Simulation Modelling of a Shift to Service-Based Offerings

Resource efficiency and operational implications in the
context of the circular economy

Raphael Wasserbaur

Linköping Studies in Science and Technology
Dissertation No. 2119

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Linköping 2020

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Cover:

The cover illustrates the interlinkages between societal actors on the left, the 3Rs of waste management – reduce reuse recycling – in the centre and data on the right. The feedback from the data icon to the actors symbolises how, we, as a society, can adapt improve our behaviour through databased knowledge.

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Printed in Sweden by LiU-Tryck, Linköping, Sweden, 2020

ISBN: 978-91-7929-711-4

ISSN: 0345-7524

Prediction is very difficult, especially if it's about the future.

Niels Bohr

Abstract

The unsustainable levels of resource use and emissions of our economies and their threat to future generations are core issues of our time. The circular economy (CE) conceptualises a different type of economy that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.

The novelty of the CE requires the development of new analytical tools and methods as well as ways of thinking to understand its consequences. This research summarises four years of research on the topic of systems analysis and simulation modelling in the domain of the CE. Three topics were of major interest: First, what are the resource efficiency implications of a shift toward a CE? Second, what are the operational implications of a shift to a CE? And finally, how can systemic changes towards a CE be understood and planned?

Four studies were conducted addressing the three research questions. The first study applies material flow analysis to a washing machine manufacturer case and looks at how different business models affect the resource flows of critical resources. It finds that service-based offerings lead to higher overall resource efficiency. The second study focuses on the implications of CE initiatives on the maintenance activities of a heat-as-a-service provider. It shows that the shift to service-based offerings requires service providers to face worse-before-better situations where long-term benefits offset short-term disadvantages. The third study is a simulation-based case study of laundry practices in Sweden. It compares a sharing economy scenario where a population shares washing machines with a scenario where the majority of people own the washing machines they are using. The results indicate that in Sweden and Europe in general, sharing has significant resource savings potential in the domestic laundry sector. The fourth study is a conceptualisation of design fixation to higher levels of analysis. It identifies examples of fixations on the organisational and institutional level. In addition, it argues that in order to design sustainable sociotechnical systems, aspects like governmental policies and business models need to be considered design parameters.

A shift to a CE needs to happen on many levels of society. This research presents simulation models that can support corporate and political decision makers in the shift to a CE. It shows that in order to understand the CE, the analysis has to be, on the one hand, able to simulate system dynamics, and on the other hand connect the multiple levels of society.

Keywords: resource efficiency; resource effectiveness; circular economy (CE); sociotechnical systems; systems thinking; simulation; product/service system (PSS); system dynamics

Sammanfattning

De ohållbara nivåerna av resursutnyttjande och utsläpp av våra ekonomier och deras hot mot framtida generationer är en av dagens nyckelutmaningar. Cirkulär ekonomi (CE) är en konceptualisering av en ny typ av ekonomi som är baserad på återställande och regenerativ design, som siktar på att behålla nyttan och värdet så högt som möjligt i produkter, komponenter och material, indelad i deras teknologiska och biologiska cykler.

Nymodigheten av CE erfordrar utvecklingen av nya analytiska verktyg och metoder så väl som annorlunda sätt att tänka för att förstå dess konsekvenser. Den här rapporten summerar fyra år av forskning på ämnet systemanalys och simulationsmodellering i domänen av CE. Tre ämnen var av högt intresse. Vilka är de miljömässiga konsekvenserna av ett skifte till CE? Vilka är de operationella konsekvenserna av ett skifte till CE? Hur kan den systematiska förändringen till en CE bli planerad och förstådd?

Vi utförde fyra studier för att undersöka de tre frågorna. Första artikeln använder materialflödesanalys i en fallstudie på en tvättmaskinstillverkare, och undersöker hur olika affärsmodeller påverkar flödet av kritiska resurser. Den visar att erbjudande baserade på service leder till en högre övergripande resurseffektivitet. Den andra artikeln fokuserar på implikationerna av CE initiativ på underhållsaktiviteter för en värme-som-tjänst-distributör. Den visar att skiftet till en CE kräver att möta sämre-innan-bättre-situationer där långsiktiga fördelar kompenserar för kortsiktiga nackdelar. Tredje artikeln är en simulationsbaserad fallstudie på tvättvanor i Sverige. Det jämför ett delningsekonomicenario där en population delar tvättmaskiner mot ett scenario där majoriteten av population är ägare av egna tvättmaskiner. Resultaten indikerar att det finns en signifikant besparingspotential av resurser både i Sverige och i Europa generellt. Fjärde artikeln är en konceptualisering av design fixation till högre analytiska nivåer. Den identifierar exempel på fixation på en organisationell och en institutionell nivå. Utöver det så argumenteras det att i design av hållbara sociotekniska system aspekter som myndighetspolicyers och affärsmodeller behöver vara designparameter.

CE är ett koncept som finns i många nivåer av samhället från produktdesign till myndighetspolicyers. Det här forskning presenterar simulationsmodeller som kan stödja affärsmässiga och politiska beslutsfattare inom skiftet till en CE. Denna uppsats visar att för att förstå CE, så måste analysen dels kunna simulera systemdynamik, samt dels koppla till de multipla nivåerna i samhället.

Zusammenfassung

Der hohe Ressourcenverbrauch und das hohe Emissionsniveau, die mit der westlichen Lebensweise einhergehen sind ein Hauptproblem unserer Zeit. Die Kreislaufwirtschaft (zu englisch „circular economy“) ist ein alternatives Wirtschaftsmodell, das darauf abzielt, den Wert von Produkten, Komponenten und Materialien über deren Lebenszeit zu erhalten.

Die relative Neuheit dieses Wirtschaftsmodells erfordert es, neue analytische Methoden, Werkzeuge und Denkweisen zu entwickeln. Diese Doktorarbeit umfasst vier Jahre Forschung an den Themen Systemanalyse und Simulationsmodellierung im Bereich der Kreislaufwirtschaft. Drei Fragen standen im Zentrum: Erstens, welche Auswirkungen hat ein Wechsel zur Kreislaufwirtschaft auf die Ressourceneffizienz? Zweitens, welche Auswirkungen hat ein Wechsel von produzierenden Unternehmen zur Kreislaufwirtschaft auf deren Betriebsführung? Drittens, wie können die notwendigen systemischen Veränderungen verstanden und geplant werden.

Diese Dissertation basiert auf vier Studien, die unterschiedliche Aspekte eines gesellschaftlichen Wandels zur Kreislaufwirtschaft beleuchten. Die erste Studie ist eine Materialflussanalyse, die die Ressourceneffizienz unterschiedlicher Geschäftsmodelle eines Waschmaschinenherstellers vergleicht. Dabei stellt sich heraus, dass servicebasierte Angebote zu einer erhöhten Ressourceneffizienz führen können. Die zweite Studie untersucht die Auswirkungen einer Umstellung auf Heat-as-a-Service-Angebote aus der Sicht eines Heizgeräteherstellers und dessen Betriebsführung. Die Studie zeigt, dass der Hersteller in Situation gerät, in der kurzfristige erhöhte Kosten mit langfristigen Prozessverbesserungen und geringeren Instandhaltungskosten abgewogen werden müssen. Als drittes wird eine Simulationsstudie präsentiert, in der die Wäschepraxis in Schweden im Fokus steht. Mehrere Szenarien werden verglichen, in denen die Bevölkerung dazu übergeht, Gemeinschaftswaschküchen anstatt eigener Haushaltwaschmaschinen zu verwenden. Die Simulationsergebnisse zeigen, dass, falls umgesetzt in großen Teilen der Bevölkerung, diese Sharing Economy-Praxis ein großes Potential zur Einsparung von Ressourcen hat. In der vierten Studie wird das Konzept der „design fixation“ als mögliche Ursache für die Trägheit unserer gesellschaftlichen Systeme festgemacht. Design fixation als Phänomen beschreibt das Festhalten eines Designers an bestehenden Ideen und Konzepten, das das Endergebnis des Designprozesses einschränkt. Diese vierte Studie liefert eine Einschätzung des Einflusses von design fixation auf den Ressourcenverbrauch in sociotechnischen Systemen.

Eine Umstellung zur Kreislaufwirtschaft bedeutet ein Wandel auf mehreren Ebenen der Gesellschaft. Die Komplexität dieses alternativen Wirtschaftsmodells, erfordert die Verwendung adäquater Modelle, die in der Lage sind, Gesellschaftsebenen kausal zu verknüpfen, und die entsprechenden Systemdynamiken zu simulieren. In dieser Doktorarbeit werden mehrere Simulationsmodelle präsentiert, die für Entscheidungsträger in Politik und Industrie nützlich sind, um die Kreislaufwirtschaft in ihrem Milieu besser verstehen zu können.

Acknowledgements

First and foremost, I would like to thank Dr. Tomohiko Sakao, my main supervisor, for his great support and continuous feedback throughout the entire PhD process. Dr. Erik Sundin provided very important support in various stages of this journey as well.

The education underlying this thesis was co-funded by an EU Horizon 2020 programme called “CircEuit” (Grant 502 Agreement number 721909) as well as by a MISTRA programme called “Resource-Efficient and Effective Solutions” (Grant No. 2014/16). Both projects had a focus on inter-university collaborations. The EU programme consisted of a network of fifteen PhD positions in seven universities, whereas the MISTRA programme was based on three universities and close collaboration with manufacturing companies. In both projects, I focused on the interlinkages between governmental policies and manufacturing companies and how they can be used to further CE activities.

Sustainability issues are typically interdisciplinary and international. It was a great privilege that my work happened within interdisciplinary collaborations across universities in an international context. I believe this is the most adequate *modus operandi* to develop the kind of knowledge necessary for a sustainable future. I would like to express my gratitude to my colleagues at the Division of Environmental Technology and Management at Linköping University, who helped me over the course of four years to develop my research skills.

I would like to give special thanks to Mårten Wiktor, Sergio Brambila, Wisdom Kanda, Don Huising, Yang Liu and Mattias Lindahl for their ideas and guidance during my time at Linköping University.

Appended articles

Article I

Sakao, T., Wasserbaur, R. and Mathieux, F., 2019. A methodological approach for manufacturers to enhance value-in-use of service-based offerings considering three dimensions of sustainability. *CIRP Annals*, 68(1), pp.33-36.

<http://www.diva-portal.org/smash/get/diva2:1313952/FULLTEXT02.pdf> (green open access)

Article II

Wasserbaur, R., Beltagui, A., Schröder, A., 2020. A complex adaptive systems perspective on servitization: A hybrid simulation model to inform decision-making for Heat as a Service. (Submitted to *International Journal of Operations and Production Management*, currently under major revision)

Article III

Wasserbaur, R., Sakao, T., Söderman, M.L., Plepys, A. and Dalhammar, C., 2020. What if everyone becomes a sharer? A quantification of the environmental impact of access-based consumption for household laundry activities. *Resources, Conservation and Recycling*, 158, p.104780.

<http://www.diva-portal.org/smash/get/diva2:1432012/FULLTEXT02.pdf> (green open access)

Article IV

Wasserbaur, R. and Sakao, T., 2020. Conceptualising Design Fixation and Design Limitation and Quantifying Their Impacts on Resource Use and Carbon Emissions. *Sustainability*, 12(19), p.8104.

<http://liu.diva-portal.org/smash/get/diva2:1504219/FULLTEXT01.pdf> (gold open access)

Contributions to the articles

Article I

Tomohiko Sakao led in the conceptualisation and the writing of the manuscript. The author was responsible for data collection, which included a series of workshops with the case company in order to understand the internal processes that occur during the transition to CE-oriented business models. The authors also contributed to the writing and feedback for all revisions.

Article II

The author was responsible for developing the simulation model and, in particular, integrating the three model paradigms and combining qualitative with quantitative modelling aspects. The two co-authors contributed significantly in conceptualising the article, the writing and feedback during the entire process.

Article III

The author's responsibilities were collecting and analysing the empirical data, developing the simulation model, and writing major parts of the manuscript. Tomohiko Sakao contributed to the writing and provided feedback on revisions during the publication process. Maria Ljunggren Söderman contributed to the simulation modelling by providing lifecycle analysis expertise, while Andrius Plepys contributed with critical feedback and ideas during the conceptualisation. Finally, Carl Dalhammar contributed with critical feedback and policy-related writing.

Article IV

The author was responsible for writing major parts of the manuscript, the simulation modelling and the revisions during the publication process. Tomohiko Sakao contributed majorly during the ideation phase of the article with significant parts to the writing, feedback of the revision and ideas during the article's conceptualisation.

Related publications

Wasserbaur, R. and Sakao, T., 2018. Extending environmental impact assessments of consumer products with System Dynamics. In *The 36th International Conference of the System Dynamics Society, Reykjavik, Iceland, August 7-9, 2018*.

<http://proceedings.systemdynamics.org/2018/proceed/abstracts/2313.html>

Wasserbaur, R. and Sakao, T., 2018. Analysing interplays between PSS business models and governmental policies towards a CE. In *10th CIRP IPS2 Conference 2018* (Vol. 73, pp. 130-136).

<https://www.sciencedirect.com/science/article/pii/S2212827118305195> (gold open access)

Wasserbaur, R., Milios, L., 2019. Spurring remanufacturing through public procurement: A case study in the Swedish automotive industry. In *4th International Conference on Remanufacturing*.

<http://www.diva-portal.org/smash/record.jsf?pid=diva2:1324315>

Wasserbaur, R., Sakao, T. and Lindahl, M., 2019. System analysis including aspects of governmental policies, business models and product/service design. In *11th CIRP Conference on Industrial Product-Service Systems, CIRP IPS2 2019; Zhuhai; China; 29 May 2019 through 31 May 2019* (Vol. 83, pp. 32-37). Elsevier BV. Recipient of best student article award.

