From resource efficiency to resource conservation

Studies, developments and recommendations for industrial implementation of circular manufacturing systems

Michael Lieder
Doctoral thesis

KTH Royal Institute of Technology
School of Industrial Engineering and Management
Department of Production Engineering

Stockholm 2017

TRITA-IIP-17-08
ISBN: 978-91-7729-489-4

Akademisk avhandling som med tillstånd av KTH i Stockholm framlägges till offentlig granskning för avläggande av teknisk doktorsexamen fredag den 22 september kl. 10:00 i F3, Lindstedtsvägen 26, KTH, 10044 Stockholm

“We cannot solve our problems with the same thinking we used when we created them.”

– Albert Einstein

Abstract

Manufacturing industry is under permanent pressure to maintain its economic growth and profitability as strong societal backbone. At the same time pressures of waste generation and resource consumption are increasing as result of manufacturing operations. Since manufacturing industry is one of the major consumers of natural resources it is therefore essential to reduce dependency on natural resources by decoupling economic growth from consumption. Resource efficiency approaches can improve the performance of production systems by reducing resource losses. However, the fundamental assumption at the basis of resource efficiency approaches is that resources are available infinitely. As a consequence, challenges of sustainability and resource scarcity remain inadequately addressed.

The objective of this research is to develop analysis methods and decision support tools for manufacturing industry to facilitate its transition from linear production systems to circular manufacturing systems, which are economically viable and environmentally sustainable.

The initial scope of study focuses on industrial resource efficiency assessment in production systems. Expanding the view to a manufacturing system perspective, the current research is explored with regard to circular manufacturing systems in the context of economic benefits, resource scarcity and waste generation. Systematic analysis methods and decision support tools are developed for industrial companies to facilitate the adaption of circular manufacturing systems. These developments are supported by industrial case studies. The analysis methods are to the largest extent based on agent-based simulation approaches. The tools are capable of assessing the economic and environmental impact of different business models, design strategies as well as supply chains settings. Moreover, the tools are able to determine whether introductions of new (circular) business models will be adopted by customers. One empirical market study is performed to investigate value propositions of a circular business approaches based on customer decisions.

Keywords: Circular economy, Circular manufacturing systems, Resource conservative manufacturing, ResCoM, Agent-based modelling, Multi-method modelling

Table of Contents

Abstract .... **IV**

Table of Contents .... **V**

List of Figures .... **VII**

List of Tables .... **X**

Acknowledgement .... **XI**

List of Publications .... **XII**

Critical terminology .... **XIV**

1. Introduction **1**

1.1. Research background and motivation 1

1.2. Scope and research context 2

1.3. Problem statements, objectives and research questions 6

1.4. Research methodology 7

1.5. Thesis outline and relation to the appended papers 11

1.6. Research contributions 11

2. Modelling of socio-technical systems **13**

2.1. Why agent-based modelling? 13

2.2. Fundamentals of agent-based modelling 14

2.3. Implementation of socio-technical customer systems 17

2.3.1. Agent-based model formulation 19

2.3.2. Submodels: Concepts, coding and testing 24

3. Research contributions **41**

3.1. Response to research question 1 41

3.2. Response to research question 2 47

3.3. Response to research question 3 57

3.4. Response to research question 4 66

4. Implementation of decision-support tools **79**

4.1. Case company-specific circular manufacturing system 79
4.2. Tool overview and implementation 82
4.3. Exemplary scenario for exploring circular business approaches 83
4.4. Product-specific analysis for circular manufacturing systems 85
5. Discussions and conclusions 89
References 93
Paper A
Paper B
Paper C
Paper D
Paper E
Paper F

List of Figures

Figure 1: Economic activity within manufacturing in constant 2005 prices (in US dollars as share of the GDP) for the 20 largest countries from year 2006 until 2015, based on (Lieder 2014) with updated data from (UN Statistics Division 2016) 1
Figure 2: Scope of the ResCoM systems perspective............................... 4
Figure 3: Overview of the ResCoM consortium (ResCoM consortium 2013) 5
Figure 4: Comparison of the conventional lifecycle (dotted curve) and the multiple lifecycles (solid curves) (Rashid et al. 2013)........ 6
Figure 5: Adapted research cycle.. 8
Figure 6: Abstraction levels of main modelling methods (Borshchev & Filippov 2004) and research focus (in red) 10
Figure 7: Publication roadmap 11
Figure 8: Example of changing customer demand over time due to interaction of system elements in a customer system 15
Figure 9: A schematic overview of a customer purchasing decision model including three stimuli (single customer) based on (Engel et al. 1995) 16
Figure 10: Example of a statechart for single customers including associated computer code 16
Figure 11: Example of a statechart description with rule-based transition types 17
Figure 12: A schematic customer purchase decision model including underlying factors and influences 18
Figure 13: Detailed statechart for customer agents 21
Figure 14: Behavior curves using attribute indices price ip, environmental friendliness ie and service-orientation is for socio-demographic factors income, age and education (assumed in collaboration with industry).............................. 26
Figure 15: Attribute index “price” for the socio-demographic factor “income”... 27
Figure 16: Replication and validation of income distributions using Weibull distributions and agent recording 28
Figure 17: Simplified code for expected and actual part utilities 31

Figure 18: Time plots of a single customer agent showing the change from satisfactory to unsatisfactory state due to unfulfilled expectations (green line) 32
Figure 19: Simplified code for emergence of social network structures.. 35
Figure 20: Examples of identified continuous space values and network factors per population size for calibration purposes 36
Figure 21: Simplified code for communication events 39
Figure 22: Effect of different degrees of follower tendency and number of connections on customer agent expectations 40
Figure 23: Concept of resource efficiency as part of productivity rationale based on (Lieder 2014) (Tangen & Stefan 2005) 42
Figure 24: Steps of assessment approach 43
Figure 25: Physical resource efficiency measures 44
Figure 26: Monetary resource cost allocation 44
Figure 27: Distribution of reviewed academic publications including geographic focus in which CE has been published without specified research perspective 48
Figure 28: Summary of research articles analyzed from the perspectives "resource scarcity", "environmental impact", "economic benefits" and their combinations 49
Figure 29: Number of research articles with explicit focus on China and geographically independent CE research, categorized into research field and type of research 50
Figure 30: A comprehensive CE framework 54
Figure 31: Proposed CE implementation strategy applying top-down and bottom-up approach 56
Figure 32: A schematic customer purchase decision model including three stimuli and underlying factors and influences 60
Figure 33: Average simulation results after 30 replications (in grey) for pay-per-use scenario with launch at t=1827 days (5 years) including market share (a), customer satisfaction (b), diffusion of product attributes (c) and communication occurrences per product attribute (d) 62
Figure 34: Customer choice probabilities for different washing machine (WM) profiles taking purchase of a new WM with a 5-year warranty as reference 65
Figure 35: Explorative and optimization approach to connect design and business strategy in circular manufacturing systems 67

Figure 36: Overview and connection points of component-specific data, component agent and circular supply chain 70
Figure 37: Number of customers served per washing machine, aggregated lifecycle cost and impact for distinct 3 design options and 3 supply chains in a 15 year scenario 72
Figure 38: Results of cost optimization experiment for pay-per-use model (2000 consecutive simulation runs, 15 year scenario) 74
Figure 39: Comparison of aggregated lifecycle cost for 33 washing machine components in a 15 year scenario (cases: linear, design option 1, optimized pay-per-use design) 76
Figure 40: Material savings in kg of optimized design compared to linear scenario 76
Figure 41: Overview of user steps from data input, simulation run to results 83
Figure 42: Report extract: Average generated demand per week (a), aggregated number of customers in use phase (b), market shares at the end of year 10 (c) and demands not served over time (d) 85
Figure 43: Procedure for in-depth product analysis for circular manufacturing systems 86
Figure 44: Exemplary strategic recommendations based on investment need and material criticality as a result of explorative simulation study 87

List of Tables

Table 1: Chosen research methods per research question 9
Table 2: Summary of generic part utility functions for product attributes price, environmental friendliness and service-orientation 29
Table 3: Product offers and their attribute value for washing machines (WMs) 61
Table 4: Summary of attributes and their levels for B2C survey 64
Table 5: Washing machine design options considering different EoL strategies (based on number of components) 70
Table 6: Differences of case-specific decision support tools 82
Table 7: Overview of end-of-life strategies for 33 washing machine components for an optimized pay-per-use design 88

Acknowledgement

This doctoral thesis contains research work conducted at the Department of Production Engineering at KTH Royal Institute of Technology in Stockholm during the time period of roughly three years. Without support from people in academic fields and industry this work would not have been possible.

To start with, I would like to thank my main supervisor and mentor Associate Professor Amir Rashid for excellent support, a strong vision and superb guidance during the process of my research. Amir Rashid has supported me and my work with extraordinary patience and at all times with seminal advice.

I would like to give my appreciation for Professor Mauro Onori for his supervision and support during my PhD studies. It was a great pleasure to work with him.

I would like to thank my PhD colleague and partner in crime Farazee Mohammad Abdullah Asif for his support, great discussions as well as a lot of fun moments during the hard project and research work. We finally made it!

My sincere thanks also go to the PhD students and staff of the department who have supported me in many ways with their friendship, particularly Bita Daemi, Ove Bayard, Constantinos Frangoudis, Abdullah Mohammed, Alireza Khodaee Kalatehbali, Navid Shariat Zadeh, Tigist Fetene Adane, Qilin Fu, Johan Pettersson, Tomasz Ociepa and Robert Romejko. Thank you for the past years!

Last but not least, I would like to thank my girlfriend Shadi for her patience during this time of research and her confidence in my abilities as well as my parents and brothers for their indefatigable encouragement.

The research presented in this dissertation has been funded by the ResCoM project which has received funding from the European Union's Seventh Programs for research, technological development and demonstration under grant agreement No 603843.

Michael Lieder
Stockholm, August 2017

List of Publications

Appended papers:

Paper A "Resource efficiency assessment system", Lundholm T., Lieder M., Rumpel G., In: Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Berkeley, USA, May 2012 (DOI: http://dx.doi.org/10.1007/978-3-642-29069-5_72)

Paper B "Towards Circular Economy implementation: A comprehensive review in context of manufacturing industry", Lieder M., Rashid A., Journal of Cleaner Production, Volume 115, 1st March 2016, Pages 36–51 (DOI: https://doi.org/10.1016/j.jclepro.2015.12.042)

Paper C "Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems", Asif, F.M.A., Lieder, M., Rashid, A., Journal of Cleaner Production, Volume 139, 15th December 2016, Pages 1261–1281 (DOI: https://doi.org/10.1016/j.jclepro.2016.08.122)

Paper D "Towards Circular Economy Implementation: An agent-based simulation approach for business model changes", Lieder M. et al., Journal of Autonomous Agents and Multi-Agent Systems, 2017, (DOI: http://dx.doi.org/10.1007/s10458-017-9365-9)

Paper E "Towards circular economy implementation in manufacturing systems using a multimethod simulation approach to link design and business strategy", Lieder M. et al., International Journal of Advanced Manufacturing Technology, 2017 (DOI: http://dx.doi.org/10.1007/s00170-017-0610-9)

Paper F "A conjoint analysis of circular economy value propositions for consumers: using “washing machines in Stockholm” as a case study", Lieder M. et al. Journal of Cleaner Production (under review)

Other related work written by the author:

1) "An event-driven manufacturing information system architecture for Industry 4.0" Theorin, A. et al., International Journal of Production Research, Volume 55, Issue 5, 2017, Pages 1297-1311

2) “An IT-platform prototype as enabler for service-based business models in manufacturing industry”, Lieder M. et al., 7th Swedish Production Symposium, Lund, Sweden, October 2016

3) "Measuring sustainability - an empirical investigation of deployed performance measures in manufacturing settings", Salloum M., Lieder M., 5th Swedish Production Symposium, Linköping, Sweden, November 2012

4) "A theoretical foundation for resource efficiency and effectiveness in production systems", Lieder M., 6th Swedish Production Symposium, Gothenburg, Sweden, September 2014

Theses:

5) Licentiate: “Integrated evaluation of resource efficiency and cost effectiveness in production systems”, Licentiate thesis, KTH Royal Institute of Technology, Department of Production Engineering, Stockholm 2014

6) Diploma: “Development of a tool for consistent assessment of resource efficiency in small and medium-sized enterprises”, Diploma thesis, KTH Royal Institute of Technology, Department of Production Engineering, Stockholm 2011

Critical terminology

Since this dissertation addresses an evolving area in which the use of terminology is not standardized the following definitions are supposed to provide a basic understanding. The selection of terms has been partly adapted from previous work in this area (Asif 2017) and complemented with further definitions where necessary.

