pension funding services	p66	Services
167	Services auxiliary to financial intermediation (67)	p67	Services
168	Real estate services (70)	p70	Housing and infra
169	Renting services of machinery and equipment without operator and of personal and household goods (71)	p71	Communications
170	Computer and related services (72)	p72	Services
171	Research and development services (73)	p73	Services
172	Other business services (74)	p74	Services
173	Public administration and defence services; compulsory social security services (75)	p75	Services
174	Education services (80)	p80	Services
175	Health and social work services (85)	p85	Healthcare
176	Food waste for treatment: incineration	p90.1.a	Nutrition

	EXIOBASE product group	Code	Societal Function
177	Paper waste for treatment: incineration	p90.1.b	Other
178	Plastic waste for treatment: incineration	p90.1.c	Other
179	Intert/metal waste for treatment: incineration	p90.1.d	Other
180	Textiles waste for treatment: incineration	p90.1.e	Consumables
181	Wood waste for treatment: incineration	p90.1.f	Other
182	Oil/hazardous waste for treatment: incineration	p90.1.g	Other
183	Food waste for treatment: biogasification and land application	p90.2.a	Nutrition
184	Paper waste for treatment: biogasification and land application	p90.2.b	Other
185	Sewage sludge for treatment: biogasification and land application	p90.2.c	Housing and infra
186	Food waste for treatment: composting and land application	p90.3.a	Nutrition
187	Paper and wood waste for treatment: composting and land application	p90.3.b	Other
188	Food waste for treatment: waste water treatment	p90.4.a	Nutrition
189	Other waste for treatment: waste water treatment	p90.4.b	Other
190	Food waste for treatment: landfill	p90.5.a	Nutrition
191	Paper for treatment: landfill	p90.5.b	Other
192	Plastic waste for treatment: landfill	p90.5.c	Other
193	Inert/metal/hazardous waste for treatment: landfill	p90.5.d	Other
194	Textiles waste for treatment: landfill	p90.5.e	Other
195	Wood waste for treatment: landfill	p90.5.f	Other
196	Membership organisation services n.e.c. (91)	p91	Services
197	Recreational	p92	Healthcare
198	Other services (93)	p93	Services
199	Private households with employed persons (95)	p95	Services
200	Extra-territorial organizations and bodies	p99	Services

Appendix 3: Dissemination LinCS

LinCS scientific journal papers

1. Harris, S., Martin, M., Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption, 26, 172–186. Available at: https://www.sciencedirect.com/science/article/pii/S2352550920305236?via %3Dihub
2. Martin, M., Heiska, M., Björklund, A. (2021). Environmental assessment of a product-service system for renting electric-powered tools. *Journal of Cleaner Production, 281*. Available at: https://www.sciencedirect.com/science/article/pii/S0959652620352896
3. 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. Available at: https://www.sciencedirect.com/science/article/pii/S0959652620356730
4. Martin, M., Herlaar, S. (2021). Environmental and social performance of valorizing waste wool for sweater production. Sustainable Production and Consumption, 25, 425–438. Available at: https://www.sciencedirect.com/science/article/pii/S235255092031397X
5. Martin, M., Herlaar, S. Jönsson, A., Lazarevic, D. (NA) Trouble brewing: Assessing the sustainability of circular and linear beer 2 keg system. Submitted to Resources, Conservation and Recycling (Nov 2020).

LinCS Conference papers and presentations

6. Van Loon, P., Diener, D., Kazmierczak, K. (2019). Circular principles and environmental impact reductions: current knowledge and the way forward. International Conference on Life Cycle Management, 1–4 September 2019, Poznan, Poland.
7. Van Loon, P., Diener, D., Harris, S. (2019). The environmental impact of circular products: what do we really know? European Roundtable on Sustainable Consumption and Production. 15–18 October 2019, Barcelona, Spain. Available at: https://forskning.ruc.dk/files/66851680/Volume_1_Proceedings.pdf (page 355–371)
8. Martin, M., Heiska, M., Lippert, P. (2019). Tool sharing platforms and sustainability: Environmental implications and life cycle management of sharing services. European Roundtable on Sustainable Consumption and Production. 15–18 October 2019, Barcelona, Spain.
9. Martin, M., Herlaar, S., Betros, Y.F. (2020). Exploring the environmental and social performance of a new value chain for valorzing waste wool in outdoor garments. Social Life Cycle Assessment. 15–17 June 2020, online. Available at: https://www.researchgate.net/

publication/342200592_Exploring_the_environmental_and_social_performance_of_a_new_value_chain_for_valorizing_waste_wool_in_outdoor_garments

10. Martin, M., Herlaar, S. (2020). From circular to linear? Assessing the environmental performance of steel and plastic kegs in the brewing industry. 12th International Conference on Life Cycle Assessment of Food, 13–16 October 2020, Berlin. Available at: https://www.researchgate.net/publication/344665742_From_Circular_to_Linear_Assessing_the_Environmental_Performance_of_Steel_and_Plastic_Kegs_in_the_Brewing_Industry

Other LinCS presentations (Industry & Education)

11. Webinar environmental and economic implications of circularity. Organized by Swedish Life cycle Center. Patricia van Loon, Steve Harris, Derek Diener. 18 November 2019.
12. Webinar dags att ställa om – verktyg, metoder, och goda råd. Organized by Cradlenet. Patricia van Loon. 2 April 2020.
13. Case studies used in teaching – Tillväxtverket, University of Gothenburg and Chalmers.