<https://www.sciencedirect.com/science/article/pii/S2212827119302574> (gold open access)

Wasserbaur, R., Sakao, T., Milios, L., 2019. A literature review on the interactions of governmental policies and business models for a CE. (Submitted to *Journal of Cleaner Production*, currently under major revision).

Definition of key terms

Business model

Describes how a company conducts business. It is a conceptual model that explicitly states how the business functions and how strategic goals are operationalised. It describes how value is created, captured and delivered (Osterwalder *et al.*, 2005).

Circular economy - CE

The circular economy is “*an economic model based inter alia on sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop, which aims to retain the highest utility and value of products, components and materials at all times*” (European Parliament, 2015).

Product/service systems - PSS

A combination comprising of tangible and intangible elements for fulfilling specific customer needs (Tukker, 2015).

Provider

A manufacturing company that is delivering value to customers without selling a physical product.

Resources

Resources are “*naturally occurring assets that provide use benefits through the provision of raw materials and energy used in economic activity*” (UNEP, 2010).

Resource efficiency

“*Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising impacts on the environment. It allows us to create more with less and to deliver greater value with less input*” (European Commission, 2020b).

Servitization

The transformation of manufacturers from selling products and basic services towards advanced services and product/service systems (Baines and Lightfoot, 2014).

Sociotechnical systems – STS

The wholeness of the system elements and their interlinkages necessary to fulfil societal functions (Geels, 2004), for example, sociotechnical laundry systems (Pettersen *et al.*, 2013), sociotechnical heating systems (Rohracher, 2016) and sociotechnical transport systems (Olsson, 2015).

Sustainability

The ability of society to exist perpetually without compromising the well-being of people or planet (own interpretation).

Sustainable Development

“*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (Brundtland, 1987).

List of abbreviations

ABM.....	Agent-based modelling
CE.....	Circular economy
DEM.....	Discrete event modelling
GHG	Greenhouse gas
MFA	Material flow analysis
OEM.....	Original equipment manufacturer
PSS	Product/Service System
SD.....	System dynamics
SDM	System dynamics modelling
STS.....	Sociotechnical system

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1 Introduction

The chapter starts by presenting the motivation for the research of this doctoral thesis. It then lines out the key research problems, followed by the aim and research questions. Following that, the scope and thesis outline are presented.

1.1 Background

The transformation towards a more sustainable future, where humanity operates within the planetary boundaries, is one of the major challenges of our time (Steffen *et al.*, 2015). Our economies are capable of producing immense utility for people, which unfortunately comes at the cost of high resource use and unsustainable emission levels (Balsalobre-Lorente *et al.*, 2018). This, in turn, leads to detrimental impacts like climate change or loss of biodiversity (Thomas *et al.*, 2004). In order to decrease resource use and emission levels, we need to depart from the current “take-make-dispose” economic paradigm (EMF, 2013). We urgently need systemic changes in the global economic system (IPCC, 2018). These changes refer to developing different consumer behaviour, product design, business models, infrastructure and governmental policies (Planing, 2015; Esposito *et al.*, 2018; Hopkinson *et al.*, 2020).

Governments all over the world have defined goals to decrease environmental impacts. The United Nations has developed the 2030 Agenda for Sustainable Development to ensure peace and prosperity for people and the planet (UN, 2015; UNDESA, 2015). Under the United Nations Framework Convention on Climate Change, countries have committed significant resources towards the goal of stabilising the greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The European Commission, in its European Green Deal (European Commission, 2019), aims towards no net emissions of GHGs by 2050. With circular economy (CE) being a major part of the European Green Deal, the European Commission expects it to significantly contribute to environmental sustainability while also creating jobs (European Commission, 2015).

The CE applies concepts from scientific disciplines like industrial ecology and environmental economics (Ghisellini *et al.*, 2016; Bruel *et al.*, 2019). The EU (European Parliament, 2015) defines the CE as “*an economic model based inter alia on sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop, which aims to retain the highest utility and value of products, components and materials at all times*”.

From a material perspective, the objectives of the CE are a reduction of virgin material consumption, the elimination of waste and the decoupling from economic growth and materials usage (Campbell-Johnston *et al.*, 2020). These objectives are attainable if resource productivity is drastically improved, supply chains are closed, and there is a shift toward fulfilling society’s needs with services instead of products. From a business perspective, the CE revolves around maximising the value created from products, components and materials by finding ways to use them longer or more intensively or use them multiple times before disposal (EMF, 2013; Ghisellini *et al.*, 2016).

Despite the promising benefits of a CE, in Europe, little progress has been made when it comes to large-scale implementations. The EU is currently ~11% circular (Eurostat, 2020), which means that 11% of material resource needs are covered through secondary raw materials. The global circularity lies at approximately 9% (De Wit *et al.*, 2018). This means that only a fraction of the resources used to satisfy societal needs are “cycled” once they are waste, and conversely, the share of secondary raw materials in new products is relatively low (De Wit *et al.*, 2018; Aguilar-Hernandez *et al.*, 2019). In Europe, only 1.9% of the total production value stems from remanufacturing (Parker *et al.*, 2015). Recently identified barriers to CE are lack of customer interest (Rizos *et al.*, 2016; Kirchherr *et al.*, 2018; Camacho-Otero *et al.*, 2019), supply chain limitations (Rizos *et al.*, 2016; Vermunt *et al.*, 2019), low virgin material prices (Kirchherr *et al.*, 2018), legal barriers (Salmi *et al.*, 2012; Kirchherr *et al.*, 2018) and economic and technological constraints of waste recovery (Esguerra *et al.*, 2019; Gunaratne *et al.*, 2020), to name only a few.

A shift to a CE requires a fundamental change in our society (Savaget *et al.*, 2019; European Commission, 2020a). It is necessary to reorganise supply chains; redesign business models that slow down, narrow and close resource loops (Bocken *et al.*, 2016); design products that are resource-efficient and effective. Also, consumers need to adapt their respective behaviour (Camacho-Otero *et al.*, 2019), and finally, we need a policy framework that facilitates all this (Milios, 2018; European Commission, 2020a). The interrelatedness of all these aspects calls for transformative change, or, as de Jesus *et al.* (2019) frame it, a “systemic eco-innovation”.

This thesis addresses the complexities of CE activities by applying a systems perspective. The complex nature of the economic system requires adequate analytical tools that are not limited by a single perspective but rather combine perspectives and look at systems as a whole (Meadows, 2008; Onat *et al.*, 2017).

1.2 Research motivation

Both policymaker and corporate decision-makers face uncertainties when it comes to the implementation of the CE (Linder and Williander, 2017; Dewick *et al.*, 2020). By improving the resource efficiency of products and services, the CE is a vehicle to mitigate environmental impacts (European Commission, 2020a). An understanding of the system dynamics of sociotechnical systems (STSs) is crucial for effective CE policymaking and business activities (Bolton and Hannon, 2016). In this thesis, STSs are broadly defined as the wholeness of the system elements and their interlinkages necessary to fulfil societal functions (Geels, 2004). An STS consists of interconnected material objects such as products and infrastructure and, as well as immaterial aspect like services or legal systems that are necessary to provide the desired functionality. The dynamics of STSs were recently analysed from the technological (Onat *et al.*, 2016), organisational (Bolton and Hannon, 2016), economic (Schmidt-Costa *et al.*, 2019), institutional (Geels, 2004), socio-cultural (Pettersen *et al.*, 2013) and political perspectives (Hoppmann *et al.*, 2014).

The CE actions of managers need to be guided by systems-thinking-based tools that are able to show the implications of one system level on another system level (Papachristos, 2019). For example, the resource efficiency of a product is not just determined by the product’s

characteristics over its lifecycle. The analysis may also include the user (Camacho-Otero *et al.*, 2019), the services, multiple product lifecycles (Asif *et al.*, 2015) or another purpose for the product (Bräuer, 2016; Campbell-Johnston *et al.*, 2020). Other aspects that are crucial for an understanding of the resource efficiency of a product are the infrastructure it is embedded in (Fischer and Pascucci, 2017) and the policies that regulate it (Wilts *et al.*, 2016; Schmidt-Costa *et al.*, 2019). Analysing the interrelatedness of these aspects requires a systems perspective (Papachristos, 2019). Similarly, corporate decision-makers need to know about the implications of CE initiatives, for example, regarding the economic feasibility, operational implications or how business model innovations affect resource efficiency (Bocken *et al.*, 2016; Linder and Williander, 2017).

Currently, product-based offerings with added services are the prevailing type of product/service systems (PSSs) in the markets. Business models are needed whose profitability does not depend on the throughput of materials but the fulfilment of needs or the provision of function (Stahel, 1997; Mont, 2002; Tukker, 2015). Besides product-based offerings there are two other concepts use-oriented PSS and result-oriented PSS (Tukker, 2015). In use-oriented PSS, product ownership remains with the provider and the customers pay only for its usage, for example, leasing, renting, sharing or pooling. In result-oriented PSS, the customer pays for a certain result independent from the means through which it is achieved. Use- and result-oriented PSSs are especially interesting for their potential to incentivise companies to apply regenerative design and value retention strategies (Stahel, 2010). However, many of the new CE business models (Bocken *et al.*, 2016) have yet to prove their ability to boost resource efficiency on a large scale (Zink and Geyer, 2017; Makov and Font Vivanco, 2018). In addition, the necessary conditions for a decoupling of economic growth from environmental impact need to be further refined (Kjaer *et al.*, 2018; de Jesus *et al.*, 2019).

There are already a series of CE indicators supporting managers (De Wit *et al.*, 2018; Aguilar-Hernandez *et al.*, 2019; Moraga *et al.*, 2019). This thesis acknowledges the ongoing CE indicator developments in the business world that improve decision support systems for companies on the subject of CE strategies, for example, the Material Circularity Indicator (EMF, 2015a) or Circulytics (EMF, 2020). Besides indicators, there is a need to elicit cause-effect and feedback structures that allow for effective actions (Moktadir *et al.*, 2020). This is valid for both corporate decision makers who want to boost the resource efficiency of their products and policymakers who want to better understand the effects of policies on people's behaviour and companies.

The research opportunities this thesis focuses on are twofold. First, within the context of the shift towards the CE, there is a lack of dynamic analyses (Pieroni *et al.*, 2019) that combine the diversity of business, operations and social aspects with resource aspects (Bruel *et al.*, 2019; Savaget *et al.*, 2019). Dynamics are a fundamental characteristic of most systems, and phenomena like varying rates of change, time delays, and differences in short- and long-term effects are ubiquitous in our societal systems. Given the urgency to act on the sustainability crisis (Van der Leeuw *et al.*, 2012; IPCC, 2018), the time dimension is a critical element and needs to be part of the analysis (Lozano, 2008). Second, despite recent progress on the matter (Di Maio *et al.*, 2017; De Wit *et al.*, 2018; Aguilar-Hernandez *et al.*, 2019), managers in both

the political and corporate sphere lack decision-support tools that allow them to develop effective policies and business initiatives that improve resource efficiency (Moraga *et al.*, 2019).

The motivation for this research comes on the one hand from the above-mentioned societal need to become more sustainable, and on the other hand, from the existing knowledge gaps in the literature. This thesis acknowledges that the implementation of a CE is a dynamic issue that runs across multiple levels of society.

1.3 Research aim and research questions

This research aims to contribute to developing knowledge around the dynamics that occur during a societal shift towards a CE and their environmental and operational implications and develop decision support for managers.

The environmental aspects are expressed in terms of how resource efficiency is affected by the introduction of service-based instead of product-based offerings. The operational aspects refer to how a manufacturer's maintenance operations are affected by the introduction of service-based instead of product-based offerings. In this thesis use- and result-oriented PSS (Tukker, 2015) are subsumed to service-based offerings.

It has been acknowledged in sustainability-oriented research that in order to understand and assess resource efficiency, the analysis needs to apply systems thinking (Sterman, 2012; Williams *et al.*, 2017). In the CE context, systems thinking is defined as “an understanding of how organisations, individual decisions and activities interact within the wider systems they are part of” (BSI, 2017). Systems thinking puts as much emphasis on system elements as on the interactions between system elements. Systems thinking considers feedback loops (see, e.g., (Lindkvist Haziri *et al.*, 2019), nonlinearities and time delays (Sterman, 2012). The system is a fractal concept, that is, what is regarded as the system and what the system elements depend on the level of analysis. For example, products can be systems or system elements in wider social or organisational systems.

Service-based offerings and PSSs (Tukker, 2004) emerged due to the benefits the bundling of products with services can have for overall resource use. In widening the scope, sustainable business models include not only products and services but also aspects of the organisation and its eco-system (Bocken *et al.*, 2019). Subsequently, for evaluating the resource efficiency of entire societal systems, the concept STS lends itself as a unit of analysis (Olsson, 2015; Kanda *et al.*, 2016). For a large-scale transition like that to a CE, systems thinking helps in being able to link system elements across domains (Webster, 2013; Pieroni *et al.*, 2019). Therefore, the systems perspective is adopted throughout this research.

Recent studies on drivers and barriers (Rizos *et al.*, 2016; Kirchherr *et al.*, 2018; Vermunt *et al.*, 2019) of the CE have underlined the importance of external factors for the implementation of CE activities. Pieroni *et al.* (2019) point out that CE research applies relatively narrow analytical boundaries. A systems perspective suggests that an analytical approach with a multi-level systems perspective is the most adequate to investigate the CE (Sterman, 2012; Papachristos, 2019).