A *business model* is “the rationale for how an organization creates, delivers, and captures value” (Osterwalder & Pigneur 2010). In industrial practice a transition from a linear (take-make-dispose) to a circular product system (considering reuse/remanufacturing/recycling) requires changing the business model. In doing so, the manufacturer’s focus switches from selling physical products to providing access to functionality through business innovation.

Circular economy (CE) is “an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (Ellen Macarthur Foundation 2013).

Circular manufacturing system refers to a system that is designed intentionally for closing the loop of components or products in their original form for multiple lifecycles. In this dissertation the term circular manufacturing system is used to replace terms such as closed-loop manufacturing system, closed-loop product system, circular product system and ResCoM product system. It is worthwhile to note that the terms closed-loop system (Nasr & Thurston 2006) and closed-loop supply chain (Guide & Van Wassenhove 2009) are commonly used in literature and refer to value recovery through product reusing, remanufacturing and material recycling in the context of the conventional (linear) manufacturing paradigm. However, within the conventional manufacturing paradigm the collection of products and value recovery may happen as the consequence of unplanned end-of-life (EoL) scenarios which are mainly motivated by waste management and material recovery principles with limited business cases of reuse or remanufacturing.

Customer behavior "is the study of individuals, groups, or organizations and the processes they use to select, secure, and dispose of products, services, experiences, or ideas to satisfy needs and the impacts that these processes have on the consumer and society" (Kuester 2012). Since a fundamental assumption at the basis of ResCoM is that customers are perceived as integral part of the manufacturing enterprise it is a manufacturer's objective to understand its customers to gain full control over the back end of the market, i.e. quality, quantity and timing of product returns which is considered as one of the critical barriers of circular manufacturing systems (Asif et al. 2012).

Economic and environmental viability is proposed as measure to identify the feasibility of circular manufacturing systems implementation. Given the realistic possibility that proposed circular manufacturing systems may either be more capital-intensive (costly) or environmentally damaging than the current practices, the potential solutions should be carefully assessed. In cases where circular manufacturing systems may result in both higher cost and increased environmental harm than the current practices, then the solutions should be completely abandoned and new solutions should be sought.

Linear production refers to an industrial production rationale which is limited to a take-make-sell rationale. In a linear production setting natural resources are extracted, processed and used to manufacture products, which are finally to be sold. Typical linear production systems do not consider the disposal of products after use.

Manufacturing system vs. *production system*: In this thesis "manufacturing system" is defined as an entire organization in the manufacturing industry for the creation of production and integrates different functional groups, such as sales, design, production and logistics. On the other hand, a "production system" has a narrower meaning as it is defined as a group of technical production facilities, which are linked with each other for a certain type of production including their interaction. Examples of technical production facilities are machines, assembly stations, material flow systems etc. (International Institution for Production Engineering Research 2004). Production systems are usually efficiency-related whereas aspects of resource conservation and regeneration are discussed on manufacturing system level.

Productivity is "the relation between output quantity and input quantity" of a system in manufacturing context (Tangen & Stefan 2005). The concept of efficiency and effectiveness constitutes the underlying basis for productivity and is therefore of high relevance when it comes to resource use especially from a production system perspective.

Regenerative system approach stands for manufacturing activities that are based on the value of maintaining economic viability and environmental sustainability within the limits of available renewable resources. This definition originated from regenerative design strategies (Lyle Center 2006) and has been adjusted to fit into manufacturing context. Background is biomimicry of ecosystems is intended to function as a fully regenerative closed ecological-economic system including both human as well as industrial systems, which requires renewal or regeneration of sources of energy and materials that have been consumed. Manufacturing systems which are regenerative by design are intentionally prepared to receive and recover products after their return from the customer.

Remanufacturing is the process of restoring a non-functional, discarded, or traded-in durable product to a new-like condition. Key steps of remanufacturing as an industrial process are defined as disassembly, cleaning, inspection and sorting, reconditioning and reassembly (Steinhilper 1998).

ResCoM stands for Resource Conservative Manufacturing and has been introduced by a group of researchers belonging to the department of Production Engineering at KTH Royal Institute of Technology. The ResCoM concept has received funding by the European Commission (EC) for a 4-year project, which started in 2013 with the title "Resource Conservative Manufacturing- transforming waste into high value resource through closed-loop product systems" (ResCoM consortium 2013).

Resources in the context of ResCoM refer to material, energy and manufacturing value added. The labor, plant and equipment related overheads that are added to a product during manufacturing processes are included in the manufacturing value added.

Resource efficiency can be expressed as how well human and physical resources are utilized in order to achieve a desired outcome (Lundholm et al. 2012). There is strong consensus among researchers that efficiency is linked to utilization of resources in production.

1. Introduction

The purpose of this introductory chapter is to describe the background and objective of the presented research. The chapter highlights the importance of resource utilization in manufacturing industry. The vital role of the concept Resource Conservative Manufacturing is outlined. Then, the problem area for the research is described, followed by a presentation of the objective and research questions. The chapter is concluded with an outline of the entire research and relation of appended papers.

1.1. Research background and motivation

Globally, there has been a remarkable increase in manufacturing activities. Figure 1 shows the development of economic activity within manufacturing over the recent years for the 20 largest countries by GDP (UN Statistics Division 2016).

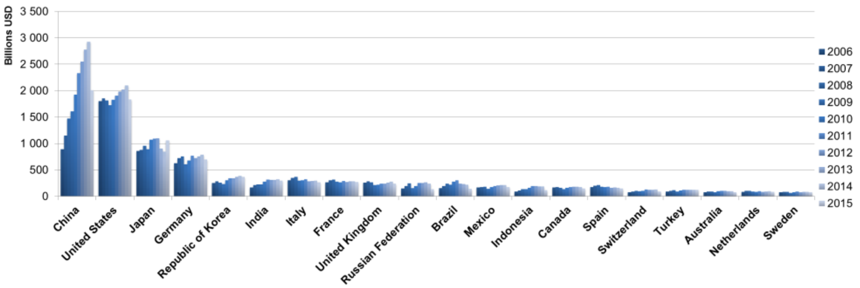


Figure 1: Economic activity within manufacturing in constant 2005 prices (in US dollars as share of the GDP) for the 20 largest countries from year 2006 until 2015, based on (Lieder 2014) with updated data from (UN Statistics Division 2016)

While in the past global resource extraction can be numbered with an aggregated growth of 45% between 1980 and 2005 (World Resource Forum 2017), further significant increase of natural resource extraction is being predicted for the future (Giljum et al. 2008), particularly due to a growing world population and strong middle-class growth. As it is obvious that natural resource supplies are limited and cannot meet the requirements of steady growth (Meadows et al. 1972) the problem of scarcity tends to get acute in future. Consequently, in order to be sustainable, i.e. to meet the needs of the present without compromising the abilities of future generations to meet their own needs (UN World Commission on Environment an Development 1987), the manufacturing industry plays a key role as one of the main resource consumers.

1.2. Scope and research context

This research focuses on resource utilization and the paradigm shift from resource efficiency to resource conservation through implementing circular manufacturing systems. While approaching the challenges of resource consumption and waste the initial research focus has been on efficiency increases in production systems. Due to this focus, the preliminary work targeted the improvement of available measures concerning operational resources, such as material, energy as well as time-related measures for personnel and equipment. Main findings highlighted that approaches of resource efficiency can improve performance of a production system, however, assuming that resources are abundant and always available. Once resource scarcity evolves to a limiting factor for the production system, need of resource conservation including regenerative approaches becomes highly relevant. Anticipated potentials in this area are estimated with roughly 12%-23% of material cost savings or 250-456 billion Euro respectively (European Parliament 2017) (Ellen Macarthur Foundation 2014). As a consequence, an expanded perspective is required where the focus changes from processes and production systems to manufacturing systems.

On manufacturing system level, conventional closed-loop supply chains and remanufacturing activities have been of interest for research and business during past decades. In most cases, however, efforts for closing the loop of products at their end-of-life are done in the conventional linear production paradigm, where products are neither designed nor manufactured to close the loop. As a consequence, reuse and remanufacturing activities are not turning into mainstream business operations despite their sound benefits, which have been highlighted by researchers and industrial practices. In this perspective the recent

Circular Economy (CE) movement pushed by the Ellen MacArthur Foundation has gained a lot of momentum as it highlights the needs for a paradigm shift towards systems that are industrially restorative or regenerative by intention and design.

Most of the reports about CE so far mainly discuss motivation, advantages, disadvantages and challenges of CE. Even though existing cases and examples seem promising, practical aspects such as *how to implement relevant CE concepts in industry* are quite rare. At this point implementation approaches need to be emphasized that make CE favorable for manufacturing companies and their business operations. If CE will not appear favorable for manufacturing companies from a business point of view there is a risk that the value of the CE initiative may be lost. As a consequence, CE may be perceived as constraint to industrial activities rather than an opportunity for sustainable business and growth.

On the other hand, the Resource Conservative Manufacturing (ResCoM) initiative shares the same vision as the CE initiative, which is resource conservation by design and moreover focuses on industrial implementation. Focusing on manufacturing industry ResCoM promotes a paradigm shift to support implementation of circular manufacturing systems. A framework has been developed for ResCoM which maintains a systems perspective towards implementation of circular manufacturing systems in order to cope with the challenges of resource scarcity and conventional closed-loop systems mentioned above.

The ResCoM framework is based on a concept which has evolved at the department of Production Engineering at KTH, and "considers the conservation of energy, material and value added with waste prevention and environment protection as integrated components of the product design and development strategy" (Rashid et al. 2013). The ResCoM framework outlines some fundamental requirements which need to be fulfilled for successful implementation of circular manufacturing systems:

- Business model, product design, supply chain as well as information and communication technology need to be considered simultaneously as they are interlinked when it comes to resource conservation.

- Appropriate business models need to be in place, which define value propositions as well as how the value will be created, delivered and captured.
- Forward and reverse supply chains need to be integrated.
- Predefined end-of-life (EoL) strategies are defined and in place.
- Original equipment manufacturers (OEMs) that own the final product are the major stakeholders of the ResCoM framework. First tier suppliers can also be in the leading role if the supplied products are the major part of a final product.
- Closing the loop of products should be both economically and environmentally viable.

In its current form the ResCoM framework is unique and provides suggestive guidelines as well as supports new implementation approaches. Research and tools of this work aim at strengthen the foundation of the ResCoM framework. Figure 2 shows an overview of the scope of the system perspective covered by ResCoM.

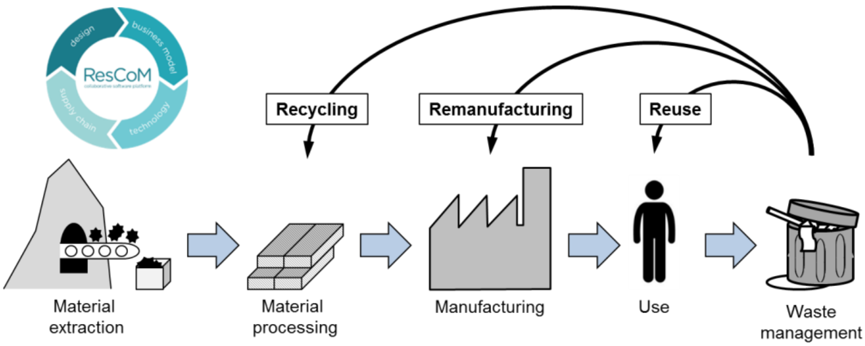


Figure 2: Scope of the ResCoM systems perspective

The ResCoM concept received funding from the European Commission resulting in a collaborative European project, which started in the end of 2013. The ResCoM project aims at developing an innovative methodology and software platform for the industrial implementation of circular manufacturing systems. Four large companies are involved in this research and have contributed with important insights in this thesis. Figure 3 shows an overview of the entire ResCoM consortium.

Figure 3: Overview of the ResCoM consortium (ResCoM consortium 2013)

Based on the work in the ResCoM project, this thesis aims at contributing to the implementation of circular manufacturing system approaches and accelerate the transition towards a regenerative manufaturing industry. In the context of circular manufacturing systems the concept of multiple product lifecycles plays a crucial role. The manufacturing of products with multiple lifecycles puts a fundamentally different perspective on the product lifecycle in comparison to the conventional (linear) product lifecycle. Products with multiple lifecycles encompass the stages of product distribution, use, return, recover, reuse, remanufacture and/or recycling of the product. In doing so, the entire life of the product is divided into multiple lives of predetermined periods. After each designed lifecycle the product is taken back for reuse, remanufacturing or recycling activities to restore the product to its original performance specifications or to upgrade the returned product to new specifications. Figure 4 illustrates the conventional lifecycle approach in comparison to the multiple product lifecycle approach.