LinCS master theses

14. Heiska, M. (2019). Assessing environmental impacts of a tool rental service from Husqvarna using life cycle assessment. Master thesis, KTH Royal Institute of Technology, Stockholm, Sweden.
15. Longnell, F. (2019). Environmental performance from circularity in products: a case study on LED lighting fixtures. Master thesis, Karlstad Business School, Sweden.
16. Nellström, M., Saric, M. (2019). A comparative life cycle assessment of nudie jeans' repair and reuse concept. Master thesis, Industrial Ecology Chalmers, Göteborg, Sweden.

Appendix 4: Questionnaire industry insights CE policy

- Are there currently any restrictions (in terms of policy or other) that prevent you from implementing a circular business model, or prevent you from expanding and/or adjusting a circular business model already in use?
  - If yes, what kind of restrictions? What policy?
  - If yes, in what way does it restrict?
- What kind of policy would you like to see that is not currently in place (specifically or generally)?
- What policies *are* currently in place that are beneficial to your business in terms of circularity?
- Please mark with "YES" or "NO" for each category if you currently have circular processes in place. If not, please motivate.
  - **Product design.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Business model.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Manufacturing.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Remanufacturing.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Reparation and after-sales service.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Return logistics.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Sales.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Sourcing/material use.**
    If not, are you planning on implementing circularity in this area? Why/why not?
  - **Other**, [please specify here].

- What obstacles/difficulties are you experiencing with your circular business model?
- Do you perceive your company to have the knowledge and competence needed to transition to a circular business model?
- What gains in terms of environmental sustainability does CE contribute to, or does it have the potential to contribute to, at your company?
- What drawbacks in terms of environmental sustainability does CE cause, or does it have a risk of causing, at your company?
- In what area(s) do you currently have the biggest and/or most problematic environmental impact?
  - Do you think that CE will solve that issue?
- Have you identified any trade-offs between circularity and environmental impact? That is, have you seen any cases within your company where circular business models have a higher environmental impact than linear ones?
- In what cases are closed-loop systems *not* sustainable? Why?
- What gains in terms of economic sustainability does CE contribute to, or does it have the potential to contribute to, at your company?
- What drawbacks in terms of economic sustainability does CE cause, or does it have a risk of causing, at your company?
- What do you perceive to be the most prominent obstacles for the implementation of CE in your business?
  - Economy
  - Management
  - Policy context/regulations. Swedish context and EU context
  - Lack of knowledge/information/expertise
  - Other, [please specify].

  Please explain your choice(s) here:
- What guidelines are missing in today's policy context? (general or specific).

Linking circularity metrics at product and society level (LinCS)

Final report

PATRICIA VAN LOON, SAAMET EKICI, STEVE HARRIS, MICHAEL MARTIN,
SJOERD HERLAAR, TOMAS RYDBERG, DEREK DIENER, MARCUS LINDER

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The report is the result of a research project, aimed to generate knowledge and understanding on the environmental and financial implications of circular products and circular economy at micro and macro level.

Ten case studies were conducted in which the environmental, economic, and circularity performance of a product in a linear and circular business model were quantified. The case studies show that the circular offer reduced the greenhouse gas impacts significantly in all but one case (where the rental business model led to increased emissions from transport for the customer and was highly dependent on rental location). Most cases resulted in a 50 to 60% reduction.

The results from macro-economic modelling suggest potential rebound effects and that there is a limit to what can be achieved with circularity. More traditional reductions in energy and improvements in resource efficiency are still required. The evidence shows that circular products have great potential to reduce impacts on micro level, but their fostering requires careful management and monitoring to avoid potential rebound effects.

Many challenges and potential pitfalls of circular products are because they currently operate within a linear market and within a system based on cheap fossil fuels, where the cost and impact of raw material extraction is undervalued and underestimated.

The research project has been funded by the Swedish EPA's environmental research grant, which aims to fund research in support of the Swedish EPA and the Swedish Marine and Water Authority's knowledge needs.

Swedish EPA SE-106 48 Stockholm. Visiting address: Stockholm – Virkesvägen 2, Östersund – Forskarens väg 5 hus Ub. Tel: +46 10-698 10 00, e-mail: registrator@naturvardsverket.se Internet: www.naturvardsverket.se **Orders** Ordertel: +46 8-505 933 40, e-mail: natur@cm.se Address: Arkitektkopia AB, Box 110 93, SE-161 11 Bromma. Internet: www.naturvardsverket.se/publikationer