The intuitive environmental benefits of service-based offerings need to be shown in more large-scale implementations, for example, national markets, or on the STS level. Simulation modelling approaches can help in better understanding transitional dynamics (Papachristos, 2019). There is a knowledge gap about the resource benefits of changing business models in order to cater to a CE. Such shifts are, for example, the shift from mainly selling products to providing services (Lindahl *et al.*, 2014), and known examples are mobility as a service instead of selling cars (Polydoropoulou *et al.*, 2020), washing as a service instead of selling washing machines (Bocken *et al.*, 2018), or heat as a service instead of selling heating devices (Schroeder *et al.*, 2020). The interrelations that should be considered are, for example, the impact of policies (e.g., regulations, subsidies, or taxes) on the provision of services or on product properties or the impact of business model designs on value retention strategies, for example, remanufacturing, repair or recycling (Sundin and Bras, 2005).

One of the core questions around the CE is how circular activities affect resource efficiency. Whereas it seems intuitive that a CE uses fewer resources, there still is a need to develop adequate analytical tools that support decision makers to reshape our STS towards more resource efficiency (Zink and Geyer, 2017). RQ1 focuses specifically on the CE activities of an organisation.

RQ1 What are the resource efficiency implications of a manufacturing company introducing a service-based offering?

An important aspect is also the feasibility of CE activities (Ghisellini *et al.*, 2018; Dewick *et al.*, 2020). Due to the relative novelty of the CE, manufacturers struggle to understand the uncertainties related to it (Linder and Williander, 2017). There is a gap of knowledge regarding the costs and benefits of CE activities for the manufacturers. For example, the transition from selling products to offering functions entails that a provider needs to maintain the products' functionality (Barquet *et al.*, 2013). As with a lifelong warranty, the provider needs to maintain the products and cover service requests. A benefit for providers is to better understand their customers, but it also means that providers have more responsibility (Matschewsky *et al.*, 2020). The second research question investigates operational implications of a shift from product- to service-based offerings.

RQ2 What are the operational implications of a manufacturing company introducing a service-based offering?

In order to get a better understand of the implications of the introduction of service-based offerings on a larger scale, the scope is broadened from an organisation to an STS. RQ3 addresses the effects of a shift to a CE on a higher level of abstraction. The shift to CE is operationalised through a shift of an STS, where the focal product, is not owned by customers, but rather provided as a service.

RQ3 What are the resource efficiency implications of a shift from a product-based to a service-based sociotechnical system?

For a better system understanding, it is necessary to investigate how its components are interlinked. Whereas there is a growing body of literature on what the CE is (Stahel, 2016;

Kirchherr *et al.*, 2017; Pieroni *et al.*, 2019), there is little knowledge about how the main components of the CE, such as the business models and governmental policies, interact (Boons and Baumann, 2002). Various literature sources evidence research efforts to analyse and understand the interactions between the building blocks of a CE and offer a partial understanding of the systems' components and their interactions. There have been a few attempts to synthesise literature insights between product design and policy interactions, such as in the case of the EU eco-design regulation (Bundgaard *et al.*, 2017) and the setting of mandatory product standards (Tecchio *et al.*, 2017). Similarly, the scholarly literature studied the interactions between reverse supply networks and business models (Bressanelli *et al.*, 2018), policies (Govindan and Hasanagic, 2018), interactions between CE business initiatives on regulations (Salmi *et al.*, 2012; Fischer and Pascucci, 2017), or interactions between CE product design and business model strategies (Lieder *et al.*, 2017; Franco, 2019).

The fourth research question aims to explore the core motivation of the thesis, which is not just to advance academic knowledge but also to be a tool for practitioners. Both political and corporate decision-makers need to understand the implication of a shift to CE in their domains.

RQ4 How can systemic changes towards a circular economy be understood and planned by managers?

A primary interest is how to steer existing systems in the right direction and experiment with system changes to find out how to best increase resource efficiency. This directly addresses recent calls for more systems thinking to solve sustainability problems (Sterman, 2012; Williams *et al.*, 2017).

1.4 Scope, limitations and target audience

By looking at the abstract system elements of the CE, that is, product design, business models, and the enabling conditions, this research applies a systems perspective. From the underlying literature, the concept of STS proved most suitable as the unit of analysis.

The research objectives have varying scopes in order to draw a more complete picture by looking at the shift from the CE's multiple angles. As the main actors during design (Lindahl and Sundin, 2013; Braun *et al.*, 2018), an OEMs' decisions have the most far-reaching consequences on the aptitude of products for circularity such as reusability, reparability, remanufacturability and recyclability. Therefore, two of the four research questions (RQ1 and RQ2) take the point of view of a manufacturing company, and the two remaining research questions (RQ3 and RQ4) apply an STS perspective.

Data was collected in Sweden, the Netherlands and the United Kingdom, and a few data points refer to average European measures. The results are limited to the European context. These countries exhibit a high per capita resource use.

This research aims to contribute to research in the CE, STS, and simulation modelling fields in the sustainability context. The audience this thesis is most valuable to consists of policy analysts interested in reshaping the current policy framework towards the CE and managers interested in the feasibility of CE initiatives and their effect on resource efficiency.

1.5 Thesis outline

In Chapter 2, the theoretical foundation of this doctoral thesis is outlined, including key concepts and theoretic lenses. This chapter is an amalgamation of the theoretical input required for this essay, as well as the components of the peer-reviewed, appended articles.

Chapter 3 presents the research methodology, including the philosophical considerations that underlie this thesis. It further elaborates on the chosen research methods and data collection.

Chapter 4 elucidates the research articles that preceded this kappa. The chapter focuses on the essential findings of the articles, which also serve as the thesis' cornerstones. Each article will be shortly summarised and its contributions to the kappa discussed.

Chapter 5 presents a discussion and concise conclusion of how the entirety of my research journey, including this kappa and the appended articles, contributes to the research aims.

Chapter 6 concludes this thesis and gives an outlook for future research avenues. It also brings forward the implications for policy and corporate decision-makers, as well as the research implications.

2 Theoretical cornerstones

To help the reader to be able to fit this thesis into the bigger picture, this chapter provides the necessary background information. The current state of the research and key theoretical concepts are presented as well as crucial assumptions and delimitations. The chapter starts with a discussion of the circular economy concept, continues by describing the role of systems thinking for this thesis, and concludes by addressing simulation modelling.

2.1 The circular economy

2.1.1 The evolution of the circular economy

Already in 1928, Leontief conceptualised the economy as “Wirtschaft als Kreislauf” (Leontief, 1928), or in English, “an economy of circular flows” (Leontief, 1991). Leontief used the analogy of a circular road system in which materials, components and products flow through the economy. He argued that economic flows are eventually circular when production outputs of one period *causally* feed back as inputs to the same process at a later period (e.g., $A + B \rightarrow C$, $C + D \rightarrow A$). However, in Leontief’s conceptualisation of the economy, only the flow of money is actually circular, whereas the flow of commodities remains linear.

As a concrete conceptualisation, “CE” was used in 1990 by Pearce and Turner (1990), where it is depicted as circular flows of material, energy and utility. Building on the famous essay of Boulding and Jarrett (1966) about “the economics of the coming spaceship earth”, Pearce and Turner (1990) stress that the Earth is a closed economic system in which economy and natural environment are interlinked through circular relationships. Further, the natural environment provides three economic functions: resource supply, waste assimilation and aesthetic commodity. For a sustainable future in which humanity thrives, two rules follow: resource use should not exceed resource regeneration, and waste and emission flows into the natural environment should be less than its ability to assimilate them. An interesting observation that also serves as motivation for this thesis, Pearce and Turner highlight the lack of “*analysis that demonstrates whether any particular economy is consistent with the natural environments*” (Pearce and Turner, 1990, p.42). Since then, progress has been made. Concepts like the planetary boundaries (Rockstrom *et al.*, 2009) or the ecological footprint (Wackernagel and Rees, 1998) allow us to assess whether an economy is following the two rules of Pearce and Turner.

There is a notion that CE is an operationalisation of sustainable development for business (WEF, 2014). Sustainable development is a “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (Brundtland, 1987). Surprisingly, Kirchherr *et al.* (2017), who analysed 114 academic definitions for CE, find that there is actually no strong link between the CE and sustainable development. In fact, a criticism of the CE by several authors is the lacking of the social dimension of sustainability (Kirchherr *et al.*, 2017; Murray *et al.*, 2017).

Nonetheless, the CE is an evolving concept (Mahanty *et al.*, 2019) that has become a global agenda. It has been specifically used in the last five-year plans in China (Zhijun and Nailing, 2007), before Germany passed laws for closed-loop recycling in 1996, which included, inter

alia, extended producer responsibility, a waste hierarchy, and a clear definition of waste (Merkel *et al.*, 1996). Japan implemented policies for a sound material-cycle society in 2000 (Hashimoto and Moriguchi, 2004). Today, the European Union considers the CE (European Commission, 2014) as one of its main components for the European Green Deal (European Commission, 2019).

Nowadays, the CE is a concept that stands on various theoretical fundaments such as ecological economics, environmental economics and industrial ecology (Ghisellini *et al.*, 2016; Kalmykova *et al.*, 2018; Bruel *et al.*, 2019). It adapts concepts like the functional economy (Stahel, 1997), biomimicry (Benyus, 1997) or cradle-to-cradle (Braungart *et al.*, 2007). Core to the CE are also the “Rs” of the waste hierarchy (European Commission, 2008), with the “9Rs” as the most elaborate version (Van Buren *et al.*, 2016): *refuse*: preventing the use of raw materials; *reduce*: reducing the use of raw materials; *reuse*: product reuse (second-hand, sharing of products); *repair*: maintenance and repair; *refurbish*: refurbishing a product; *remanufacture*: creating new products from (parts of) old products; *repurpose*: product reuse for a different purpose; *recycle*: processing and reuse of materials; and *recover energy*: incineration of residual flows (see also Figure 2-1). The waste hierarchy advocates for “small loops” (Stahel, 2013); that is, reuse is generally more resource-efficient than recycle, and recycle is more resource-efficient than recover.

Further seminal work on the way to today’s CE conceptualisation was developed by Walter Stahel (Stahel, 1994; Stahel, 2010). Stahel underlines the principles of access- over ownership realised through rental, lease, or sharing business models (Stahel, 2016). In the “loop” or “performance” economy, consumers use a product only for its utility, and producers design long-lasting easy-to-repair products used for multiple use cycles resulting in overall higher resource efficiency.

The CE is often depicted as an antidote to the “linear” economy (Didenko *et al.*, 2018). A linear economy transfers, in a “take-make-dispose” fashion, virgin materials into waste and neglects opportunities of returning resources back into industrial cycles. However, the proclaimed dichotomy of the linear and CE is semantically inconsistent (Murray *et al.*, 2017) and at times appears to be manufactured for marketing reasons; both concepts carry elements of the other, and they cannot be clearly separated. What is meant by linear might be better expressed by *unidirectional* (Esposito *et al.*, 2018). Products and their materials tend to flow in one direction, starting from virgin material extraction, production, consumption, and ending in landfills; there is no feedback or reverse flow in a linear economy. By contrast, the CE promises feedback loops at various places in the supply chain; resources are flowing *bidirectional*, realising a circular supply chain (De Angelis *et al.*, 2018). There are voices saying that the CE is more likely than industrial ecology to enter the mainstream because it has a business-friendly narrative. This might be because the CE did not start out as a new academic discipline, like ecological economics, but rather as a response to legislation (Murray *et al.*, 2017).

Furthermore, it needs to be mentioned that several aspects of our economies have been circular already before the term emerged. Examples are existing recycling schemes or agricultural processes that depend on, for example, cycles of water, nitrogen and phosphorous (Rockstrom

et al., 2009). An additional circular human-made artefact is money. Money is a non-consumable that flows in a circular fashion through the economy (Leontief, 1991).

2.1.2 Three definitions of the circular economy

The CE is an economy that is *“restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles”* (EMF, 2015b, p.4).

In this sense, the CE is conceptualised as a closed, multi-loop economic system that is organised to cater to value retention and regenerative design (Campbell-Johnston *et al.*, 2020). Value retention includes activities that maintain the value of products that was once given to them through industrial manufacturing processes. Examples of value retention are the various forms of reuse or repurposing (Bauer *et al.*, 2016), repairing (Gelbmann and Hammerl, 2015), refurbishing or remanufacturing of used products (Sundin and Bras, 2005), recycling of the materials embedded in the products (Chang *et al.*, 2016), or least favourably, some other forms of recovery (European Commission, 2008). The CE applies to manufacturing industries as well as chemical industries (Keijer *et al.*, 2019) and agricultural industries (Donner *et al.*, 2020).

A second definition shows that the CE is also understood very broadly as *“an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human wellbeing”* (Murray *et al.*, 2017, p.369).

Thirdly, the EU (European Parliament, 2015) defines the CE in a narrower sense as *“an economic model based inter alia on sharing, leasing, reuse, repair, refurbishment and recycling, in an (almost) closed loop, which aims to retain the highest utility and value of products, components and materials at all times”*. This thesis adheres to the EU's definition due to its clarity in terms of what actual activities contribute to a CE.

A picture that is often drawn sees materials used in products as perpetually flowing nutrients for the industrial metabolism, in which waste has been designed away (Braungart *et al.*, 2007; EMF, 2013) (see Figure 2-1). The conceptual CE framework distinguishes between biological nutrients which can be assimilated by nature and be part of biological metabolisms and technical nutrients that can be fed back to industrial metabolisms (EMF, 2015b). A goal is to keep biological and technical nutrients apart so that they do not compromise each other. Further principles are the use of bio-mimicry methods as well as supplying society's energy needs predominantly from renewable energy sources (EMF, 2015b).

Despite the lack of a uniform definition, two aspects are considered key for a CE: a systems perspective on the one hand (Kirchherr *et al.*, 2017; Lieder and Rashid, 2016; Zhijun and Nailing, 2007) and the operationalisation of the waste hierarchy (European Commission, 2008).