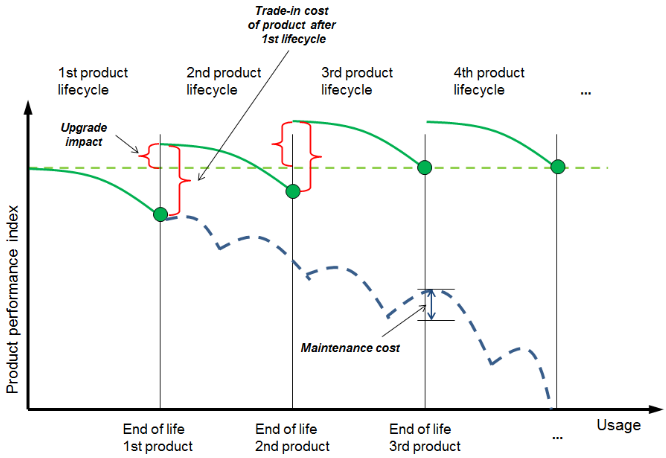


Figure 4: Comparison of the conventional lifecycle (dotted curve) and the multiple lifecycles (solid curves) (Rashid et al. 2013)

1.3. Problem statements, objectives and research questions

The current practice of improving resource use in manufacturing systems is limited to production systems and internal operations of a manufacturing enterprise. In line with the previous discussions one main problem statement can be formulated as:

There is a lack of systematic analysis approaches for analyzing manufacturing systems beyond the linear paradigm. This is especially true when it comes to the analysis of circular manufacturing systems where economic and environmental impacts need to be analyzed in a concurrent manner.

Given the problem description, main objective of this thesis has been derived as:

Development of analysis methods and decision support tools for manufacturing industry to facilitate its transition from linear to circular manufacturing systems, which are economically viable and environmentally sustainable

Based on the problem description and the objective the following research questions (RQs) are in focus of the presented research.

RQ1: What are main factors of resource efficiency and how can resource efficiency be assessed comprehensively?

RQ2: How much the current research has explored and supports the idea of circular (closed-loop) manufacturing systems, characterized by reuse, remanufacturing and recycling, in the context of economic benefits, resource scarcity and waste generation?

RQ3: How can customer behavior be assessed and determined on whether introductions of new (circular) business models will be accepted/rejected considering that customers are perceived as integral part of the circular manufacturing enterprise?

RQ4: How can economic and environmental impact of different circular manufacturing systems be quantified and assessed considering different business models, design strategies and supply chains?

Chapter 3 and papers A through F appended to this dissertation provide answers to these questions.

1.4. Research methodology

A cyclic research approach has been adapted to ensure a systematic process of collecting, analyzing and interpreting data in order to increase understanding about phenomena that are of interest or concern (Paul D. & Ormrod 2013). The intention is to create a sound scientific foundation for new methodologies based on qualitative and quantitative studies which are practically useful. In this work the area of interest is resource conservation in manufacturing industry. Figure 5 shows an overview of the research steps which have been driving the research in this case. Beginning with logical steps of problem and goal definition the research work can be divided into sub-problems. In the following steps, tentative problem solutions and data collection lead to resolutions, learnings as well as new problem statements to be further investigated.

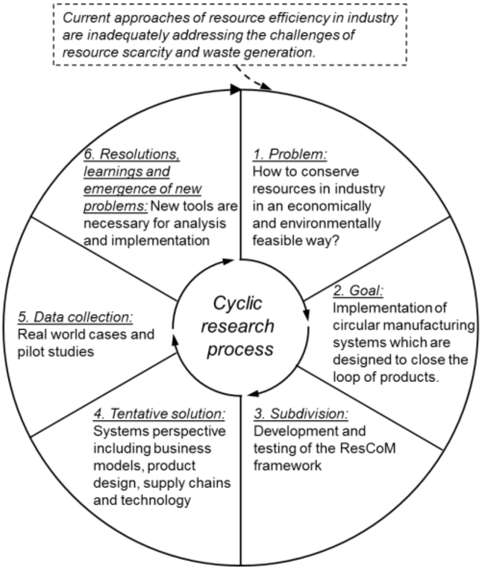


Figure 5: Adapted research cycle

The first research question (RQ1) is an analysis of the current state to investigate existing practices and approaches in the linear production paradigm. A descriptive stepwise approach has been developed and data collected from a production system to test the approach.

The second research question (RQ2) is rather explorative as it intends to frame existing research based on the newly adapted perspective of resource conservation. Hence, a systematic review of research article has been carried out based on published articles from Web of Science and Scopus using the keyword “circular economy” for the years 1950 until 2015. Identified articles have been filtered and categorized for analysis purposes.

The third (RQ3) and fourth (RQ4) research question aim at filling the gap identified resulting from the previous explorative study. RQ3 focuses on behavioral aspects of customers / product users to explore the dynamics of adoption and rejection of new offers in ResCoM context. RQ4 is based on models and experiments to describe the dynamics of circular manufacturing systems. For both RO3 and RQ4 complex modelling approaches have been developed starting with literature review on existing approaches. As a next step conceptual models have been formulated and converted to mathematical models for implementation purposes. The models have been run with data from industry or public databases. In addition to answering RQ3 an empirical study has been carried out using a conjoint analysis approach to include real market data. Table 1 provides an overview about chosen research methods for each research question, corresponding articles published and sections in this thesis.

Table 1: Chosen research methods per research question

Research question	***Chosen research method***	***Correspon-ding paper***	***Section in this thesis***
1) What are main factors of resource efficiency and how can resource efficiency be assessed comprehensively?	Quantitative study (Case experiment)	Paper A	3.1
2) How much the current research has explored and supports the idea of circular (closed-loop) manufacturing systems, characterized by reuse, remanufacturing and recycling, in the context of economic benefits, resource scarcity and waste generation?	Qualitative study (Literature review of public peer-reviewed articles)	Paper B	3.2
3) How can customer behavior be assessed and determined on whether introductions of new (circular) business models will be accepted/rejected considering that customers are perceived as integral part of the circular manufacturing enterprise?	Quantitative study (Model development and case experiments)	Paper D	3.3
	Quantitative study (Empirical study using conjoint analysis)	Paper F	
4) How can economic and environmental impact of different circular manufacturing systems be quantified and assessed considering different business models, design strategies and supply chains?	Quantitative study (Model development and case experiments)	Paper C Paper E	3.4

When it comes to decision support in circular manufacturing systems, classical industrial engineering approaches may not be the best tools to solve the practical problems in industry as they are not able to handle the dynamics of circular product systems (Rashid et al. 2013). As a consequence, the development of simulation models is needed which are capable to capture and connect aspects of business models, product design as well as supply chains (RQs 3 and 4). Figure 6 provides an overview of relevant system modelling methods including their abstraction levels, which are of relevance for this thesis. Major development work in this thesis is based on agent-based modelling (ABM) approach, as indicated by the dashed marks in the Figure. Some contributions have combined the agent-based (AB) approach with discrete-event and system dynamics methods, thus resulting in multi-method-models (indicated by the arrows). For the simulation and implementation of the developed models the Anylogic software platform has been used since this platform allows for considering all three system modelling methods simultaneously while connecting them. Motivations for choosing and combining particular modelling methods are provided in the corresponding subsections of chapter 3.

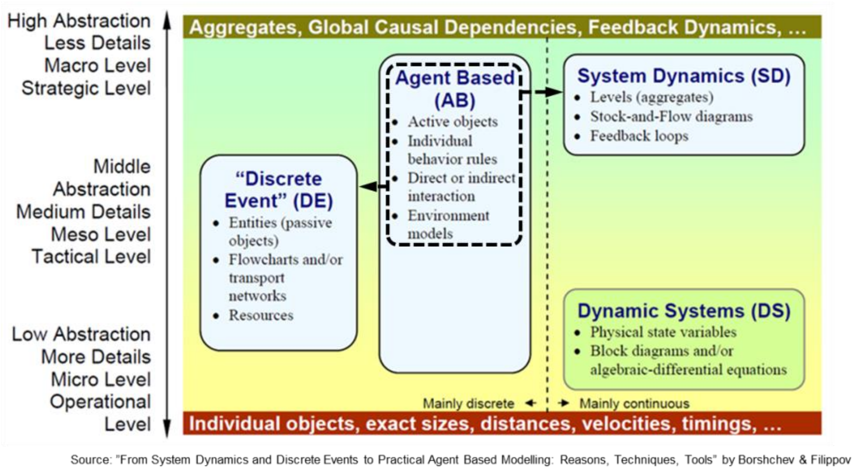


Figure 6: Abstraction levels of main modelling methods (Borshchev & Filippov 2004) and research focus (in black)

1.5. Thesis outline and relation to the appended papers

In total the thesis consists of five chapters. The following chapter 2 introduces modelling of complex system based on agent-based simulation approaches. Chapter 3 accounts for the research contributions. Five appended journal papers and one conference paper constitute the core of this dissertation. Figure 7 shows a publication roadmap and how the publications are interrelated. While paper A concerns efficiency improvements of production system operations within the linear production paradigm, the papers B through F consists of contributions within the resource conservative manufacturing paradigm.

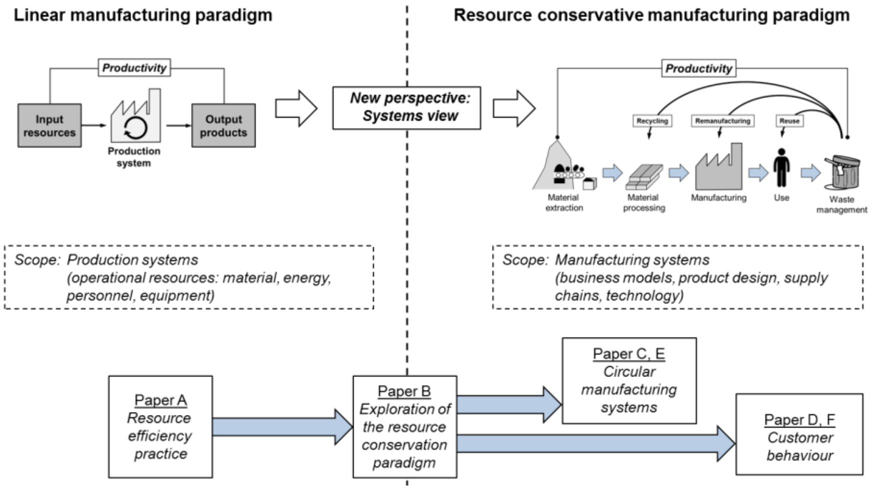


Figure 7: Publication roadmap

1.6. Research contributions

This section briefly outlines the author's contributions to each paper. It is worthwhile to note that main contributions are always provided by the first author who has been responsible for writing and editing the respective paper.

In paper A relevant literature has been reviewed and the initial thoughts have been conceptualized. The assessment approach and physical resources measures have been defined and discussed with the co-authors. Moreover, the case study has been carried out including documentation, data collection, aggregation and visualization.

For paper B the structure of the review process has been developed and database searches and documentation have been performed. The actual review of all identified articles has been carried out and continuously reviewed with the co-author. The framework and implementation strategy has been elaborated in collaboration with the co-author.

In paper C the agent-based model has been developed, connected to the system dynamics model and tested to ensure interoperability.

In papers D and E literature reviews have been carried out to found a theoretical basis. Relevant existing concepts have been discussed with co-authors to define the overall concept at the basis of the work. The parametrization and implementation of the models have been performed. The models were tested and revised based on feedback from the co-authors. Case study-specific data was provided by industrial partners (paper D) or co-authors (paper E).

For paper F the literature review has been carried out and the experimental setup has been developed. The co-authors have continuously provided feedback and students have supported the data collection and data formatting process. The data analysis has been performed including visualization and presentation of results.

2. Modelling of socio-technical systems

2.1. Why agent-based modelling?

From a socio-technical system perspective, a social network of actors and a physical network of technical artefacts together can form a complex adaptive system (Dam et al. 2013). In the context of circular manufacturing systems industrial businesses form such a complex adaptive system between customers (actors) and manufacturing systems (technical artefacts) producing products. Thus, a multi-customer network determines the development, operation and management of the manufacturing system, which in turn affects the behavior of its customers. The CE-view increases the level of complexity in the system because CE expands the perspective beyond the prevailing linear manufacturing systems in order to gain control over product returns. Since a fundamental assumption of the ResCoM framework is that customers in a CE are perceived as integral part of the manufacturing enterprise a reduction of complexity in socio-technical systems is needed with the support of customer behavior simulation.