CIRCULAR ECONOMY - an industrial system that is restorative by design

Figure 2-1. Circular economy developed by EMF (2013)

2.1.3 Circular economy business models

A business model describes the value creation, value delivery and how value is captured in a company (Bowman and Ambrosini, 2000). Value is the sum of the perceived product- and service qualities of an offering (Scheepens *et al.*, 2016). A customer may experience a surplus value if the perceived value of an offering is higher than its price. A business model presents a company’s strategic orientation. It describes the logic of the company’s value propositions to the customer (Teece, 2010), its place in the value chain, and customer relationships and segments. Further, it clarifies the key assets of the organisation and describes the company’s profit formula (Osterwalder, 2004).

Several reconfigurations of the business model canvas (Osterwalder, 2004) have been developed in order to cater to the peculiarities of sustainability-oriented companies. In the literature, PSS business model frameworks can be found (Reim *et al.*, 2015; Tukker, 2015; Adrodegari *et al.*, 2017; Yang and Evans, 2019), as well as CE business model frameworks (Bocken *et al.*, 2016; Lewandowski, 2016). In short, CE business models fulfil the same functions as conventional business models but contribute to regenerative design or value retention. This also means that, CE business models lead to the implementation of the waste

hierarchy (Lahti *et al.*, 2018). Business models typically need to arrange the relations between customers and suppliers differently and adapt the sourcing of materials and the supply chain in general (Fischer and Pascucci, 2017; Bocken *et al.*, 2019). Interestingly, many companies apply value retention strategies without being aware of contributing to the CE (Barreiro-Gen and Lozano, 2020).

According to Stahel (2016), business models that implement renting, leasing or sharing can contribute to the CE. Use- or result-oriented PSSs have more potential to improve resource efficiency than product-oriented PSSs (Tukker, 2015). The fundamental difference between product-oriented PSSs on the one hand and use- or result-oriented PSS on the other is that the former preserves the product, while the latter preserves the function (Moraga *et al.*, 2019). Bocken *et al.* (2016) present six CE business model strategies, namely, closing, slowing down or narrowing resource loops: access- and performance models; extending product value; classic long-life models; encourage sufficiency; extending resource value; and industrial symbiosis. Recent business model experiments try to facilitate access- over ownership (Bosch, 2018; Homie, 2018), within companies but also with supply chain partners (Bocken *et al.*, 2019).

In a CE, products need to be designed and produced under the extensive use of eco-design principles and adequate material selection (Mont, 2008; Bakker *et al.*, 2014). This means, for example, regenerative design or design for long product lifespans that enable value retention but also a mind-set in companies to maximise utility and value of products and components (Russell, 2018). Based on eco-effectiveness (Braungart *et al.*, 2007), Zink and Geyer (2017) formulate three conditions in order for CE activities to decrease environmental impact: (I) secondary products need to be true substitutes for primary products with a similar price, (II) aggregate demand must not increase, and an (III) increase of relative demand for secondary products is needed.

Customers play an important part by changing purchasing behaviour as well as by care of product usage; the reuse potential of products depends on their careful use, a problematic issue for the reuse of products that are not owned by the customers (Tukker, 2015). Kirchherr *et al.* (2017) found that in the literature, consumers are not considered as a key enabler for a CE in the majority of definitions. This is surprising because the kind of change that a shift to a CE requires seems impossible without respective fundamental behavioural adaptations by consumers.

2.1.4 Enabling conditions

The CE is a holistic economic narrative (Webster, 2013). In order to have an economy where material flows circulate, policies need to support the closing of resource loops by addressing all phases of the lifecycle of material products. For governments, the CE holds two interesting incentives: On the one hand, it promises to save resources and decreases the burden on the natural environment, and on the other hand, the labour-intensive activities around value retention (e.g., repair, remanufacture, refurbish) hold the opportunity for higher employment rates (EMF, 2015b).

In this thesis, institutions are understood as the rules that shape the activities of economic actors (Geels, 2004). Existing institutional systems have evolved around a linear economic paradigm

(Fischer and Pascucci, 2017). However, companies that engage in new CE activities need to find favourable institutions that do not block their circular activities (Whalen *et al.*, 2018). Business models in the photovoltaic industry are very influenced by regulations (Overholm, 2015; Schmidt-Costa *et al.*, 2019) and subsidies (Huijben and Verbong, 2013; Huijben *et al.*, 2016); see more in the related publication by the author (e.g., Wasserbaur and Sakao, 2018). Industrial symbiosis has been hampered by regulatory obstacles that are in place when turning waste back into raw materials (Salmi *et al.*, 2012). Multiple policy barriers were reported for small- and medium-sized enterprises that tried to engage in CE activities (Rizos *et al.*, 2016).

China has incorporated the CE in the last two five-year plans (Zhijun and Nailing, 2007). Chinese CE policy programmes are centrally planned and operate at large scales ranging from zones to regions to cities. This consistency throughout policy levels may be useful to upscale niche successes. China has also developed particular CE indicators and incorporates CE policies into land-use planning. The large trade flows between Europe and China could be a future opportunity for common standards in product design, eco-industrial processes and secondary materials (McDowall *et al.*, 2017).

Europe, on the other hand, has set up a policy landscape that provided incentives to producers to make the management of material flows easier (design for remanufacturing, repair, etc.), which is important for an economy with high consumption levels. The European Union has developed an increasing number of policies to address environmental issues throughout product life cycles. “Closing the loop” – an EU action plan for the CE – distinguishes between actions on production, consumption and waste management. Priority areas are plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based products and innovation and investments (European Commission, 2015). The CE Action plan is only part of an initiative addressing resource efficiency. Other strategies focus on the sustainable use of natural resources, sustainable consumption and production and the prevention and recycling of waste (Milios, 2016).

The specific regulations can be divided into three main categories: making products more energy efficient, banning hazardous substances and making sure products are disposed of in an appropriate way in the end-of-life stage (e.g., European Commission, 2008, 2011). Other interests in the field lie in setting standards that promote durability, resource efficiency and reuse at the EU level; such standards have been set for some product groups, including vacuum cleaners and printers (Dalhammar, 2014). Various other instruments, such as mandatory and voluntary labelling schemes and public procurement that are mainly applied at the national level, complement these mandatory EU rules. One ideal of the CE is to “design waste away”. The EU’s waste framework provides guidance. It defines the reduction of waste as most desirable, followed by the reuse, recycle, and recovery of discarded products (European Commission, 2008).

In each of the lifecycle phases, that is, beginning of life (Song *et al.*, 2020), middle of life (Li *et al.*, 2016) and end of life (Dace *et al.*, 2014), the policy landscape may foster or hinder the CE. The EU policy framework related to resource efficiency currently does not implement a full lifecycle (Milios, 2020). There are opportunities when it comes to policies for reuse, repair

and remanufacturing, green public procurement and innovation procurement and policies for improving secondary material markets (Milios, 2018). For realising a lifecycle perspective in the policy framework for the CE, three phases are relevant for resource circulation: production and product design, use phase and consumption and end of life and waste (Milios, 2020).

2.1.5 CE indicators

Existing indicators in the CE context measure the circularity of products, components, materials and embodied energy or compare differences to linear reference scenarios (Moraga *et al.*, 2019). Indicators may also measure the circularity of the provision of functions or societal needs (Scheepens *et al.*, 2016; De Wit *et al.*, 2018). This plethora of indicators gets even more diverse by including aspects like dissipation of materials (Aguilar-Hernandez *et al.*, 2019), material quality (Huysman *et al.*, 2017), inclusion of social and economic sustainability (Azevedo *et al.*, 2017), scarcity (Di Maio *et al.*, 2017), geopolitical issues (Adibi *et al.*, 2017) or biological nutrients (Mayer *et al.*, 2019). Stahel (2010) suggested three indicators that can help in the decoupling process: value-per-weight ratio, labour-per-weight ratio, and value-from-renewable-resources ratio.

2.2 Systems thinking

2.2.1 Introduction

A system is a holistic way of representing reality; it consists of system elements and their interactions; it has boundaries that define where it starts and where it ends and it displays a purpose or a function (Meadows, 2008). Systems exhibit structure and behaviour. The structure consists of the interlinked stocks and flows as well as the feedback loops. These interlinkages are what drives the system's behaviour (Sterman, 2000). Feedback loops are reinforcing or balancing. The combination of the two may produce more complicated dynamics, and once delays are introduced into a system, the dynamics can become very surprising (Meadows, 2008).

Systems thinking means to perceive the real world as interacting wholes (Meadows, 2008). It can be classified into three types: hard, soft and critical systems thinking (da Costa Junior *et al.*, 2019). Each of the three types is based on different assumptions. The specific problem domain determines the most adequate type. Hard systems thinking is based on the idea that systems can be reduced to fundamental variables, which determine the system's behaviour. Hard systems thinking lends itself to simulation modelling for predicting and explaining system behaviour quantitatively. Soft systems thinking tries to deal with the complexity and ambiguity of social reality, while critical systems thinking is a branch of systems thinking that is especially aware of the power struggles within social systems.

Systems thinking can be considered its own discipline with a methodology and theoretical concepts such as system, feedback, and information and control feedbacks (Mingers and White, 2010). Many aspects of systems thinking are core to research in sustainability (Sterman, 2012) and the CE (Lieder and Rashid, 2016; Murray *et al.*, 2017; Korhonen, Honkasalo, & Seppälä, 2018).

Systems thinking in the CE context is closely related to life cycle thinking, which looks at production and consumption processes as a whole, including design, production consumption or use, recovery and disposal.

2.2.2 Sociotechnical systems

Historically, research on sociotechnical systems (STSs) originates from the question of how the work environment affects human performance, such as in coal mines (Pasmore *et al.*, 2019). According to Hughes (1987), elements of an STS can be categorised into physical artefacts, organisations, scientific research, legislative artefacts, and natural resources. In general, much research on STSs focuses on the relationship between society and technology. Geels (2004) defines an STS “*as the linkages between elements necessary to fulfil societal functions*” (p.900). STS supports this thesis approach to consider multiple levels of analysis.

This thesis acknowledges the fact that the various sub-systems of an economy affect each other. For example, in a sociotechnical laundry system (Pettersen *et al.*, 2013), customers use washing machines. Customers own them (Pakula and Stamminger, 2010) or use them as a service (Homie, 2018); companies provide various types of washing machines as product-based, service-based or result-based offerings (Retamal and Schandl, 2017); and policymakers may regulate, subsidise or tax activities related to it (Maitre-Ekern and Dalhammar, 2016). The sub-systems within an STS can have long-lasting effects on each other. For example, compared to other industrialised countries (Pakula and Stamminger, 2010), Sweden has a relatively low household ownership rate of washing machines. This is interesting, because in Sweden, practically every person can afford a washing machine. The low ownership rate goes back to policies from the 1950s that started a long tradition of sharing of community-based washing centres (Lund, 2009). Swedish washing machine manufacturers developed offerings that were suited to this context (Electrolux, 2018). Despite their relatively high wealth (Eurostat, 2018), it still seems normal for people in Sweden to share washing machines with other people. This short example shows that STSs are a useful unit of analysis for this thesis because they expand the analysis from only technological to social and legal aspects.

2.3 Simulation modelling

2.3.1 Need for simulation

Companies, consumers, infrastructure, the product and the regulatory environment affect each other and appear as complex systems characterised by non-linear behaviour and feedback (Liu *et al.*, 2017). In order to create a conducive environment for resource-efficient solutions that fulfil society’s needs, there is a challenge to describe and understand the interplay between the system elements, and methods able to depict the dynamics of complex systems are required (Shafiei *et al.*, 2013; Onat *et al.*, 2016).

There is a long tradition of computer simulation models to inform on issues related to sustainable development. Almost 50 years ago, Meadows and colleagues published “The Limits to Growth” (Meadows *et al.*, 1972). This ground-breaking computer simulation interlinked human population growth trends, agricultural production, resource depletion, industrial output and pollution generation. The authors argued for a drastic improvement in global resource use and waste production if humanity wanted to live in harmony with the planet in the decades to

come, a message still valid today. The underlying model for The Limits to Growth report was a system dynamics simulation model anchored in the field of systems science.

Simulation can show the dynamic non-linear behaviour of organisational or strategic processes (Mingers and White, 2010). As a scientific method, simulation can test, specify or extend underlying theories (Davis *et al.*, 2007). At the core of a simulation is a model that consists of mathematical equations and algorithms that represent a real or hypothetical system (Davis *et al.*, 2007). This model is implemented within computer software through which it can be dynamically simulated. Typical steps of simulation are (1) creating a theory-based computational representation of the system of investigation, (2) verification of this representation, (3) experimentation in order to verify a theory or to develop new theories and the (4) validation by comparing simulation results to empirical data (Stermann, 2000). Benefits for companies or decision-makers in general are, for example, testing new designs, policies, processes, decision rules, organisational structures and information flows (Forrester, 1961). They can do so without the dedication of substantial resources nor the disruption of operations. Real-world experiments can be too risky or too expensive. Academically, it also allows hypothesis testing, problem identification, time manipulation, the detection of dominant variables and the testing of scenarios (Davis *et al.*, 2007; Karlsson, 2016). A simulation is simply based on a set of assumptions about the object of investigation – wrong assumptions usually result in a wrong representation of reality. Disadvantages of simulation-based research are, among others, the difficulty in developing simulation models and the dependence and the limitedness of data (Shannon, 1998).

2.3.2 Dynamic simulation modelling paradigms

There are several simulation modelling paradigms with different strengths and weaknesses. An approach's usefulness depends on the specific problem, such as an adequate level of abstraction or the time scale. The three paradigms relevant in this thesis are agent-based modelling (ABM), discrete-event modelling (DEM) and SD modelling (SDM). These three dynamic modelling paradigms or methods are highly relevant in sustainability research and each have their strengths and weaknesses (Borshchev and Filippov, 2004; Moon, 2017).

ABM sees the world as the result of interacting agents that have a certain set of properties and individual behaviour. It applies a micro-level perspective in which the accumulation of micro-level interactions leads to macro-level behaviour (Abar *et al.*, 2017), just like in an ant farm where each ant is simulated, yet the behaviour of a single ant does not allow a conclusion about the behaviour of the whole ant farm. ABM is used to experiment with variations of rules and agent properties in order to see how they affect outcomes of the entire system. The ability of ABM to model the heterogeneity of each agent makes it especially helpful to investigate heterogeneity and emergence aspects of complex systems. (Farmer and Foley, 2009).

Discrete-event modelling (DEM), on the other hand, sees the world as the result of interlinked processes; entities move through these processes (Silver *et al.*, 2011). The process structure, together with events, determines the system behaviour. DEM offers more of a meso-level perspective (Borshchev and Filippov, 2004). Discrete-event models simulate entities moving through processes, events that trigger decisions or actions, and resources such as machines or personnel. DEM is very useful for the simulation of business processes (Rondini *et al.*, 2017).

System dynamics (SD) models represent reality in terms of accumulations and feedback. These models offer a high-level systems perspective, useful in sustainability-oriented research (Sterman, 2012). It describes a system's internal causal relationships and internal feedback structures through stocks and flows (Sterman, 2000). Stocks represent constructs in a system that accumulate or dissipate over time. The dynamics of stocks are determined by flows. Feedback consists of circular causal loops that either lead to self-reinforcing or balancing behaviour. SDM emphasises causal mechanisms and is well-suited to simulate high-level systems behaviour (Borshchev *et al.*, 2014).

While each method can individually offer experimentation to understand complex systems and make informed decisions, greater value comes from combining the methods to overcome the limits of each. For example, Wang, Breme, *et al.* (2014) integrate SDM, ABM and DEM to develop a model for a lifecycle assessment of a beverage, including production, supply chain and consumption. Modern computer software enables the computation of extensive models and even creates hybrid simulation models that bring together all three approaches to jointly understand the dynamics of complex systems (Borshchev *et al.*, 2014).

2.3.3 Simulation modelling for a shift to the circular economy

There is much research that uses simulation modelling to investigate the impact of public policies on CE aspects like the production of biogas (Eker and van Daalen, 2015), recycling and remanufacturing (Wang, Chang, *et al.*, 2014), green transportation (Trappey *et al.*, 2012) and heat pumps (Majuri, 2016). Other simulations investigate the effect of the EU directives on waste management systems (Dace *et al.*, 2014) or the influence of legislation on recycling and e-waste recycling (Georgiadis and Besiou, 2008). These cases mostly deal with an industry sector or market but do not touch on the micro-level or on aspects across system levels.

Only a few articles look between multiple levels of analysis. An SD model examines the dynamics that occur when companies try to implement CE-oriented product designs, aiming at slowing or closing resource loops and adapting their supply chains accordingly (Franco, 2019). An additional example shows a combination of DEM with ABM in order to support an OEM in understanding how CE business models and end-of-life strategies are interlinked (Lieder *et al.*, 2017).

2.3.4 Simulation modelling in operations management

OM is the process of design, planning, controlling and executing operations in manufacturing and service industries. OM research may be categorised into either axiomatic or empirical and prescriptive or descriptive research. Operations research is part of the quantitative research in OM and focuses on solving operational process problems. Scientific models are able to predict the performance outcome of operational processes. Such quantitative models consist of sets of dynamic variables and the causal relationships between those variables. By defining the relationship, this kind of model can be used for predicting future states (Bertrand and Fransoo, 2016).

3 Research methodology

The chapter begins by explaining the philosophical position of the thesis. It then continues by presenting the research approach chosen to address the research aims, followed by a discussion of the quality criteria of the research.

3.1 Research philosophy

A research philosophy is a system of beliefs and assumptions about how scientific activity leads to knowledge (Saunders *et al.*, 2016). Research produces knowledge that helps to explain, understand and predict reality. Good research produces results and conclusions that are replicable, valid and generalisable (Karlsson, 2016). All research is embedded in a research community and framed by research paradigms (Kuhn, 1970), which guide a researcher's ontological and epistemological positions and methodological choices. The ontology describes the researcher's belief on what is reality, the epistemology describes the researcher's understanding of what constitutes knowledge, and the methodology refers to the adequate means and ways of how knowledge gets created in a specific field.

The positions of critical realism are the most adequate for this thesis. For critical realists, the perception of the world is limited by empirical sensation. Critical realists employ a stratified ontology consisting of the nested domains of the "empirical", the "actual" and the "real". The domain of the empirical at the centre includes the events that are experienced and observed. It is surrounded by the domain of the actual, which involves events both observed and not observed. The all-encompassing domain of the real includes structures and mechanisms with causal powers, whose interactions are causing actual events (Groff, 2004).

3.1.1 Simulation as experimentation

There are various ways of contributing to knowledge. Depending on the maturity of a field, different research approaches are adequate to contribute to the body of knowledge (Karlsson, 2016). For example, surveys are adequate for mature theories that benefit from being challenged and refined, whereas a nascent theory benefits from approaches that allow theory building and identifying new phenomena and relationships, which can be provided by case research or action research (Karlsson, 2016).

Simulation modelling, as a scientific method, can be used to test, specify or extend underlying theories (Davis *et al.*, 2007). It is based on mathematical equations and algorithms that represent a real system. Such a model is typically implemented within computer software through which it can be dynamically simulated. Simulation models inform about the implications that are confined to the causal stories that the models represent, not necessarily to the real world.

In this thesis, a series of simulation-based case studies are presented that show various implications of a shift from linear to circular activities. The applied simulation methods allow a deeper understanding that would be difficult to test through real-world experiments otherwise. Both simulations and experiments manipulate an object in order to understand it better. Moreover, simulation can be seen as an experimental system that can be used to explore theories about how the real world works, using an artificial world that researchers can control (Peck, 2004).

3.1.2 The philosophy of system dynamics

Three of the four appended articles apply SDM. The research paradigm that SD is embedded in serves to explain the main philosophical position of the thesis as well. The bulk of system dynamicists develop models of systems that exist in the real world, that is, the stocks, flows, non-linear relationships and feedback loops represent the external reality; this hints towards a moderate realist ontology of SD (Pruyt, 2006).

In SD models, causality is a fundamental concept. In the pursuit of understanding why systems behave the way they do (Lane, 2001) or how a system actually works (Sterman, 2000), system dynamicists use available data and information, including experts or groups of experts (Rouwette and Vennix, 2006), to build causal models of the systems under study. The participating individuals' values and judgements influence the model building. This implies a moderately subjective epistemology, where the real world is modelled based on mental models (Pruyt, 2006).

In addition, in SD models, humans seem to be modelled as fully deterministic with behaviour fully determined by its environment; here, humans are just "cogs" in the systems' wheels (Lane, 2001). A counter-argument against this raw determinism is that systems created by human decisions determine behaviour. Moreover, SD models do not model single human behaviour but rather aggregates. Therefore, SD tends to treat human agency moderately deterministically (Lane, 2001).

Another critical realist aspect, which is part of the studies underlying *Articles III* and *IV*, is the inclusion of historical considerations in order to understand how organisations have evolved. This induces a shift away from purely statistical and quantitative methods to a mix of data types and methods that fit the subject matter to elicit the causal structure underlying the researched phenomena (Saunders *et al.*, 2016).

3.2 Research approach

At this point, the CE concept is still a long way from being mainstream; in fact, only 9% of the world's economy is circular (De Wit *et al.*, 2018). This thesis looked at the environmental and operational impacts of a shift to a future CE (see Chapter 1.3).

All the research questions bare an aspect of change and address a dynamic phenomenon. This expresses this thesis' inclination to focus on the dynamic aspects of a shift to a CE. Therefore, methods that are able to dynamically simulate system behaviour were used. The CE field is still a nascent one that can benefit from simulation modelling and exploratory simulation studies (Karlsson, 2016; Yin, 2018).

In addition, the questions address various levels of analysis. Research Questions 1 and 3 address an organisational level, whereas Research Questions 2 and 4 have a wider analytic scope.

3.2.1 Overview of articles

The research process was guided by the four research questions, which look at different issues of CE. The research questions complement each other and, as a whole, aim to contribute to a better understanding of issues that occur during a shift from a linear economy to a circular one.

This doctoral thesis is formulated in a compilation style, which means that the appended articles serve as a structure of scientifically written articles, on top of which the thesis delivers additional insights. Table 1 presents how the four appended articles relate to the research questions.

Table 1. Article contribution matrix

Research question	Article I Sustainability assessment of a PSS	Article II Operational implications of a shift to a CE	Article III Environmental implications of a shift to a CE	Article IV Design fixation in design for sustainability
1	x			
2		x		
3			x	
4	x	x	x	x
Method(s)	MFA	ABM, DEM, SDM	SDM	SDM
Data collection	Workshops, public data	Workshops	Workshops, public data	Workshops, public data
Unit of analysis	PSS	Maintenance operations	STS	Design process
Industry	Washing machine	Heating device	Washing machine	Washing machine

*MFA – material flow analysis, SDM – system dynamics modelling, AB – agent-based modelling, DE – discrete event modelling.

The research was mainly based on quantitative research methods and looked at the various implications of a shift to CE. The studies presented in the appended *Articles I and II* informed guidance on subsequent ones. The primary means of eliciting the causal structures and the underlying systems' processes were workshops with company representatives and researchers. Publicly available data complemented the data collection.

The research approach was mostly exploratory, which is appropriate when explaining contemporary circumstances (Yin, 2018), which is suitable for the studied topics.

3.2.2 Applied methods and data collection

The nature of the interdisciplinary research conducted requires to include the viewpoints of other stakeholders. The applied research methods imply both quantitative and qualitative aspects.

As a scientific method, simulation modelling can be used to test, specify, or extend underlying theories (Davis *et al.*, 2007). It is based on mathematical equations and algorithms that represent a real system. Such a model is typically implemented within computer software through which it can be dynamically simulated. Both simulations and experiments manipulate an object in order to understand it better (Parke, 2015). The simulation models inform about the implications that are confined to the causal stories that the models represent, not necessarily to the real world. The simulation methods used in this thesis are SD, ABM, DEM and MFA.

As a means of data collection, interviews and workshops are adequate for the task of gaining a systems understanding. They allow to flexibly change the flow of conversation towards novel issues or issues interviewees have unexpected special knowledge about. Both methods allow the interviewee or the workshop attendant to explain causal and dynamic aspects to the

researcher. Group workshops allow a group of participants to develop a shared understanding that is complemented by each individual (Andersen *et al.*, 2007).

For RQ1, a method is needed that is able to quantify the material effects of a service-based offering on the market. Aspects of product design, supply chain and resource efficiency were relevant in this study. MFA was selected as the main method, as it was adequate to present how product materials flow in supply chains. The data collection is based on group workshops with case company representatives.

RQ2 focuses on how a company's service operations are affected by the implementation of CE activities. The study's design revolved around the exploration of a servitizing organisation as a complex system. This means that multiple levels and time scales needed to be part of the analysis. As every simulation modelling approach has its limitations, a hybrid approach consisting of SD, ABM and DEM was chosen for this study. The data collection is based on workshops with the manufacturer. The manufacturer provided insights regarding the operations as well as strategic considerations.

Applying an STS scope, RQ3 focuses on the environmental implications of the shift of an STS from mainly products to mainly services. This requires data collection from a variety of sources, such as publicly available statistics regarding laundry behaviour, emissions and technology. SD was chosen because of its aptness to model aggregates of populations, materials and emissions and the respective dynamics.

All the case studies complement each other in answering RQ4. The goal is to support leaders to understand and plan the necessary changes for a CE. Answering the three previous questions aims to produce simulation models that help to understand the implications of a shift to a service-based offerings by providing quantitative results, and consequently, help to efficiently plan for CE activities.

As part of basic research practice, literature reviews were an inherent part of every study conducted. Initial literature reviews were the first step for each appended article to get an overview of the field and existing works that conducted similar studies. The literature reviews were based on keyword searches in various scientific online databases (Web of Science, Scopus, and Google Scholar). In multiple steps, ranging from title and abstract screening to in-depth analysis, publications were excluded if deemed irrelevant. Snowballing techniques complemented this process. After several iterations, a core of publications remained, which served as a starting point for the respective study.

For a detailed description of the methodology, the reader is referred to the respective appended article.

3.2.3 Progression of the articles

The appended articles form a progression from a narrow to a wide system scope and from static to dynamic modelling, as illustrated in Figure 3-1. *Article I* analysis material flows from a company perspective and shows how the introduction of service-based offerings affects resource efficiency; time is treated statically. *Article II* has a company perspective as well but advances by adopting a dynamic instead of static analysis and looks at how a manufacturer’s maintenance operations are affected by the introduction of service-based offerings. Yet another progression is shown in *Article III*, which adopts a dynamic approach and extends the scope from an organisational to an STS point of view. This article assesses the environmental implications associated with the large-scale shift to service-based offerings on an STS level. Finally, *Article IV* encompasses the previous levels of analysis and introduces a new concept that helps explain the shape of systems across the analytical levels. These studies are designed to complement each other, as individual companies and STSs shift to more CE activities.

Figure 3-1. Overview of the appended articles' system levels and time scale.

Note: The ovals indicate the articles' scopes; the overlaps bear no meaning. STS stands for sociotechnical system and PSS for product/service system.