When it comes to industrial practice of single manufacturers a transition from a linear (take-make-dispose) to a circular product system (considering reuse/remanufacturing/recycling) requires the change of business models through new value propositions. Hence, the focus of the value proposition shifts from selling a physical product to providing services through business innovation. This usually involves creating new markets or renewal of a market and leads to the question of customer adoption or rejection (Martin et al. 2016). Using washing machines as example, service-oriented offers which provide access to functionality instead of product ownership have been examined in addition to conventional sales offers. In such a business model the return of the washing machine is determined by the chosen business rationale, i.e. leasing, pay-per-use or other, which in turn is dependent on market acceptance and behavioral aspects of the customers. As a result, the linkage between technical systems (e.g. manufacturing systems) and social systems (e.g. customer networks) becomes enormously significant and influential. It is a manufacturer's objective to fully understand this linkage, particularly in how to handle the consequence and impact of business innovation in the form of new value propositions. An increased understanding in this area would enable manufacturers to gain control over the back end of the market, i.e. quality, quantity and timing of product returns which is considered as one of the critical barriers to CE implementation (Asif et al. 2012).

Various simulation paradigms are available to date, each one with own benefits and drawbacks. The use of ABMs to understand the behavior of complex adaptive systems over time has recently gained attention in both research and business. Compared to system dynamics ABMs are advantageous since overall system behavior can be obtained as a result of modelling individual entities and their interactions on micro level (Borshchev & Filippov 2004). This furthermore allows for modelling individual behavior in detail which is characterized as nonlinear and discontinuous (Bonabeau 2002). In relation to discrete event approaches ABMs allow for modelling active entities which themselves can take initiatives and carry out actions in a decentralized manner (Siebers et al. 2010). Aiming at behavioral aspects ABMs seem most appropriate as it is possible to model single customers as active entities with individual characteristics including their interaction to replicate real-world business problems such as diffusion processes and their consequences. To be more specific, the possibilities provided by agent-design principles appear to be the most appropriate means in order to develop a simulation tool which can be supportive in the search for explanatory insight into the collective behavior of agents (in this research e.g. customers as part of a manufacturing system in CE context).

2.2. Fundamentals of agent-based modelling

In the process of describing system behavior most existing approaches remain on rather high level, describing mainly the bulk behavior of a system. In many cases elements of a system are considered independently without their mutual interaction. As a result, even though decision-makers may have the impression of a sufficiently described system the actual results deviate strongly from the anticipated results. Figure 8 illustrates how overall demand for a product after market launch may change based on experiences of single elements in a system (customers) and their interaction over time.

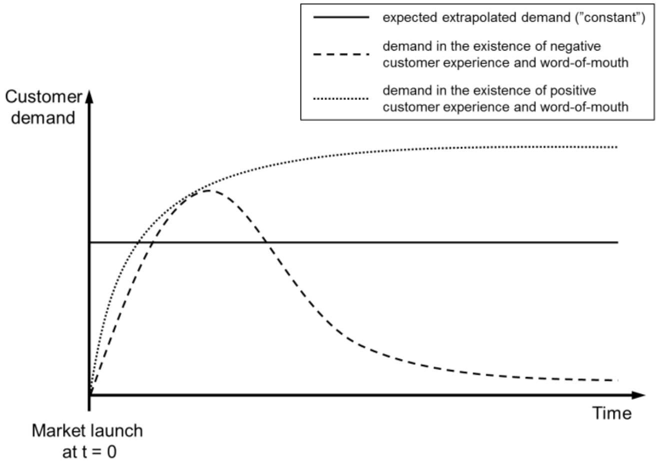


Figure 8: Example of changing customer demand over time due to interaction of system elements in a customer system

A simplified approach frequently used in practice is the assumption of a constant demand stream, which ignores dynamics in the system over time. As can be imagined, the more realistically a system should be described the more elements and properties need to be added to the system elements. This in turn leads to more complex structures and unpredictable final outcomes in terms of system behavior. To continue the example of customer demand, the modelling of *customer experiences* and *word-of-mouth* features will require a definition and logic for satisfactory levels, communication events, network structures and adaptability, to name a few. The outcome in terms of overall demand can then be obtained as a result of a combination of these system properties and configurations. In doing so, subjectivity inherent to social systems can be described while maintaining higher level of objectivity. The final model can be used to obtain new perspectives on how systems can be studied and explored. This leads to increased knowledge on how desirable system behaviors can be obtained.

In ABMs problems and actors are identified before the model is formulated and implemented. Then the problem at hand is represented conceptually. Based on the previous example, Figure 9 shows a decision-making process in purchase of commodities as a cognitive process (Engel et al. 1995).

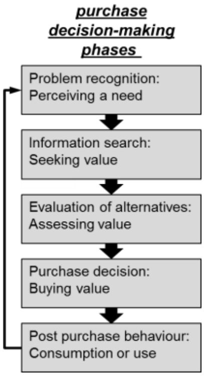


Figure 9: A schematic overview of a customer purchasing decision model (single customer) based on (Engel et al. 1995)

The conceptual models are logically formulated, which may require development of sub-models to be tested. Continuing the reasoning from Figure 9 a statechart has been created with associated logical operations (see Figure 10).

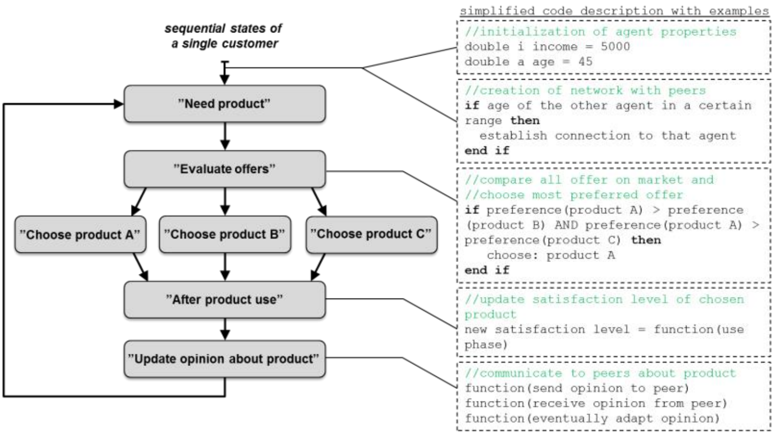


Figure 10: Example of a statechart for single customers including associated computer code

In the following step the logical formulations are implemented with computer code in simulation programs. In the software of Anylogic statecharts are used to describe event-driven and time-driven behavior of agents. A state is a specific collection of parameters defining an agent (Wooldridge & Jennings 1995). If agents change from one state to another or if agents are meant to carry out actions a description of rules is required. Rules in this context can be understood as logical rules which may contain mathematical formulations. As shown in Figure 10 the states are connected with arrows (transitions) defining time and the state the customer agent is in as well as the conditions under which that customer agent will transit to another state. A more detailed description with different implementation possibilities of states and transitions is shown in Figure 11.

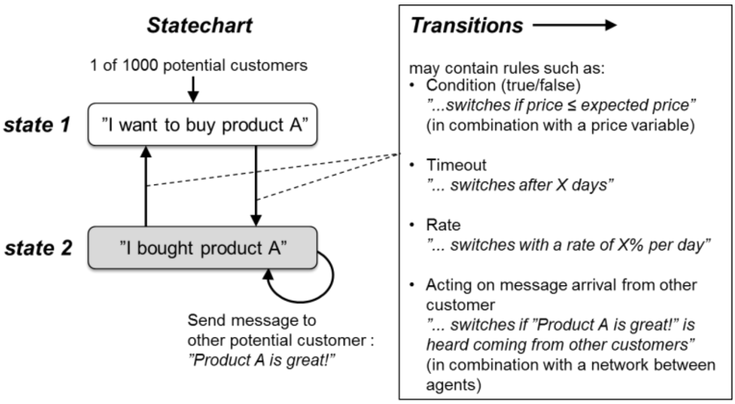


Figure 11: Example of a statechart description with rule-based transition types

2.3. Implementation of socio-technical customer systems

In order to bring circular approaches and capabilities of ABMs together, a conceptualization of purchase decision-making processes for purchase of commodities on individual customer level is needed, which has already been introduced in Figure 9. As indicated, a decision-making process in purchase of commodities can be commonly described as a cognitive process of five stages. The sequence of stages consists of:

1) Need recognition, which can be triggered by internal as well as external stimuli
2) Search for information in order to find a solution for the identified need
3) Evaluation of different solutions on the basis of varying product attributes
4) Purchase decision where the actual purchasing transaction takes place
5) Post purchase behavior in which products are compared with expectations resulting in satisfied or unsatisfied customers

For a comprehensive model the outlined concept needs to be extended in order to account for underlying factors and influences. These underlying factors and influences constitute submodels of the ABM, which are modeled and described independently. Figure 12 provides an overview of all underlying factors and influences of the purchase decision-making process.

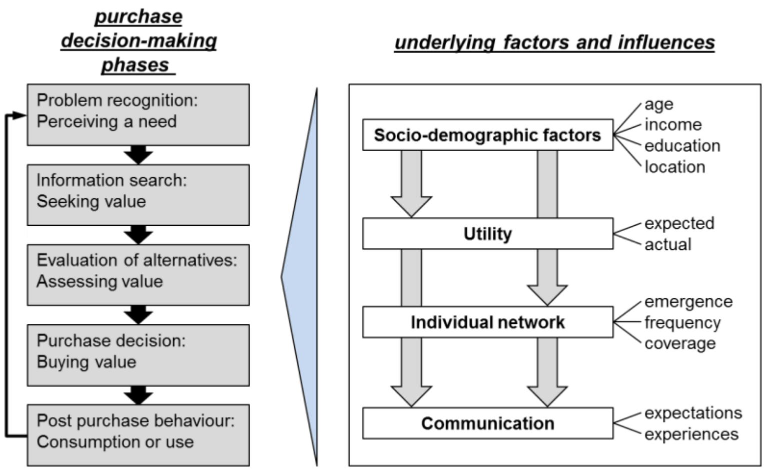


Figure 12: A schematic customer purchase decision model including underlying factors and influences

Beginning with socio-demographic factors intrinsic preferences are derived which assume correlations between socio-demographic factors and attributes of a product offer. These intrinsic preferences furthermore build the basis to form product utility and individual networks. The former applies the concept of product utility as a measure for expected and actual preference for an offer. The latter is based on the sociological theory of homophily in social networks which predicts that the probability of information exchange between two individuals depends on the similarity of their socio-demographic factors (Mcpherson et al. 2001). Communication between customers is defined as information exchange within a network. Communication depends on individual agent connections to other agents as well as its expected and actual perceived product utilities. The structure of the agent network determines how information is spread and transferred to other agents. The comparison of expected and actual product utility leading to (dis)satisfaction is crucial for deciding the type of information which is to be transferred.

In summary, each single customer is passing continuously through all purchase decision-making phases (left side in Figure 12) while learning from purchase experiences and exchanging information with other customers and advertisement over time. All underlying factors and influences have continuous effect on the purchase decision-making process making it highly dynamic and complex.

2.3.1. Agent-based model formulation

In order to provide a standardized manner of ABM presentation the model description follows the ODD (Overview, Design, concepts, Details) protocol (Grimm et al. 2010) to detail the AB model based on the previous section.

Purpose

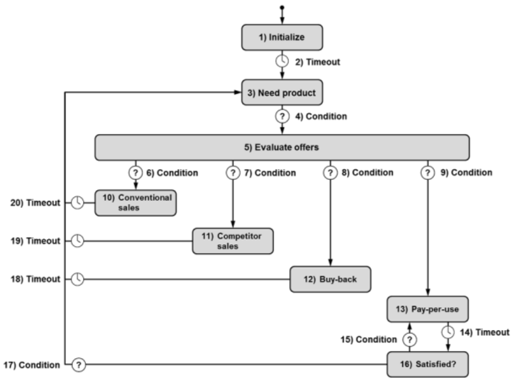
The purpose of this model is to simulate customer behavior with regards to business model changes in the CE context. In order to observe changes in demand based on different business models, a customer population is exposed to new offerings (e.g. buy-back or pay-per-use) in addition to a conventional sales offer in a competitive market.