3.3 Quality of the research

The evaluation criteria for good research are validity and reliability (Bryman, 2015). This subsection reports on the quality of the research process. First, validity will be addressed, followed by reliability. For a discussion of the quality of the research results, the reader is referred to Chapter 4.5.

3.3.1 Validity

In general, validity describes the integrity of the conclusions drawn from the research (Bryman, 2015). It is a composite construct consisting of construct validity, internal validity and external validity.

The quality of construct validity describes the degree of congruency between the research findings and phenomena under study (Karlsson, 2016). A big part of scientific work is to develop mental models that reduce the complexity of the real world so that we can understand it. However, no model perfectly represents the real world; *“a model that is a perfect representation of the real-world is about as useful as a map in the scale of 1:1.”* (unknown source). Validation is about showing the usefulness of the models we create (Sterman, 2000).

Internal validity relates to the causal structure of a model’s variables and the question of whether conclusions based on causal relationships are correct (Bryman, 2015). For internal validity, the separation of independent and dependent variables is necessary (Yin, 2018). Triangulation is a common approach to improve internal validity. Triangulation means to use multiple sources of data such as theoretical perspectives, research methods and analytical perspectives, combined in a complementary fashion to study a phenomenon. Throughout the thesis, triangulation has been used to improve the validity of all four appended articles. In particular, method triangulation, sources triangulation, analyst triangulation and theory triangulation were used.

External validity is the degree to which the findings of one study can be transferred to other contexts (Bryman, 2015). Striving for external validity improves generalisability (Yin, 2018).

3.3.2 Reliability and replicability

Research work is reliable when other researchers looking at the same data, would arrive at similar findings and conclusions (Yin, 2018). This aspect of the quality of research can be problematic in our field. Collaboration with companies often underlies non-disclosure agreements. It may be legally infeasible to get an external party to audit the data collection process, analysis and the validity of the results; certain details may unveil sensitive corporate materials.

Replicability is closely related to reliability. It is an appreciated aspect of social science that allows others to confirm study results. Replicability requires good documentation and clarity with regard to the procedures that were conducted.

4 Findings and article analyses

This chapter presents the results of the appended articles relevant to the discussion and the findings of this thesis. For each article, the background, findings and author's contributions are provided.

4.1 Article I: A methodological approach for manufacturers to enhance value-in-use of service-based offerings considering three dimensions of sustainability

Authors: Tomohiko Sakao, Raphael Wasserbaur, Fabrice Mathieux

Journal: CIRP Annals

<https://doi.org/10.1016/j.cirp.2019.04.084>

Status: Published

Background of the article

One way for manufacturing companies to approach the CE is by adding service-based offerings into their portfolio. In many industries, this is beneficial because it is an opportunity for companies to take back products and remarket them after the first use (Bauer *et al.*, 2016). A requirement is usually to re-design products to be more durable, easier to maintain or easier to recycle or remanufacture (Lindahl *et al.*, 2014), and, in general, to make them fit for reuse by multiple customers (Amasawa *et al.*, 2018). Additional benefits are a decreased dependence on virgin raw materials as well as opportunities for value retention, which is a key aspect of a CE. Value retention means that the value embodied in the products does not get lost after use. Instead, through the remarketing of products, they keep generating value for customers without the need for producing entirely new products (Whalen *et al.*, 2018). Because of the general novelty of service-based offerings in many industries, companies face many uncertainties. *Article I* contributes to the field by proposing a new design method for service-based offerings. The approach developed in the article supports companies to assess various sustainability aspects of their business models.

Resource efficiency of service-based offerings

This article addresses RQ1. It proposes a PSS design method touching upon all three sustainability dimensions. The measure selected to indicate environmental consequences was the rate of recycled materials related to each business model (with respect to landfilled materials).

The case company was introducing a new service-based offering in a pilot market. The basic idea was to lease a washing machine instead of selling it. Customers received highly energy efficient premium washing machines. The offering was based on monthly payments instead of having to bear the high upfront costs, which can be a hurdle for socially disadvantaged people. Interestingly, considering the entire lifecycle, premium machines often are cheaper due to their relatively high-energy efficiency and durability (van Loon *et al.*, 2019). After the lease term, the company would take back the asset, refurbish and remarket it. By applying a material flow

analysis, the resource flows of different variations of the service-based offerings could be compared.

The peculiarity of the investigated offerings was the retention of ownership for the OEM. Consequently, the OEM possessed more reliable information regarding the state of the products and, therefore, ambitious end-of-life operations became more feasible. Remanufacturing aspires to restore used or end-of-life products to the same quality, functionality and warranty as new products. The economic feasibility of remanufacturing depends, among other things, on accurate information regarding the state of the returning products. Through service-based offerings where OEMs retain ownership and have potentially lifelong remote-monitoring capability, remanufacturing is much more likely to be cost efficient.

Figure 4-1. Comparison of rates of recycled materials and landfill per washing machine (Sakao et al., 2019). This includes Al (aluminium), Be (beryllium), Bi (bismuth), Co (cobalt), Cu (copper) and Sb (antimony), where A0-A5 are scenarios and BAU is business as usual.

Article I looked at five scenarios (A0-A5, see Figure 4-1) differing by the overall use length of the washing machines (11.7-18.9 years), the market (Dutch or Belgian), and the entity that keeps ownership (customer, or manufacturer). A critical question of this study was whether a service-based offering (A1-A5) is more sustainable than a conventional offering (A0). Several of the service-based offerings showed significantly better recycling outcomes than the business as usual. However, the recycling of certain materials (Be and Co) remains unlikely throughout the scenarios because they are embodied in product components that cannot be reused for multiple lifecycles. On the other side, certain materials (Sb and Bi) have better utilisation because of the service-based offerings.

The article’s scope is limited to countries with a well-developed reverse supply chain for the waste of electrical and electronic equipment included in their national collective extended producer responsibility systems, for example, The Netherlands and Belgium (Borner and Hegger, 2018).

Method discussion

For RQ1, the first article investigated resource aspects and a new sustainability assessment for service-based offerings. A series of workshops (Ørngreen and Levinsen, 2017) was conducted with company representatives that helped gain insights about the internal processes around the development of service-based offerings as well as expected social and environmental benefits. The workshop included interactions with experts about, for example, product development, marketing, environmental assessments and supply chains. *Article I*, which applied a material flow analysis, provided insight with regard to how service-based offerings affect the overall

resource efficiency. It also showed that in order to understand the effects of service-based offerings in the big picture, it is necessary to apply a broader scope. The MFA was useful in comparing resource efficiency aspects of various offerings. However, the analysis does not allow a deeper analysis of the causal structure within the organisation. These insights were used to inform on the study design of *Article III*, where a dynamic modelling approach was chosen to be able to simulate the dynamics of the shift to service-based offerings.

Author's contributions

Tomohiko Sakao led in the conceptualisation and writing of the manuscript. As the second author, I was responsible for data collection, which included a series of workshops with the case company in order to understand the internal processes that occur during the shift to CE-oriented business models. I also had a supporting role in the writing and gave feedback for all revisions.

4.2 Article II: A complex adaptive systems perspective on servitization: A hybrid simulation model to inform decision-making for Heat as a Service

Authors: Raphael Wasserbaur, Ahmad Beltagui, Andreas Schröder

Journal: International Journal of Operations and Production Management

Status: Under revision

Background of the article

Servitization is a manufacturer's transformation from selling products to offering services or PSSs (Baines *et al.*, 2009). In many ways, a servitizing company is a complex adaptive system. Complex adaptive systems have the characteristics self-organisation, hierarchy and resilience (Buckley, 1968). For example, relevant actors for servitization may be customers, manufacturers or service providers; products and data generated by actors; and products and processes (Naik *et al.*, 2020). These actors possess agency and are self-organising and often organised in a hierarchical system. The complex nature of the servitization transition requires a systems perspective (Meadows, 2008). This study was created in collaboration with a European-based heating device manufacturer.

A hybrid simulation model for a multi-level complex system

A complex adaptive systems lens was used to develop a hybrid simulation model consisting of SDM, ABM and DEM parts. The purpose of this model was to simulate the dynamics that occur in an OEM's maintenance organisation during a servitization process.

The discrete event model was used to model the repair process. It includes the call of a customer, the resource allocation of a technician, the repair and the delays in the process. The Agent-based model was used to zoom into the technicians' activities of idling, travelling to customers, diagnosing and repairing. This modelling approach is apt to consider the actors' heterogeneity, for example, by including their individual experience levels and that effect of experience on the time to diagnose. The SD model was used for long-term changes. A central assumption was that through the accumulation of repair jobs, which is depicted as an SD stock, the

organisational efficiency in dealing with repair jobs increases such that overall, each repair can be conducted more efficiently. Fig. 4-2 shows an overview of how the three model parts are integrated.

Fig. 4-2. Overview of the hybrid model. The AB (agent-based) model shows the statecharts of technician and boiler agents; the SD (system dynamics) model shows how the data-based learning affects the organisation's diagnostic accuracy; and the DE (discrete event) model shows the repair service process. The grey dashed lines indicate the interaction points between the models.

Article II contributes to answering RQ2. The operational implications of a shift from product-based to service-based offerings are directly modelled. Through an array of scenarios, different rates of the uptake of service-based offerings, paired with different service-levels, are analysed. The results give an indication of how the service load for the OEM increases when engaging in a CE transition. It was found that the large-scale implementation of service-based offerings will lead to a massive increase in service requests that occur over the entire lifecycle of the products.

Method discussion

In order to answer RQ2, a study focusing on a manufacturer for heating devices was conducted and presented in *Article II*. The study design revolved around the exploration of a servitizing organisation as a complex system. This means that multiple levels of analysis and time scales were applied in the simulation modelling. The data collection was based on three workshop rounds in which the manufacturer could explain the role they expected servitization to play in the future. These inputs were used to develop a multi-level hybrid simulation model that combined SDM, ABM and DEM. The hybrid method was fairly difficult to apply as it requires knowledge in three different modelling approaches. The applied AnyLogic software allowed for several ways to combine the three modelling approaches (Borshchev *et al.*, 2014). The benefit of this type of analysis is that it allows one to “zoom” in and out of the research object and look at various aspects, such as the individual technician's activities or the organisation's process metrics.

Authors' contributions

As first author, I was responsible for integrating the three model paradigms and combining qualitative with quantitative modelling aspects. The two co-authors contributed in conceptualising the article, the writing and feedback during the process.

4.3 Article III: What if everyone becomes a sharer? A quantification of the environmental impact of access-based consumption for household laundry activities

Authors: Raphael Wasserbaur, Tomohiko Sakao, Maria Ljunggren Söderman, Andrius Plepys, Carl Dalhammar

Journal: Resources, Conservation and Recycling

<https://doi.org/10.1016/j.resconrec.2020.104780>

Status: Published

Background of the article

In order to meet the EU's climate and resource efficiency targets (European Commission, 2019), not just technological but also social innovations are needed (Ceschin and Gaziulusoy, 2016). The motivation for this article was to investigate the environmental consequences of large-scale behavioural change towards the CE. This kind of “circular” behaviour covers various activities ranging from engaging in individual recycling, reselling products, repairing products, product care and buying products designed for a second life to sharing products with other people. (Wastling *et al.*, 2018). For decision-makers, it is important to see how beneficial or detrimental large-scale shifts of consumer behaviour are. This type of study sheds light on future states of STSs and allows decision-makers to better understand a potential CE future.

This particular study focused on the environmental impacts of sharing compared to owning. Similar studies have been conducted for car sharing (Mont, 2004; Jung and Koo, 2018) and bicycle sharing (Retamal, 2017). Most people in Western countries use individually-owned retail washing machines, but in Scandinavia, and especially in Sweden, large parts of the population use shared laundry facilities despite relatively high income levels (Mont and Plepys, 2007; Pakula and Stamminger, 2010). The proliferation of such sharing systems has great potential to save resources and emissions.

A Simulation of behavioural change and a quantification of the environmental impact

We applied SD methodology (Sterman, 2000) in order to simulate a shift in behaviour of parts of the population towards sharing. The analysis includes the entailing changes in washing machine stocks, as well as the related environmental impacts. The article uses an STS, in this case, a sociotechnical laundry system, as the unit of analysis. The study underlying *Article III* was designed to answer RQ3.

The wide scope of this research question required the choice of a rather holistic approach including behavioural, demographic, technological and energy-related aspects. Various scenario simulations of the Swedish and European contexts are presented in Figure 4-3. The

mass of materials used in the machines and the emissions during the washing machines’ lifecycles serve as indicators for the resource efficiency. The results indicate that the sharing of laundry facilities causes lower environmental impacts than owning washing machines.

Figure 4-3. Total accumulated CO₂eq emissions of six scenarios from 2019–2049.

Note: The upper group of lines represents three EU scenarios, the lower three lines Swedish scenarios. The functional unit is the washing needs of the population living in multi-family housing expressed in wash cycles per household (Wasserbaur *et al.*, 2020). Adopters refer to the population that practices or adopts sharing behaviour, compared to owning behaviour.

The results also show that in the Swedish context, laundry-related emissions are lower than the European average. The higher emissions are explained by higher emissions during the use phase. Whereas the Swedish energy mix has high shares of renewable and nuclear energy, the carbon intensity of the EU average is much higher (Moro and Lonza, 2018). These results also show that overall in the EU, behavioural change has a larger relative improvement potential than in Sweden.

Method discussion

Article III is based on an SD model, which was used for a quantitative comparison of the future states of a sociotechnical laundry system. The model structure is based on existing literature and a series of semi-structured interviews and workshops. The model simulates how a society’s shift from owning to sharing can lead to savings in materials used and emissions caused. It required data collection from a variety of different stakeholders. Initially, a workshop with researchers experienced in the field was conducted (Mont and Plepys, 2007). Afterwards followed two rounds of interviews with industry experts, which allowed the refining of the conceptual model of the underlying system. A series of scenarios is presented, and the results indicate a significant resource savings potential of sharing in Sweden and Europe in general.