Entities, state variables and scales

This AB model includes three types of entities to describe the purchase decision-making process: An environmental agent at population level, individual customer agents and spatial and temporal units. The environmental agent accommodates all individual customer agents and therefore contains states and parameters to characterize customer agents on population level. This includes population size, density and ownership tendency. An information decay factor is included at the population level to consider the decay of information after information exchange (word of mouth). Product attributes are characterized with the parameters price, environmental friendliness and service level. Based on the configuration of these attributes the overall utility of a product on the market is determined on individual agent level. Customer agents are characterized with socio-demographic factors as well as individual sensitivity towards advertisement and word of mouth. This also includes the current satisfaction state, the frequency of communication (how many times) and the content of communication (what subject). Furthermore, each customer agent holds an awareness parameter for each product attribute per offer on the market. The temporal and spatial units are the technical parameters defining elementary performance of the simulation. The simulation area is defined as continuous space and the size of the space depends on the population size and is adjusted accordingly in order to maintain a constant density within the population (in this case representing the city of Stockholm). The time proceeds in discrete steps where one time step represents one day.

Process overview and scheduling

The complete statechart at customer agent level is shown in Figure 13. Detailed explanations about the states and transitions are added on the right-hand side of Figure 13. After initialization of the population (steps 1)-3)), customer agents repeatedly pass through the need state 3), evaluation state 5) and use phase of either conventional sales 10), competitor sales 11), buy-back 12) or pay-per-use 13). At the end of each use phase the actual utility is calculated and compared with the expected utility resulting in updated expectations when evaluating offers recurrently.



Number of element in statechart	Type of element	Description of actions
1)	State: Initialize	• Initialization of agent population • Endowment with socio-demographic factors • Setup of relative weight for product attributes (for products initially available on the market) • Setting of initial (random) expectation about available products on the market • Setup of individual agent network based on socio-demographics
2)	Transition: Timeout	• Releasing of customer agents to the market in a gradual manner, i.e. in a uniformly distributed order to avoid synchronized use phases
3)	State: Need product	(No action)
4)	Transition: Condition	• Releases customer agents to the evaluation stage if products are available on the market (dependent on the configuration of each simulation run)
5)	State: Evaluate offers	(No action)
6) – 9)	Transition: Condition	• Choice of product providing the maximum expected utility
10) – 13)	State: Use phase	After deciding for one of the products on the market the customer agents switch to the use phase. • After use phase the actual utility is calculated and compared with the expected utility. • If the expected utility is greater or equal than the actual utility then the customer agent is "satisfied", otherwise "unsatisfied". • Communication topics are chosen. • The expected utility is updated with the actual utility.
15), 17)	Transition: Condition	• Only for the pay-per-use offer (after every 30 days): If the customer agent is "satisfied" after 30 days then the agent will choose to stay with the pay-per-use product for another use phase (15)). If unsatisfied the agent chooses to re-evaluate all offers on the market (17))
14), 18), 19), 20)	Transition: Timeout	• These timeout transitions specify the duration for which a customer agent stays in the use phase after deciding for a product.

Figure 13: Detailed statechart for customer agents

<u>Emergence</u>

The emerging demand for new product offers is quantified as a result of specific products advertised on the market and customer preferences resulting from the connection of socio-demographic factors, product utility, individual networks and communication events.

<u>Adaptation</u>

One adaptive trait is the awareness of product attributes which creates expectations. If one customer agent becomes aware of a product attribute and chooses to talk about it then this attribute is selected as communication subject. Other customer agents receiving information about this attribute will be made aware in case they receive information about it for the first time. Furthermore, during this event of communication customer agents also exchange their values on expected utility and relative importance of a product attribute. The extent to which these two factors are adopted depends on the parameters susceptibility to advertisement and follower tendency (ft) (Zhang & Zhang 2007). Susceptibility (sus) to advertisement stands for the perceived influence through advertisement while follower tendency stands for the perceived influence through inter-agent communication.

Objectives

Each customer agent's objective is to decide for the product offer on the market providing the maximum expected utility. Customer preferences can be represented by utility functions in order to make desire and preferences measurable and derive estimations about future demand. The underlying assumption is that if preferences can be represented by a utility function then demand can be concluded based on maximization of utility of a product. The utility of a product can be quantified as sum of all part worth utilities $u_{j_{exp}}$ resulting from product attributes j of a product. The maximum value of each of the part worth utilities ($u_{j_{max}}$) is normalized with 1. Then, the overall expected utility U_{exp} for each offer P can be described assuming a classic additive utility function:

$$U_{P_{exp}} = \sum_{j=1}^{n} u_{j_{exp}} \quad (eq. 1)$$

Learning

After the use phase the expected and the actual utility of each customer agent are compared to determine if the expectations after purchase and use have been met. If the overall actual utility of a product offer is greater than the overall expected utility the customer agent is classified as satisfied (otherwise unsatisfied). As a result of this post-purchase learning experience the current expected utility of that product is updated with the actual utility, which is then being considered in the following purchasing decision process.

Prediction

The expected utility for a product offer is a customer agent's value for anticipated utility. Each customer agent will chose the product offer that provides the highest expected utility, which then is compared to the actual value at the end of each use phase. The initial expected part utility $u_{j_{exp}}$ of an attribute is a random part utility between zero and $u_{j_{max}}$.

Sensing

A periodically scheduled communication event initiates inter-agent communication. This event chooses a random number of communication partners from each single customer agent's network (receivers) and sends a message to each of them (sender). If a product attribute has been chosen by a customer agent as communication subject the agent sends information about it, such as awareness and expected utility, to the receivers (descriptions on subject choice are outlined in section 2.3.2 "communication rationale and information exchange"). The customer agents receiving this message process the information that the sender has provided and in turn send a message back to the sender including their own communication subjects and contents.

Interaction

Customer agents can exchange information with each other based on their experience, which includes sensing as described above. A second interaction can take place with advertisement from manufacturing companies. It is assumed that advertisement of a product attribute j is associated with particular diffusion effectiveness, thus reaching only a fraction of the customer agent population per time unit.

Stochasticity

The most relevant stochastic processes in the AB model are the socio-demographic factors of the customer agent population, which are replicated based on statistics from the population in Stockholm. Furthermore, the two parameters *follower tendency* (ft) and *susceptibility to advertisement* (sus) are uniformly distributed across the entire customer agent population.

Observation

The data collected from all simulation runs are the aggregated number of customer agents in each use phase in order to identify the market shares of each product on the market over time. In parallel the diffusion of each product attribute for each product on the market is visualized as well as the count for communication occurrences per product attribute. The switching behavior from one to another product is also captured. In addition, the customer (dis)satisfaction is measured for the entire population over time. With this data thorough analysis of customer behavior can be carried out.

Initialization

Before starting the simulation, statistics about the target population is assigned which in this case described the city of Stockholm. This includes adjustment of the population density. The distributions for the socio-demographic factors are assigned as well as the behavior curves (introduced in the following section). For each simulation it needs to be determined what products and attributes are available from simulation start and what products and attributes will be added or changed during the course of the simulation (timing and intensity). The distribution of initially satisfied agents is specified as well.

2.3.2. Submodels: Concepts, coding and testing

This section introduces how the underlying factors and influences from Figure 12 have been converted to mathematical models, implemented using computer code as well as tested and calibrated where necessary.

Socio-demographic factors and behavior curves

The socio-demographic factors are used to form the initial perceived weight of product attributes such as price, environmental friendliness and service level. The forming of initial expected utility for a product attribute occurs as a result of behavior curves at population level. These behavior curves are input about assumed customer perception regarding each of the three product attributes. Given the hypothetical scenario of a circular business approach statements such as “very young and very old customer will favor service-orientation more than middle-aged customers” have been used to form assumptions about the relative importance of product attributes. These attributes are then mapped as an index i along the entire range of each socio-demographic factor. In doing so, a unit interval ranging from zero to one [0,1] is used while one stands for the maximum perceived importance and zero for no importance of any product attribute j. Figure 14 gives an overview of how attribute indices for price (i_p), environmental friendliness (i_e) and service-orientation (i_s) have been mapped for the socio-demographic factors income, age and education. To aggregate across all socio-demographic factors all attribute indices are added in order to obtain aggregated attribute index I per product attribute j:

$$I_j = \sum_{d=1}^{n} i_d \quad (eq. 2)$$

The example in Figure 14 results in the formation of individually perceived weight w for the attributes price (w_p), environmental friendliness (w_e) and service level (w_s). The weight w of product attribute j of any customer agent can be formulated as:

$$w_j = \frac{I_j}{\sum_{j=1}^{n} I_j} \quad (eq. 3)$$

It should be noted that the geographic location is solely included for the creation of network structures. The example shows a case in which one customer agent is aware of all three product attributes. If the same customer agent is not aware of e.g. environmental friendliness and service-orientation the weight for w_p would have been 1 whereas w_e and w_s would have been zero, since price in this case would have been perceived as the only relevant criteria by the customer agent.

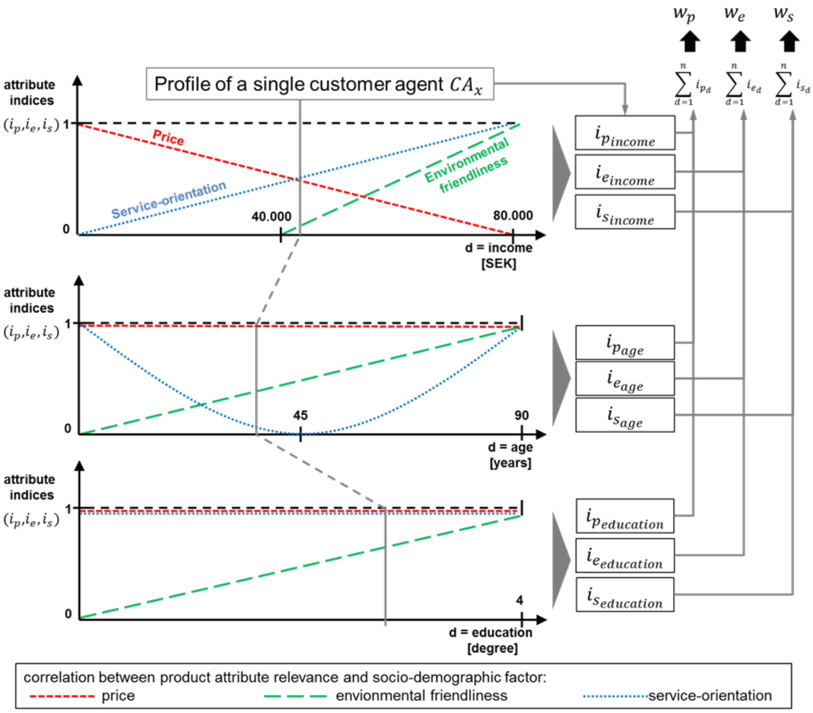


Figure 14: Behavior curves using attribute indices price i_p, environmental friendliness i_e and service-orientation i_s for socio-demographic factors income, age and education (assumed in collaboration with industry)

The following assumptions are made for the Stockholm population regarding the attribute indices for income, age and education level:

Income:

- The higher the income, the lesser the relative importance of price.
- The higher the income, the higher the relative importance of service-orientation.
- The higher the income, the higher the relative importance of environmental friendliness if above a certain threshold (mid-income).

Age:

- The higher the age, the higher the relative importance of environmental friendliness.
- Younger and older customers favor service-orientation more than mid-age customers (u-shaped curve for relative importance of service-orientation).
- The relevance of price is equal for all age groups.

Education level:

- The higher the education level, the higher the relative importance of environmental friendliness.
- The relative importance of price and service-orientation is equally relevant for all education levels.

The distributions for the socio-demographic factors are inserted at population level. The behavior curves are implemented at population level using table functions, which are functions defined in table form. Figure 15 shows a screenshot from table function in the Anylogic platform for the attribute index "price" as a function of income.

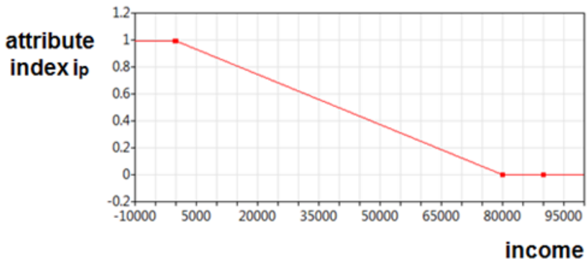


Figure 15: Attribute index "price" for the socio-demographic factor "income"

The table functions have been tested by providing a fixed income (e.g. 0) for the entire population in order to verify the expected attribute index (1 as a result of an income of 0). Socio-demographic data for the Stockholm area has been used from public databases (SCB Statistiska centralbyrån - Statistics Sweden 2014b) (City municipality of Stockholm - Stockolm stad 2014) (SCB Statistiska centralbyrån - Statistics Sweden 2014a). These socio-demographic factors have been inserted in the AB model at simulation start. Figure 16 shows how the obtained public data has been replicated and verified in the AB model.

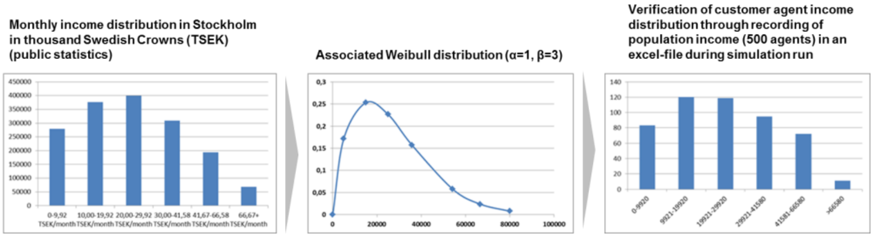


Figure 16: Replication and validation of income distributions using Weibull distributions and agent recording

Expected and actual part utilities

Part worth utilities are formed for each of the attributes i.e. the price, environmental friendliness and service level. In order to provide each customer agent with random expectations at simulation start, the initial expected part utility $u_{j_{exp}}$ for each agent is a random part utility between zero and $u_{j_{max}}$ generated through multiplication of a random number r (from a uniform distribution ranging from zero to one) with the agent's individual perceived weight w_j and $u_{j_{max}}$.

$$u_{j_{exp}} = w_j \cdot r \cdot u_{j_{max}} \quad (eq. 4)$$

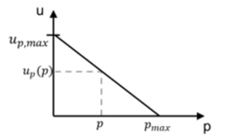
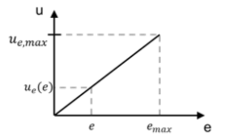
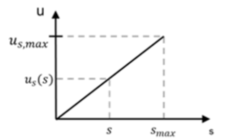
The maximum value of each of the part utilities ($u_{j_{max}}$) is normalized with 1. After the use phase the expected and the actual utility are compared in order to identify if expectations of the product have been met. As a result of the post-purchase experience the expected utility is updated with the actual utility at the end of each use phase, i.e.

$$U_{exp} = U_{actual} \quad (eq. 5)$$

Customer agents can influence each other's expectations of an attribute $u_{j_{exp}}$ if that attribute is chosen as subject for communication. Thus, as the number of agents and their parameters do not change during simulation the same customer agents can be exposed to the same market situation with changing expected utility but unchanged product offer. This feature enables the possibility to consider repeated purchase decisions and long-term adoption of customer agents.

Actual part utilities including price, environmental friendliness and service level are determined based on part utility functions as shown in detail in Table 2. These functions are generic for the entire customer population and are based on the case company's perception. At this point it is assumed for the Stockholm market that, while considering attributes independently, price increases tend to result in lower utility for customers. On the other hand, increases in environmental friendliness and service-orientation tend to result in higher utility.

Table 2: Summary of generic part utility functions for product attributes price, environmental friendliness and service-orientation

Product attribute j	*Part worth utility function $u_j(j)$*	*Graph of part worth utility function $u_j(j)$*
price (p)	$u_p(p) = u_{p_{max}} \cdot (1 - \frac{p}{p_{max}})$	
environmental impact (e)	$u_e(e) = u_{e_{max}} \cdot \frac{e}{e_{max}}$	
service-orientation (s)	$u_s(s) = u_{s_{max}} \cdot \frac{s}{s_{max}}$	

Part utilities $u_j(j)$ as a result from these generic functions in Table 2 are multiplied with the agent's individual weight for the respective product attribute w_j to reflect individual perception of that attribute after purchase. The actual overall utility $U_{P_{actual}}$ of a product offer P after use can be expressed as sum of its weighted utilities:

$$U_{P_{actual}} = \sum_{j=1}^{n} w_j \cdot u_j(j) \quad (eq. 6)$$

For the code implementation the following parameters, variables and functions have been used:

Parameters:

$a_{P,j}$	*awareness of attribute j of product P (Boolean: 0/1, default: false)*
$w_{P,j}$	*perceived weight for attribute j of a Product P*
P_j	*product on market with different attributes j*
p_P	*price of the product P (as advertised)*
e_P	*environmental friendliness of product P (as advertised)*
s_P	*service-orientation of product P (as advertised)*
satisfaction	*satisfaction parameter indicating if customer is satisfied or not (Boolean: true = "satisfied" / false = "unsatisfied"; default distributed across population 50/50)*
RV	*the monetary value that customer receives if product is returned, as part of the original purchasing price of a product (%)*
WillReturn	*customer agent decision parameter, which determines if buy-back product will be returned (true) or not (false) (default: false)*
I_j	*aggregated attribute index I for attribute j*

Variables:

$u_{P,j}^{exp}$	*expected utility of attribute j of product P (i.e. before purchase)*
$u_{P,j_{max}}^{exp}$	*expected utility of attribute j of product P (normalized with 1)*
r	*random number between 0 and 1*
$u_{P,j}^{actual}$	*actual utility of attribute j of product P (i.e. after purchase)*
U_P^{actual}	*overall actual utility for product P (sum of all part worth utilities $u_{P,j}^{actual}$) (after purchase)*
$w_{P,p}$	*perceived weight for price of a Product P*
$w_{P,e}$	*perceived weight for environmental friendliness of a Product P*
$w_{P,s}$	*perceived weight for service-orientation of a Product P*

Functions:

gpu_function$_j$()	*Generic part utility function for attribute j (see Table 2) returning part worth (between 0 and 1)*

Figure 17 provides an overview of the code used during implementation for expected and actual part utilities of the ABM.

line simplified code description

```
//initial random expected utility (formed on change of awareness variable a_{P,j}):
u_{P,j}^{exp} = r * w_{P,j} * u_{P,j max}^{exp}

//in case for the buy-back offer the customer agents decides if the product will be returned at the end of the use phase:

if r <= RV or 3*r <= I_p then
     WillReturn = true
else
     WillReturn = false
end if

//the actual part wort utilities are calculated for each of the product attributes p, e, s of a product P, if a_{P,j} is true:
//price
if a_{P,p} = true then
     u_{P,p}^{actual} = gpu_function_p(p_P)
     //for buy-back offer, if product is returned:
     u_{Buy-back,p}^{actual} = gpu_function_e(p_p*(1-RV))
           //check for validity:
           if u_{P,p}^{actual} < 0 then
                u_{P,p}^{actual} = 0
           else if u_{P,p}^{actual} > 1 then
                u_{P,p}^{actual} = 1
           end if
end if

// environmental friendliness
if a_{P,e} = true then
     u_{P,e}^{actual} = gpu_function_e(p_e)
           //check for validity:
           if u_{P,e}^{actual} < 0 then
                u_{P,e}^{actual} = 0
           else if u_{P,e}^{actual} > 1 then
                u_{P,e}^{actual} = 1
           end if
end if

// service-orientation
if a_{P,s} = true then
     u_{P,s}^{actual} = gpu_function_s(p_s)
           //check for validity:
           if u_{P,s}^{actual} < 0 then
                u_{P,s}^{actual} = 0
           else if u_{P,s}^{actual} > 1 then
                u_{P,s}^{actual} = 1
           end if
end if

U_P^{actual} = w_{P,p} * u_{P,p}^{actual} + w_{P,e} * u_{P,e}^{actual} + w_{P,s} * u_{P,s}^{actual}

//at the end of each product use phase comparison of the current expected and actual utilities results in customer (dis-)satisfaction

U_P^{exp} = u_{P,p}^{exp} + u_{P,e}^{exp} + u_{P,s}^{exp}

if U_P^{actual} >= U_P^{exp} then
    satisfaction = true
else if U_P^{actual} < U_P^{exp} then
    satisfaction = false
end if
```

Figure 17: Simplified code for expected and actual part utilities

The change of satisfaction level has also been verified by tracking single agents and visualizing their preferences. In Figure 18 two different time plots are shown. The time plot below visualizes a single customer agent's expected utility over time for a conventional sales offer (upper, green line) and expected utility of a competitive offer (lower, beige line). In the visualized duration the expectation of this customer agent for the conventional sales offer is slightly higher than for the competitive sales offer. For some short moments, however, the preference changes due to interaction with other customer agents in the network and adaptation of their opinion (which decays after a certain amount of time). As indicated by the parameter "Customer_satisfied" the customer agent is currently "satisfied" (true). At the end of the use phase, when expectations are updated with the actual utility, the customer turns "unsatisfied" (false) since the actual utility has been lower than the expected utility of that offer (in this case zero).

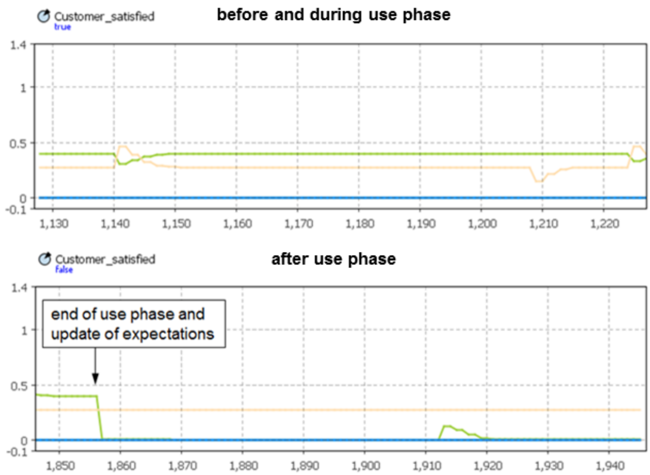


Figure 18: Time plots of a single customer agent showing the change from satisfactory to unsatisfactory state due to unfulfilled expectations (green line)

<u>Social network structure</u>

By applying the concept of homophily the probability of information exchange between two individuals depends on the similarity of their socio-demographic factors (Mcpherson et al. 2001). In comparison to a distance-based network this brings the advantage that inter-agent connections can occur even across larger distances since geographic distance is not the only measure for (dis)similarity. Furthermore, a network structure based on homophily appears more realistic as well as more practical since socio-demographic data are already applied in this AB model in order to characterize customer agents. So, the network creation is based on the social (dis)similarity s and defined as Euclidean distance D in all dimensions d (number of socio-demographic factors) (Wolf et al. 2015). Formally, the (dis)similarity between two customer agents x and y can be expressed as follows:

$$s_{xy} = \sqrt{\sum_{k=1}^{n} \left(\frac{d_{x_k} - d_{y_k}}{\max D_k} \right)^2} \quad (eq. 7)$$

Where d_{x_k} and d_{y_k} are the socio-demographic factors k for each of the two agents x and y, and $\max D_k$ is the maximum distance of the socio-demographic factor k across the entire customer population. A connection between the two agents x and y is established if a random number r following a uniform distribution falls below the following similarity tie weight θ_{xy}:

$$\theta_{xy} = 1 - \left(\frac{s_{xy}}{\max s} \right) \quad (eq. 8)$$

To give an example, if the two customer agents x and y have the same socio-demographic factors, then s_{xy} results in the value zero which in turn leads to a value of one for θ_{xy}. Since a random number r between 0 and 1 will always be smaller than or equal to 1 there is a probability of 100% that customer agents x and y would create a bond. The emerging network is static, i.e. once it is initialized in the beginning of the simulation it does not change over time.