The SD method models the real world in aggregates, which seemed adequate for the wide scope of *Article III* that does not require to consider the heterogeneity of the single customers or appliances. A critique of the chosen approach is that it allowed to see *what if* large scale behaviour change happened but not *how to* achieve the change in the first place.

Author’s contributions

The author’s responsibilities were collecting and analysing the empirical data, developing the simulation model, and writing major parts of the manuscript. Tomohiko Sakao contributed to

the writing and provided feedback on revisions during the publication process. Maria Ljunggren Söderman contributed to the simulation modelling by providing lifecycle analysis expertise, while Andrius Plepys contributed with critical feedback and ideas during the conceptualisation. Carl Dalhammar contributed with critical feedback and policy-related writing.

4.4 Article IV: Conceptualising design fixation and design limitation and quantifying their impacts on resource use and carbon emissions

Authors: Raphael Wasserbaur, Tomohiko Sakao

Journal: Sustainability

<https://doi.org/10.3390/su12198104>

Status: published

Background of the article

This conceptual article contributed to the literature on design for sustainability. The scope of the article ranged from single product design up to STS design. Design fixation describes blind adherence to known concepts during the early design stage (Youmans and Arciszewski, 2014). This article adopted the concept of design fixation and contextualised it for higher levels of analysis, namely, the organisational and institutional levels. It framed STS as a potential unit of analysis for design for sustainability. The approach enriched the discussion of why society is hindered in coming up with sustainable solutions.

Difference between design fixation and limitation, and the environmental impact of fixations

The article distinguished between design fixation and design limitations (see Figure 4-4). Interestingly, both can limit a design space, but whereas design fixations can be avoided by using techniques that solve adherences, design limitations are actual constraints the designer has to comply to. The designer cannot freely decide upon design parameters that are constrained by design limitations. She can do so only for design fixations, which may lead to a better design outcome.

Figure 4-4. Conceptual distinction between design limitation and design fixation (Wasserbaur and Sakao, 2020).

This article showed that design fixations could diminish the success of use-based offerings. An example of a design fixation on the organisational level was an adherence to a tradition of product-focused design with a lack of integration with services (Matschewsky *et al.*, 2018). By discussing the causes of inertia of organisational and institutional change *Article IV* contributes to address RQ3 and RQ4.

It drew awareness to the fact that a company's organisational structure that evolved around a product-based offering needed to be adapted to service-based offerings or PSSs. Interventions on the organisational level may range from supporting design thinkers in the organisation to changing the relative importance of service-related divisions. A critical issue is that during the early design phases, service aspects ought to be considered in the designs (Sakao and Shimomura, 2007; Matschewsky *et al.*, 2018).

By means of an SD model, the article quantified the impact of design fixations on resource use and carbon emissions. The results showed that an STS, like a country's domestic laundry system, could be fixated to unsustainable patterns. The article also exemplified the relative impact of organisational design fixation and institutional design fixations.

Method discussion

The fourth article uses the concept of design fixation, which describes a phenomenon where designers adhere to certain known concepts instead of developing new solutions. This concept gets contextualised to higher levels of analysis, like organisation or institution, and helps explain design fixations on these abstract system levels and the results eventually help explain why we do not have CE at a larger scale already. *Article IV* employs the model developed earlier to show the potential effects of design fixations on the resource efficiency of STSs.

Author's contributions

The author was responsible for writing major parts of the manuscript, the simulation modelling and the revisions during the publication process. Tomohiko Sakao had a major contribution

during the ideation phase of the article, with important parts to the writing, feedback on the revision, and ideas during the article's conceptualisation.

4.5 Method discussion

4.5.1 Construct validity

Construct validity describes the degree of congruency between the research findings and phenomena under study (Karlsson, 2016). *Article I* models the material flows related to various offerings. Company experts' input was an important part of the data collection and model development. *Article II* uses a mix of modelling approaches. A company representative confirmed the usefulness of the simulation approach for his organisation. *Article III*, based on an SD model, presents the underlying stock-flow diagrams and the causal structure of an STS. The study results were developed with experienced researchers in the field, whose feedback served as triangulation during the model development. The construct validity of *Article IV* was increased by having a domain expert in the field of design research review the article draft before submission.

This thesis is based on various methods, both quantitative and qualitative. The data sources range from academic literature, interviews and national statistical data sources to product specifications. One important aspect is that none of the articles was developed in isolation; all were a team effort in which each co-author contributed with their own analytical expertise, which mitigates individual subjective biases.

4.5.2 External validity

In *Article I*, the study compares differences in resource use of PSS offerings between multiple countries. The findings are limited by specific lifecycle aspects, and, in particular, the end-of-life operations for the waste of electrical and electronic equipment in the specific country.

The scope of *Article II*, a study of a single company during servitization, is fairly narrow. However, the article presents a new method that captures the complexity of servitizing organisations. This method is expected to be useful beyond the specific circumstances of the case study.

Article III conducts an international comparison: Swedish laundry behaviour is measured against the European average; the findings are confined to the European context. However, the advantage of quantitative modelling is that by changing parameter values, it is possible to keep the model relevant for more than its original application. The findings are specific for Europe, yet the model could be used for other countries as well.

The core of *Article IV* is the application of an existing concept of design fixations on higher levels of analysis. The article's quantitative results serve as an exemplification of the relevance of the concept. Yet, the concept itself seems to be applicable in other STSs as well.

4.5.3 Reliability and replicability

Each of the four appended articles was written in a team effort, each article's method is clearly described and all underwent peer review iterations. *Articles I, III and IV* have been published

in academic journals, while *Article II* is currently under revision. *Article III* contains all model equations and data sources.

5 Discussion

This chapter helps the reader to put this work into perspective. It revisits the research questions and presents the results in the context of the theoretical background. First, the four research questions are addressed and synthesised, after which the practical implications of the research findings are outlined.

5.1 Resource efficiency implications of a shift to services

To many observers, the CE infers an intuition that it is more resource-efficient, emits fewer emissions, and is more sustainable than a so-called linear economy. Even though historically it has not always been like this (Desrochers, 2002), current industrial systems evolved around a linear economic paradigm (De Wit *et al.*, 2018), and recent studies have found a mismatch between the theoretical potential of the CE and the extent to which it is implemented (Desrochers, 2002; Barreiro-Gen and Lozano, 2020). Changing the existing system with its consumer attitudes, product designs, business models, supply chains, infrastructures and governmental policies is obviously a herculean task (Rizos *et al.*, 2016; Kirchherr *et al.*, 2018; Korhonen, Nuur, *et al.*, 2018; Whalen *et al.*, 2018). Decision-makers will only embark on this journey if they can weigh between the pros and cons of these far-reaching changes.

Article I and *Article III* assessed the resource efficiency of CE initiatives, in particular service-based offerings. *Article I* used a company's viewpoint to investigate how a change of the business model would affect the resource flows around the offerings of washing machines. Because the new service-based offerings give better control over the appliances at the end of their lifespan, the company could implement life-extending measures while also being able to improve the collection rate. More collection enables better control of products and monitoring their histories. Recent efforts tried to improve service-based offerings by developing models that simulate the flow of products and their components throughout supply chains and value retention operations (Wang, Breme, *et al.*, 2014; Lieder *et al.*, 2017; Franco, 2019). Direct control over product cores does not just enable the creation of product "biographies" (Spring and Araujo, 2017); it also optimises the handling of the materials used in the products (Lieder *et al.*, 2017).

Article I also found that additional expected positive aspects of the offering were a reduction of energy use due to increased access to high-efficiency machines for low-income users that otherwise would not be able to bear the high up-front costs of such premium appliances. This aspect is also interesting from a social sustainability point of view. On the other hand, not all initiatives with a CE label are actually more resource-efficient (Korhonen, Honkasalo, & Seppala, 2018; Makov and Font Vivanco, 2018). Resource efficiency that leads to cost reduction and an increase in demand may lead to CE rebound effects (Zink and Geyer, 2017). For example, refurbished smartphones are sold to secondary market segments that would have had no phones otherwise. Another example where CE strategies (Bocken *et al.*, 2016) are not resource-efficient can be observed with lifespan extension measures of energy-using products. At a certain point, the efficiency improvements of a new product alone outweigh the inefficiency of the old product plus the environmental impact of the production of a new one. In these situations, it is environmentally beneficial to replace an old refrigerator or washing

machine with a new one, instead of, for example, extending its lifespan through repairs (Agrawal *et al.*, 2012). However, the topic is nuanced. For example, for cars, the emissions associated with production are so high that timely replacement is unlikely to result in more resource-efficient outcomes (Danilecki *et al.*, 2017).

Article III applied a broad systems perspective. It looked at a sociotechnical laundry system in order to see how the large-scale behavioural change of laundry practices affected the related resource use and emission levels. The new sharing behaviour gave tenants access to very efficient machines, decreased the idling time of each washing machine, and, in turn, improved resource productivity. Similar studies investigated the environmental benefits of car sharing (Firnkor and Müller, 2011; Jung and Koo, 2018). The benefits of car sharing are increased use of resource-efficient shared cars and a decreased number of cars required to cover mobility needs. However, car sharing also increases vehicle use because individuals switch from public transit to car sharing vehicles; *Article III* found similar insights. By sharing washing machines, more people get to use resource-efficient appliances, and fewer washing machines need to be produced to cover a given amount of laundry needs. A negative aspect of sharing could be a lack of care or the wrong usage of appliances not owned by the user (Tukker, 2015). For example, in the case of laundry facility sharing, it was reported that people use chloride or unnecessarily high wash temperatures in order to “clean” the appliances after others have used them (Lund, 2009).

Article III showed that sharing behaviour significantly decreased the related emissions. Sharing washing machines could replace individually owned washing machines, which resulted in less resource use during production. Based on the given assumptions, sharing resulted in GHG emission reductions of 29% with a Swedish parametrisation and 35% for an EU average. It concluded that the rapid deployment of highly efficient energy-using technology over the next years could provide a valuable contribution to the reduction of laundry-related GHG emissions.

Articles I and *III* showed higher resource efficiency outcomes for the respective CE-oriented solutions over the business-as-usual scenarios. It needs mentioning that both studies assumed a fundamental behaviour change. In *Article I*, service-based offerings were provided only in selected national markets, and the offering seemed to appeal only to certain customer segments. *Article III* assumed that major parts of the model population would shift their behaviour to the sharing of laundry facilities instead of purchasing their own washing machines. These assumptions may seem optimistic, but the CE also means a behavioural change on a societal scale. Behavioural changes, in this case, sharing laundry facilities, come with the inconvenience of not having arbitrary access as well as other issues that emerge from sharing everyday goods with neighbours or strangers (Lund, 2009).

These research questions address the need for tools that simulate the transitional dynamics from a linear to a CE and its environmental impacts. The developed models include a far range of aspects from population growth, product designs, user behaviour, business model designs and technological development. GHG emissions, the mass of materials used, and recycling rates were used as measures for the resource efficiency implications. *Article I* also included a national extended producer responsibility systems, while *Article III*, having a long-term perspective, also included forecasts for the national electricity carbon intensities for the decades to come.

5.2 Operational implications of a shift to service-based offerings

In many companies, operations grew around a linear product-based paradigm (Cavalieri *et al.*, 2018). For OEMs, servitization and adding more service-based offerings in the portfolio is a key component in the shift to a CE. OEM services are typically provided during a warranty period, which besides legal requirements is determined by the product quality (Jovanovic *et al.*, 2016). The shift to service-based offerings or servitization means that a result or a function is sold instead of a product (Mont, 2002). The provider retains ownership, has more opportunities to capture value in the supply chain (Vandermerwe and Rada, 1988; Parry and Tasker, 2014) but also more responsibilities (Pal, 2016). The provider now has to manage assets that are located at the customers' locations. Key for business success are, for example, knowledge about the total cost of ownership and the residual value of the assets (Huikkola *et al.*, 2016). Maintenance plays a major role in this new setup (Jovanovic *et al.*, 2016).

By focusing on the implications of servitization on maintenance operations, *Article II* complements existing studies that looked at the interplay between product design and CE business models (Lieder *et al.*, 2017; Franco, 2019). *Article II* showed that the operational implications of a shift to business models around service-based offerings have led to an increased load of service requests. The heating device manufacturer became a heat provider and needed to assure a defined service level. The article had three major findings. Firstly, the uptake of service requests due to the availability-based contracts shifts priority on service capacity as a critical factor in the success of CE initiatives like servitization. The current literature does not identify core operational processes as inhibiting factors. The results indicate that manufacturers need to understand the uptake of responsibilities due to servitization because of the increase in service demand. Second, the workforce needs to be restructured for service-based offerings. Digitalization and automation will decrease the need for staff for diagnosing, but the longer service agreements lead to more service requests over a product's lifetime. *Article II* argues that the additional service demand will improve maintenance processes in the long-term but in the short- to medium-term, an additional burden will fall on service operations. Thirdly, service-based offerings cause relatively fewer service requests at the beginning of a product's deployment and more maintenance demand towards the end of its lifespan. This is a challenge for assessing the total cost of ownership and the pricing of service-based offerings. Cash flows will fundamentally change from lump sums at the time of sale to subscription-like monthly payments or pay-per-use as the service is provided, which makes it quite important to understanding costs and revenues over product lifespans (Sousa-Zomer *et al.*, 2018).

Article IV argues that organisations can be fixated to given solutions, for example, the existing product-based offerings or the existing organisational structure. This may not come as a surprise in cases where a company's business success for decades depended on sales levels (Matschewsky *et al.*, 2018). Ideally, CE initiatives focus on providing functions or results (Tukker, 2015). Organisational structures need to be adapted to service-based offerings. The relative importance of the service-related departments needs to increase (Matschewsky *et al.*, 2018), such that their input becomes a constituent part of the design process (Sakao and Shimomura, 2007).

5.3 Systems thinking to understand and plan the changes to a circular economy

For a better understanding of the systemic changes towards the CE, multiple viewpoints need to be combined. This thesis tries to mix perspectives, applies varying scopes, and employs several research methods in order to draw a broad picture of relevant aspects for a shift to a CE.

The synthesis of this thesis presents a multi-level framework ranging from a product level to PSS level, to an STS level. On the product level are manufactured products consisting of components made of materials. The time scale applied in the analyses for these two levels may range from hours to a product's lifespan. The PSS level includes products and attached services with the consumers using them. It includes the PSS, the lifecycle of the product, including manufacturing, the use phase and end-of-life operations. The PSS level time scale is determined through a product's lifecycle or a manufacturer's product design cycle. The STS level incorporates larger trends like servitization, behavioural change, public policy changes, and other aspects that shape the form of an STS. The time scale ranges from years to decades.

For decision-makers, it is especially interesting to understand how measures on one societal system level affects things on another level. It is, for example, crucial to know how governmental policies affect product emissions (Liu and Xiao, 2018) or how business model changes affect consumer decisions (Bocken *et al.*, 2018). From a modelling perspective, this is a challenging problem because model variables usually need to be on the same level of abstraction, such as population growth and unemployment rate. However, the CE entails change on both a small and a large scale (Kirchherr *et al.*, 2017), as well as in the long- and short-run. This is why this thesis looks at the individual consumer's product choices as well as the population's material consumption (*Articles I,III,IV*); it also looks at the working day of the technician as well as the long-term strategy of the company (*Article II*).

In order to address the research questions, variations of the research scope were necessary. The research objects were situated on different levels of abstraction, requiring their own lenses. *Article I* and *Article II* adopted a company's point of view, while *Article III* and *IV* adopted a larger scope with an STS point of view. Given the multi-level characteristics of a CE, it was necessary to analytically zoom in and out between the studies in order to understand how its building blocks interact and what the system behaviour is.

Both *Articles I* and *III* explore resource efficiency aspects of household appliances, yet their scopes are different. *Article I* zooms in on the material level of products. The lifecycle perspective also requires including aspects of the systems for reuse and recycling. *Article III* zooms out to the STS level. It depicts a sociotechnical laundry system, including washing machines, users, utilities, lifecycle emissions, energy mix and population dynamics, over a span of 30 years.

Article II applies three simulation-modelling approaches (ABM, DEM and SDM). The three analytical "zoom levels" were the individual technician level, the repair process level and the organisational learning level. This hybrid model combines the three levels as well as their interactions. It allows for the analysis of daily operations as well as long-term strategies. An

example of such a causal interaction may be that (1) company standards and long-term organisational learning determine the efficiency of the average repair process and that (2) every repair adds to the learning and therefore improves the service quality, which (3) in turn attracts more customers and thus leads to more repairs.

Article IV varies the scope from the product to the STS level. It begins with the design fixation concept on the product level and then argues that fixations may occur on all levels of design. The STS perspective was used to express the varying magnitude of design fixations. In this way, design fixation could be conceptually lifted to the organisational as well as institutional level.

The mixing of scopes or varying the scope throughout an analysis is not an entirely new idea. Wang, Breme, *et al.* (2014) developed a hybrid model to complement existing lifecycle analysis methodology. Their model includes single consumers as agents and supply chain dynamics, as well as total energy use and global warming potential of different beverage offerings. Scheepens *et al.* (2016) presented a circular shift framework that visualises interaction between the product design of yachts, business model designs in the tourism sector, and environmental protection policy designs. This research adds to the body of research by applying multi-level analysis to the sector of household appliances and by focusing on resource efficiency.

5.4 Every concept has its own rate of change

Articles I and *Article II* have the fundamental difference that the former is a static and the latter a dynamic analysis. Adding the time dimension in *Article II* requires a different type of modelling. The MFA of *Article I* describes how the system components are interlinked while the hybrid model of *Article II* needs to zoom in and capture some of the internal cause-effect structure that is driving the behavioural dynamics of the system.

A shift is inherently dynamic. Of the many identified key aspects of the CE, such as product design, business models, or policies, each has its own rate of change. The elements of the above-mentioned washing machine or laundry systems have varying rates of change. One could say that the shift to a CE is like moving a city. Some elements are highly dynamic and mobile and move very fast, but other elements, like houses or streets, need costly dismantling or need to be rebuilt from scratch at the new location. The moving is complete when all the system elements and their interlinkages are relocated at the new site.

Every element of the economy has its own rate of change, and product properties barely change over time. They may change through deterioration or through software or hardware updates. In a trivial sense, product properties change if the product gets replaced, and the same accounts for product markets or fleets. For example, the average efficiency levels of product fleets change only if single products are replaced. It will take a long time until all the cars on the roads today are replaced by new ones. Consumer behaviour could change instantly, but research has shown that behaviour change for the environment is very difficult to achieve (Hargreaves, 2011). However, between generations, the behavioural differences can be significant (Lyons *et al.*, 2007). Governmental policies or the policy framework in a given industry may change very slowly as well. The slow legislative process and the back and forth between interest groups can

make policymaking quite inert. Whereas business models are constantly adapted to changes in the eco-system, it seems that CE initiatives still play a minor role. All companies that collaborated in this research seem to have a majority of product-based offerings in their portfolios. However, as we lined out in *Article IV*, each system element has emerged at some point, and, therefore, every object can be considered a design parameter that may change over time.

5.5 Synthesis of the findings

The CE is a conceptualisation that runs through many levels of the economy, from product design to governmental policies. This thesis suggests that in order to understand a CE, the analysis has to be on three levels: product, PSS and STS. The appended articles were used in a complementary manner (see also Section 3.2.1) to exemplify this multi-level approach. The study underlying *Article III* applies an STS point of view. At the core, it focuses on the implications that large behaviour changes in a population have on the environmental impact of laundry activities. However, the study assumes certain parameters at its periphery, for example, recycling rates of washing machines and maintenance activities of the laundry service provider.

Articles I and II complement the analysis of *Article III*. Applying an MFA, *Article I* zooms in to the recycling aspects of various washing machines' offerings. Similarly, *Article II* zooms into the maintenance operations of an OEM of heating devices. Whereas the data of the respective models cannot be plugged directly into the others, their results contribute to a common understanding of how a shift to CE activities affects resource efficiency.

Table 2 lists the most relevant system elements of a CE, with high-level properties; indicates the rate of change; elicits aspects around the impacts of the element on the system; looks at decision makers that usually have some influence; and indicates a few to-dos for every decision maker.

Looking at the current literature, it seems that the dynamic characteristic of the ongoing shift to a CE is underexplored (Pieroni *et al.*, 2019). One appeal of dynamic models lies in the fact that they can be used to explore how a desired future state can be achieved, as exemplified in *Article III*. In the article, rates of change for user behaviour were assumed to determine the environmental consequences. Another approach could be to target a certain emissions level and then ask what rate of change in behaviour, technology or regulation is necessary to achieve that.

This thesis contributes to industrial ecology in the context of a CE by providing a material flow analysis that compares multiple PSSs in *Article I*. *Articles II, III and IV* develop a system dynamics model that diversifies the existing system dynamics literature by developing multiple CE-focused case studies. The servitization literature finds a new method developed in *Article II*, a hybrid model used to simulate dynamics during the servitization of an original equipment manufacturer. This research also contributes to the domain of systems thinking in the context of sustainability management by showing how a manager could use simulation modelling to plan and understand CE initiatives.

Table 2. Overview of system elements with their rate of change, their impact as well as possible to-dos in a shift to a CE

System element [rate of change]	Impact	Decision makers	To-Dos
Products and services [months –years]	<ul style="list-style-type: none"> ▪ Direct cause of emissions and resource use. ▪ Human resources for and cash flows from services: <i>Article II</i> ▪ Societal environmental impact is caused by the sum of all products and services that are produced: <i>Article III</i> 	<ul style="list-style-type: none"> ▪ Customers / users ▪ Product designer ▪ Service designer 	<ul style="list-style-type: none"> ▪ Implement circular design for easy reuse, remanufacturing, or recycle: <i>Article I</i> ▪ Consider influences from a chosen business model: <i>Article I and II</i> ▪ Consider implementation of remedies for design fixations: <i>Article IV</i>
Business models [years-decades]	<ul style="list-style-type: none"> ▪ Lifecycle impact improved through closing resource loops: <i>Article I</i> ▪ Enable customers to access circular offerings: <i>Article I</i> ▪ Uncertainty with regard to short- and long-term benefits: <i>Article II</i> 	<ul style="list-style-type: none"> ▪ Business model designers ▪ Managers active in CE 	<ul style="list-style-type: none"> ▪ Go from CE initiatives experimentation to large scale implementations: <i>Article III</i> ▪ Offer circular offerings as attractive as linear ones: <i>Article II</i> ▪ Change mind-set from sales to provision of function: <i>Article IV</i> ▪ More market segments need access to most-efficient appliances social sustainability: <i>Article I</i>
Govern-mental policies [years-decades]	<ul style="list-style-type: none"> ▪ Impacts of policies can affect every other aspect of society: <i>Article III</i> 	<ul style="list-style-type: none"> ▪ Policy makers on CE ▪ Policy makers and indirectly their voters 	<ul style="list-style-type: none"> ▪ Create more attractive conditions for CE: <i>Article III</i> ▪ Besides recycling, targets also set reuse targets: <i>Article I</i> ▪ Nudge people toward sharing behaviour: <i>Article III</i> ▪ Consider implementation of remedies for design fixations: <i>Article IV</i>

6 Conclusions and reflections

This chapter presents the main conclusions of the thesis. A few reflections and prospective future research efforts are outlined.

6.1 Implications of a shift to a circular economy

This thesis aimed to develop knowledge for a better understanding of a societal shift to a CE. Towards this goal, a range of analytical studies was conducted in order to address the research questions that focused on the (1) resource and (2) operational implications of a shift to a CE as well as (3) finding ways to understand and plan for the systemic change to a CE.

Two studies were conducted that research the environmental implications of the shift to a CE. One focused on the level of an offering, the other on the level of an STS. The results showed the potential for resource efficiency gains of CE activities. Service-based offerings enable a more resource-efficient end-of-life treatment of products. Behavioural change on the STS level enables efficiency benefits from scaling effects and avoids resource use from individual ownership. A primary driver for the environmental benefits of a CE is the consumers' acceptance of not owning but rather sharing the products they use.

One study was conducted on the operational implications of a shift to a CE. The study was based on an OEM of heating devices. In particular, a hybrid model was used to capture aspects of the complexity of the company's servitization process. The results showed an increase in maintenance demand in the short-term, offset by long-term process improvements. This worse-before-better trade-off implies that companies, which shift from selling products to providing services, need to be willing to take risks. Key issues for the success of the service-based offering were the uncertainty of product performance over the entire product lifespan and flexible maintenance capacity.

Finally, a fourth study focused on design fixation, which, in design science, is blind adherence to known concepts during the design process. Design fixation was introduced as a potential explanation for the question of why STSs are fixated to certain shapes. The study shows that the resource efficiency of STSs may be improved by solving design fixation on the organisational as well as institutional level.

6.2 Practical implication

As the actors with the widest range of interests, policymakers may draw the most utility out of this thesis. The resource efficiency questions address the worsening climate crisis, and the operational question addresses worries regarding the economic feasibility of a CE. In addition, the fourth research question helps to see the big picture of a large-scale shift of a society to a CE. This research can contribute to the systemic changes that we need in our current economic systems.

For managers in CE, the system thinking applied in this thesis could serve as an inspiration to develop their CE strategies. Simulation methods can be used to safely experiment with business models and product designs to get an idea of the resource efficiency and operational feasibility of new CE-oriented offerings. Examples show that there is even a demand for service-based

offerings for personally intimate appliances like washing machines. Companies that are now about to engage in servitization should consider what aspects of their operations are fixated to a linear way of doing business. The work on design fixations has shown that even aspects that appear to be rigid can be considered design parameters for the next iteration.

6.3 Reflections

The research presented in this thesis focused on the dynamics around the shift to a CE. From a systems perspective, there are interacting system elements that all play a role in the functioning of a CE. This thesis attempts to bring more clarity to how the circular system elements are interrelated and how to assess such a system. CE is a complex topic, which is researched in many different fields. However, it is like the blind men investigating the elephant. In order to see the full picture, one must step back and combine multiple viewpoints, which is why this research is diverse with the applied scopes and foci. By providing a series of case studies, this thesis helped to make the CE shift more concrete and easier to understand.

6.4 Future research

Based on the conclusions drawn from the research questions, we can identify a series of research avenues that seem worth undertaking in the future. More case studies about the effects of governmental policies on business activities and product designs or user behaviour are needed. Further, not everything that is circular also improves resource efficiency. More studies are needed on the systemic effects of circular offerings in order to avoid CE rebound effects.

In addition, a research opportunity is the role of the *CE manager*. CE managers could be corporate or policy decision makers that are tasked with managing CE activities in their domain. Due to the novelty of CE, planning and implementation of CE initiatives could be led by CE managers with expertise in “closing the loop”. Such a position would require knowledge from a variety of fields ranging from industrial ecology, product design, and supply chain management. Future research could provide the methods and tools to support CE managers and define the necessary skills and educational profiles. This thesis exemplifies systems thinking for CE and is especially interesting for actors who already have the role of a CE manager today.

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FACULTY OF SCIENCE AND ENGINEERING

Linköping Studies in Science and Technology, Dissertation No. 2119, 2020
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