For the code implementation the following parameters, variables and functions have been used:

Parameters:

i	*income*
a	*age*
e	*education*
l_x, l_y	*location (determined by x and y coordinates)*

Variables:

ca	*customer agent*
i_diff	*income difference*
a_diff	*age difference*
e_diff	*education difference*
l_diff	*location difference*
max_i_diff	*maximum income difference in population*
max_a_diff	*maximum age difference in population*
max_e_diff	*maximum education difference in population*
max_l_diff	*maximum location difference in population*
max_D	*maximum Euclidean distance in all dimensions*
ca_list	*list of customer agents*
s	*similarity factor*
max_s	*maximum similarity factor in population*
r	*random number between 0 and 1*
Θ	*tie weight*
v	*multiplication factor**

Functions:

maxFactor()	*Function that scans socio-demographic factors of the entire population to determine the maximum difference for each socio-demographic factor (max_i_diff, max_a_diff, max_e_diff, max_l_diff) as well as the overall Euclidean distance in all dimensions for that population (max_s max_D).*
abs()	*Function returning the absolute value of a number*
connectTo()	*Function that established connections between agents*

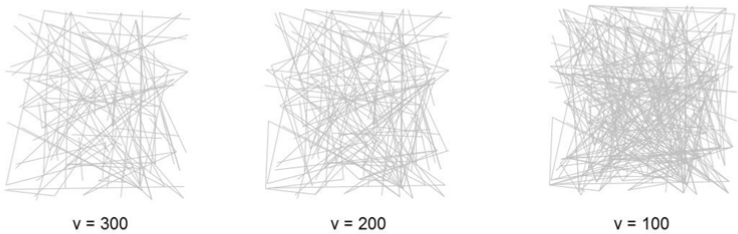
Figure 19 provides an overview of the code used during implementation to set up the social network structure of the AB model.

line simplified code description

```
maxFactor()
List <Customers> ca_List = new ArrayList<>()
  for all Customers do {
    ca_List.add(allCustomers)}
  end for
ca_List.remove(this)
for all ca ∈ ca_List do {
  i_diff = abs(this.i - ca.i)
  a_diff = abs(this.a - ca.a)
  e_diff = abs(this.e - ca.e)
  l_diff = abs(this.l - ca.l)
 s = sqrt (
  Math.pow((i_diff/max_i_diff),2)
  +Math.pow((a_diff/max_a_diff),2)
  +Math.pow((e_diff/max_e_diff),2)
  +Math.pow((l_diff/max_l_diff),2)
 )}
 r = uniform(0,1)
 θ = 1 - s/max_s
 if r*v < θ then
   connectTo(ca)
 end if
end for
```

Figure 19: Simplified code for emergence of social network structures

Figure 20 shows how the network structures have been visualized, tested, and calibrated using the population density of Stockholm city (SCB Statistiska centralbyrån - Statistics Sweden 2012). A network factor v has been introduced to further reduce and calibrate the probability that agents connect with each other. This has been based on initial test results, which indicated extremely dense network structures and the need for calibrating the average number of agent connection on individual level. As a result, an average of roughly five connections per agent was found as realistic.



Size of customer population	continuous space [m²]	network factor [v]	Average number of connections in population	Minimum number of connections in population	Maximum number of connections in population
250	69502,36	300	0,888	0	4
		200	1,296	0	5
		100	2,544	0	8
		50	**5,016**	**0**	**12**
		25	10,44	3	19
		10	27,08	11	45
500	139004,73	300	1,896	0	8
		200	2,7	0	9
		100	**5,484**	**0**	**14**
		50	11,084	2	22
		25	22,296	7	39
		10	55,66	29	80

Figure 20: Examples of identified continuous space values and network factors per population size for calibration purposes

Communication rationale and information exchange

A product attribute is chosen as subject for communication if the expected part utility of that product attribute is higher than the actual part utility at the end of the product use phase. For "satisfied" customer agents the probability of choosing a subject for communication depends on how much the actual utility of an attribute exceeds the expected part utility. The underlying assumptions on communication subjects is that negative experiences are always communicated (E. W. Anderson 1998) while positive experiences are communicated only to a certain extent. To give an example, in the moment of communication between two agents x and y their attribute weight and expectations are updated which can be formalized as:

Customer agent x:

$$u_{x,j_{exp}} = u_{x,j_{exp}} + ft_x \left(u_{y,j_{exp}} - u_{x,j_{exp}}\right) \quad (eq. 9)$$

and

$$w_{x,j} = w_{x,j} + ft_x\left(w_{y,j} - w_{x,j}\right) \quad (eq. 10)$$

Customer agent y:

$$u_{y,j_{exp}} = u_{y,j_{exp}} + ft_y\left(u_{x,j_{exp}} - u_{y,j_{exp}}\right) \quad (eq. 11)$$

and

$$w_{y,j_{exp}} = w_{y,j_{exp}} + ft_y\left(w_{x,j_{exp}} - w_{y,j_{exp}}\right) \quad (eq. 12)$$

In order to model a realistic effect of information exchange the decay of information content over time is considered. This allows for customer agents to return their original, i.e. intrinsic, values of expectation after an interaction event. Thus, it is assumed that the impact of information content declines over time which is considered through $e^{-\sigma \cdot t}$ where t is the current simulation time and σ an exponential information decline factor. To remind the reader, the follower tendency (ft) is the influence from other customer agents (peers), while susceptibility (sus) is the exposure to marketing campaign (advertisement). Assuming the interaction of agent x with agent y occurs at t while agent x has been exposed to advertisement at $t-z$, then the update of agent x's expected part utility at t can be calculated as:

Customer agent x at $t-z$:

$$\begin{gathered} u_{x,j_{exp}} = u_{x,j_{exp}} \\ + \left(ft_x\left(u_{y,j_{exp}} - u_{x,j_{exp}}\right)\right) \cdot e^{-\sigma \cdot t} \\ + \left(sus_x\left(u_{j_{max}} - u_{x,j_{exp}}\right)\right) \cdot e^{-\sigma \cdot (t+z)} \quad (eq. 13) \end{gathered}$$

Customer agent y (not having been exposed to advertisement):

$$u_{y,j_{exp}} = u_{y,j_{exp}} + \left(ft_y\left(u_{x,j_{exp}} - u_{y,j_{exp}}\right)\right) \cdot e^{-\sigma \cdot t} \quad (eq. 14)$$

Note that with each single event of interaction the information value decline $e^{-\sigma \cdot t}$ starts with a count at $t = 0$.

For the code implementation the following parameters, variables and functions have been used:

Parameters:

$a_{P,j}$	*awareness of attribute j of product P (Boolean: 0/1, default: false)*
P_j	*product on market with different attributes j*
ft	*follower tendency*
sus	*susceptibility for advertisement*

Variables:

ca_partner	*customer agent which is a communication partner in the network*
numberConnections	*number of connection that a customer agent has*
r	*random number between 0 and 1*
sender	*customer agent that has sent a message*
$u^{exp}_{P,j}$	*expected utility of attribute j of product P*
$c_{P,j}$	*choice of attribute j of product P as communication subject (Boolean: true/false)*
$\Delta u^{exp}_{P,j}$	*changed expected utility of attribute j of product P after customer agent interaction*
c_r	*Communication probability with value between 0 and 1*
t_count	*time counter beginning at the moment of information exchange*
decay_stop	*maximum duration of decay until reaching to original level (set to 50 days)*
σ	*information decay factor (set to -0,1)*
e	*Euler's number*

Functions:

send()	*Function sending a message to a specific recipient*
getConnectionsNumber()	*Function returning the number of connects that a customer agent has*
getRandomConnectedAgent()	*Function returning a random agent in the network*
set_Parameter()	*sets parameter with new value*
abs()	*Function returning the absolute value*
currentTime()	*returns the current simulation time*

Figure 21 provides an overview of the code used during implementation for communication events in the ABM.

simplified code description

```
//Choice of communication topics after use phase
if abs(u_P,p^actual - u_P,j^exp) >= r or (u_P,p^actual - u_P,j^exp) < 0 then
        c_P,j = true
else
        c_P,j = false
end if

//sender:
numberConnections = r * getConnectionsNumber()

for (int i=0; i<=numberConnections; i++){
    ca_partner=this.getRandomConnectedAgent()
    send("message", ca_partner)}
end for

//receiver:
for all P_j ∈ P {
    if sender.c_P,j = true then
        set_a_P,j(true)
        Δu_P,j^exp = ft*(sender.u_P,j^exp - u_P,j^exp)
        //in case of advertisement:
        Δu_P,j^exp = sus*(sender.u_P,j_max - u_P,j^exp)

        if abs(sender.u_P,j^exp - u_P,j^exp) >= c_r then
            sender.c_P,j = true
        else
            sender.c_P,j = false
        end if
    end if
   t_count=0
}
end for

//information decay per attribute:
decay_stop = currentTime()+50
if currentTime() < decay_stop then
   t_count++
        Δu_P,j^exp = Δu_P,j^exp * e^(σ*t_count)
        u_P,j^exp = u_P,j^exp + Δu_P,j^exp
else
   t_count=0
end if
```

Figure 21: Simplified code for communication events

The communication and information exchange intensity has been tested on single customer agent level with different values of follower tendency and different numbers of agent connections. The result of the test is shown in Figure 22 in which the expected part worth utility for two products attributes (green and brown) have been visualized over time and for different follower tendency (0,1 and 0,95) as well as number of connections in that agent's network (5 and 35). As it can be seen on the left-hand side of Figure 22, there has been one event of information exchange with another customer agent regarding the green attribute.

Based on the follower tendency, the degree of adoption and resulting amplitude is different. On the right-hand side the same agent is put in a larger network while being exposed to more frequent communication events. As can be seen, a higher degree of follower tendency and larger number of communication partners result in more oscillating expectations for both attributes.

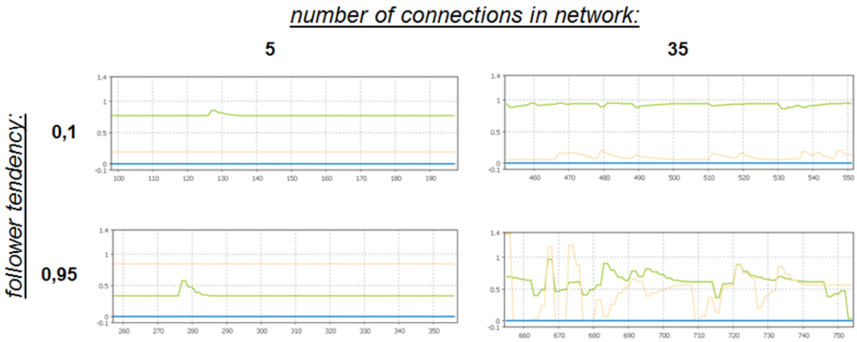


Figure 22: Effect of different degrees of follower tendency and number of connections on customer agent expectations

3. Research contributions

This chapter summarizes the research contributions posed in section 1.3 in relation to the appended papers.

In section 1.5 a list of appended papers is provided, which have been published during the course of this research work. In the following subsections all four research questions mentioned in section 1.3 are addressed and answered by summarizing contents from the appended papers. Details on the contents contributing in answering the research questions can be found in the appended papers.

3.1. Response to research question 1

What are main factors of resource efficiency and how can resource efficiency be assessed comprehensively?

Studies focusing on resource efficiency in production systems mark the starting point of this research. In the following case study operational resources, i.e. material, energy, machining equipment and staff, are assessed. The resource efficiency assessment approach has been developed for production systems of discrete part production.

Scope of resource efficient production systems

Referring to the concept of productivity, resource efficiency can be expressed as how well human as well as physical resources are utilized in order to achieve a desired output. Figure 23 delimits the scope of resource efficiency to the upstream side of the value chain.

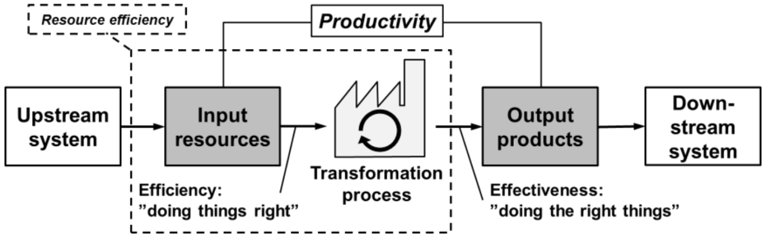


Figure 23: Concept of resource efficiency as part of productivity rationale based on (Lieder 2014) (Tangen & Stefan 2005)

Resource efficiency improvements are of interest for manufacturing companies as the amount of utilized resources can be reduced while maintaining the output of the production system. This increases the value added per resource used and is expected to result in lower cost and lower environmental impact per unit produced.

Resource efficiency assessment

In order to comprehensively assess resource efficiency in production systems a new approach has been proposed and tested with an industrial case study. This assessment approach contains two main perspectives. The first perspective is quantified efficiency of physical resource consumed is quantified for material, energy, staff and equipment (Lieder 2011). The second perspective is business-related and considers the allocation of resource costs to each of the physical resources. These two views are supposed to comprehensively quantify efficiency losses and potentials of production system operations. The stepwise assessment approach, which has been used is described below and is shown in Figure 24.

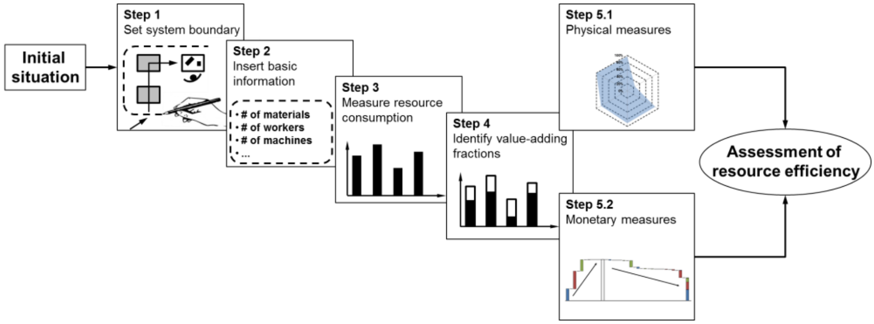


Figure 24: Steps of assessment approach

Step 1: Determination of system boundary for the assessment

Step 2: Definition of production facilities inside the boundary

Step 3: Measuring of actual resource consumption

Step 4: Identification of value-adding fractions

Step 5.1: Calculation of physical efficiency

Step 5.2: Allocation of direct resource cost

In step 5.1 the actual consumption is related to a theoretical optimum, which consists of the value-adding fractions. To give an example, for material efficiency the weight of the final product has been related to the weight of the raw material entering the system boundary of the assessment. In the case of energy efficiency the energy consumption during machining cycles has been considered as value-adding, without the baseline consumption. Corresponding formulas are listed on the right-hand side in Figure 25. The entire assessment approach has been tested in a small and medium-sized enterprise (SME). The results of step 5.1 and step 5.2 of the assessment are shown in Figure 25 and Figure 26 respectively.

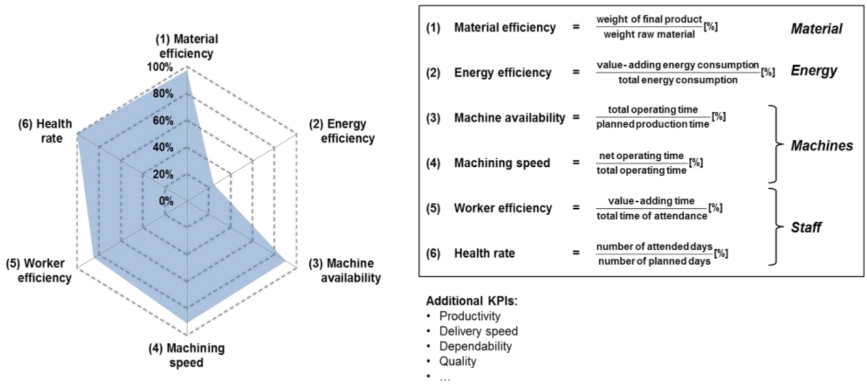


Figure 25: Physical resource efficiency measures

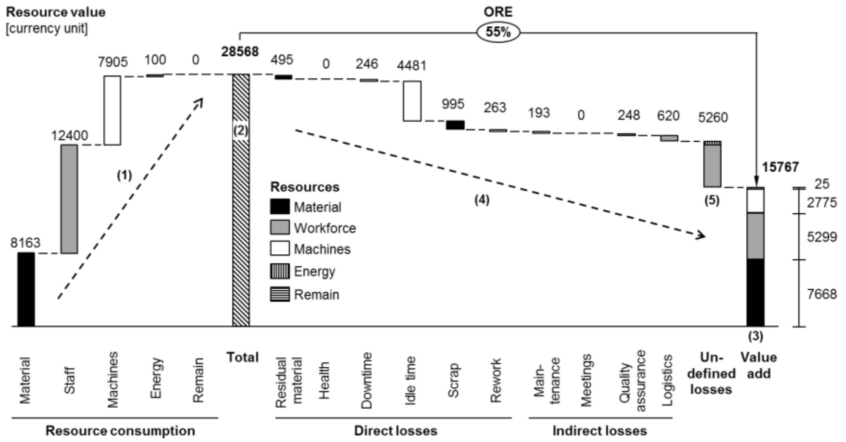


Figure 26: Monetary resource cost allocation

Assessment results

For the given SME case the radar chart in Figure 25 indicates that roughly 25% of all energy consumed is used for value-adding part production. Considering the monetary perspective in parallel, energy cost make up an extremely small fraction of the total direct resource cost (left-hand side in Figure 26). The SME processes discrete parts with mainly machining and assembly operations. As a consequence, the embedded energy content per unit produced is relatively low compared to other industries. Hence, in the given setting an increase in energy efficiency would not result in significant cost-related benefits due to its low cost in relation to other resources. It appears that idle time of the machining equipment and undefined losses of the work force hold greater potentials in terms of cost (Figure 26).

As a result of the resource efficiency assessment decision makers concluded to investigate material suppliers or renegotiate purchasing prices as first step with the aim to reduce material cost. In the second step internal improvement projects could be considered to tackle efficiency losses. Even though the decision makers claimed to be environmental conscious in general, an increase in energy efficiency for the production system at hand was not perceived as strategically relevant. This has been justified with the situation of the SME being an n-tier supplier under cost pressure without any strategic advantages of investing in a green image.

Discussion on industrial competitiveness

Based on the results and discussions above the following findings can be highlighted when it comes to resource efficiency assessment.

- Methods and tools to increase resource efficiency on production system level aim at quantifying monetary cost saving potentials of operational resources material, energy, staff and equipment. The resulting benefits contribute to competitiveness of the manufacturing business in terms of an improved internal cost structure due to increased productivity.

- Resource losses can be minimized to improve the performance of the production system by using an input-output model for the production system boundary. Taking this internal view, the largest potentials could be identified in the area of machining equipment and worker's operations (staff). On the other hand, the monetary potential of energy efficiency increases is relatively low. This is in line with other resource efficiency analyses carried out in European SMEs of discrete part production where the aggregated quantified monetary potential of energy savings is extremely low compared to the potentials of machining equipment and staff (Slawik 2012).

- Provided the case study at hand, anticipated larger potentials for reducing material cost may be sought outside the production system boundary, i.e. in the upstream and/or the downstream value chain. As the value-addition in terms of material cost is roughly 50% with an efficiency of 94%, re-negotiations with suppliers to lower material cost seem more feasible than initiating internal improvement projects to tap the 6% of material efficiency losses based on cut-off material (which usually involves changes in technology and capital-intensive structural changes).

One major potential for improved competitiveness for the case company lies in reducing material cost and material dependency. Simultaneously, it can be argued that there is a risk for the case company consisting of price volatility of the material, given its relatively high material efficiency and share of monetary value-add (Figure 26). In this scenario, the benefits of resource conservation through e.g. reuse or remanufacturing would generate cost savings of up to 50% in an ideal case, which would significantly improve cost structure and performance of the case company. However, realizing these potentials requires a strategic perspective to include stakeholders in the upstream and the downstream supply chains. In its current form, the study scope of resource efficiency is limited to a single production system leading to isolated solutions in linear production settings as operations are still carried out in a take-make-sell manner. Most importantly, challenges of sustainability and resource scarcity remain inadequately addressed since a fundamental assumption at the basis of resource efficiency approaches is that resources are available infinitely. This shortcoming is particularly critical since manufacturing industry is one of the main resource consumers on a global scale.

In order to address all of the identified shortcomings simultaneously, a change in perspective is required. In doing so, the scope needs to expand from production systems (operations) to manufacturing systems (functions) to account for comprehensive understanding of resource flows while considering industrial competitiveness. The ResCoM framework advocates such *system perspective* as it takes into account various actors and functions in the manufacturing value chain, by simultaneously considering business models, product design, supply chain and technology.

3.2. Response to research question 2

How much the current research has explored and supports the idea of circular (closed-loop) manufacturing systems, characterized by reuse, remanufacturing and recycling, in the context of economic benefits, resource scarcity and waste generation?

As mentioned previously, a system perspective has been adopted expanding the scope from production systems to manufacturing systems level with circular (closed-loop) characteristic. The concept of circularity can be seen emerging now and then throughout the history, especially in terms of closed material loops. There have been attempts to respond to challenges of resource scarcity, environmental impact or economic benefits or combinations of these by governments, industries and societies around the world. However, major part of these attempts has been lacking a systemic and systematic approach and therefore the CE approach appears not only apposite but also inevitable.

Therefore, in order to answer the research question above, a comprehensive review has been carried out. It has been investigated in what contexts CE has been researched so far to explore a comprehensive CE perspective which covers aspects of *resources scarcity*, *environmental impact* and *economic benefits* simultaneously. This will facilitate the proposition of a framework to be used as a CE implementation strategy for manufacturing industry.

Present circular economy landscape

Figure 27 provides an aggregated overview of relevant academic literature including their geographic focus since 1950. Accordingly, there has been a strong publication increase in the field of CE with a peak in this year 2015. As can be seen, the number of publications has nearly tripled since the beginning of this decade and doubled in the last three years (27 publications in 2015 by June in comparison to 14 publications in 2012 and 10 publications in 2010). Another notable result is a strong publication record for CE research with explicit focus on issues within China, which makes up the majority of all CE research articles (54%) and exceeds the sum of geographically independent research (roughly 36%). Few studies in the field of CE have been performed with focus on global regions other than China. These make up about 10% of the investigated CE research articles of which more than half have a geographic focus on Europe. It is worthwhile to note that China's enormously high publication record seems to be the consequence of China's CE strategy which took effect in January 2009 (The Standing Committee of the National People's Congress China 2008). Since the approval of this law major attention has been given towards implementation of a CE on corporate, inter-firm and social level. There appears to be a general increase of interest in CE considering the increasing number of geographically independent research articles after 2010.

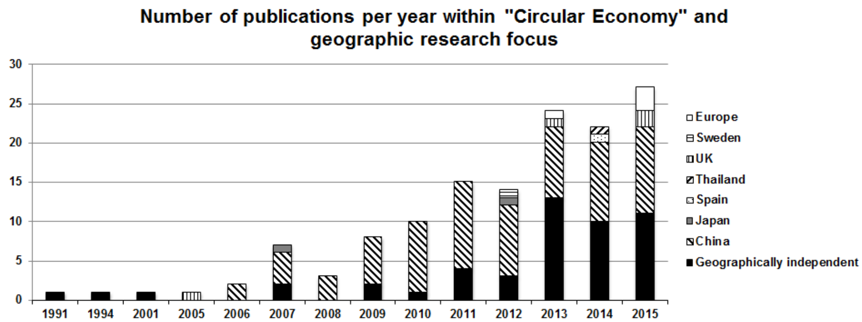


Figure 27: Distribution of reviewed academic publications including geographic focus in which CE has been published without specified research perspective

The largest share of CE research is done from the perspectives of resource scarcity and environmental impact, as shown in Figure 28. However there is also considerable CE research which takes into account economic benefits in addition to perspectives of resource scarcity and environmental impact.

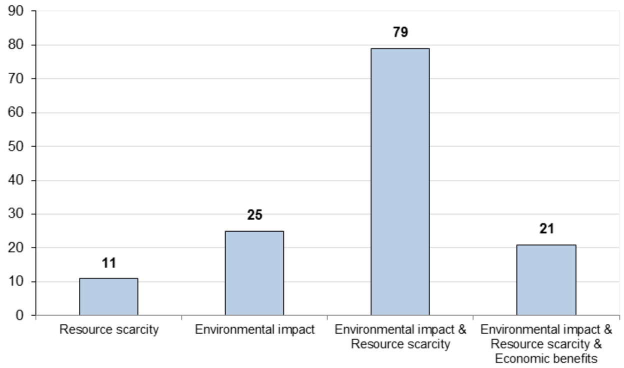


Figure 28: Summary of research articles analyzed from the perspectives "resource scarcity", "environmental impact", "economic benefits" and their combinations

The identified articles have been categorized further into two sub-categories, i.e. *research field* as well as *type of research*. As a result of the categorization and review nine research fields have been identified, which have performed research towards CE:

- Industrial ecology
- Environmental science
- Management and economics
- Business management
- Supply chain management
- Sustainability science
- Process engineering
- Management and law
- Social science

In order to obtain an overview about the type of research that has been performed in each research field three sub-categories have been formed:

- Review studies on previously published literature, which may include discussions on existing concepts to propose new ones.
- Specific studies limited to particular industries and/or geographic regions including empirical analyses. This type of research may also contain experimental setups.

- Development work resulting in frameworks, tools, models and methods for decision-making support towards CE implementation. This type of research may include conceptual as well as empirical studies to motivate the purpose of the development.

Since a major share of articles identified focus on China as a result of the "Circular Economy Promotion Law of the People's Republic of China" all articles were in the first step clustered geographically, which has led to a categorization into *research specifically targeting implementation of CE in China* and *geographically independent CE research*.

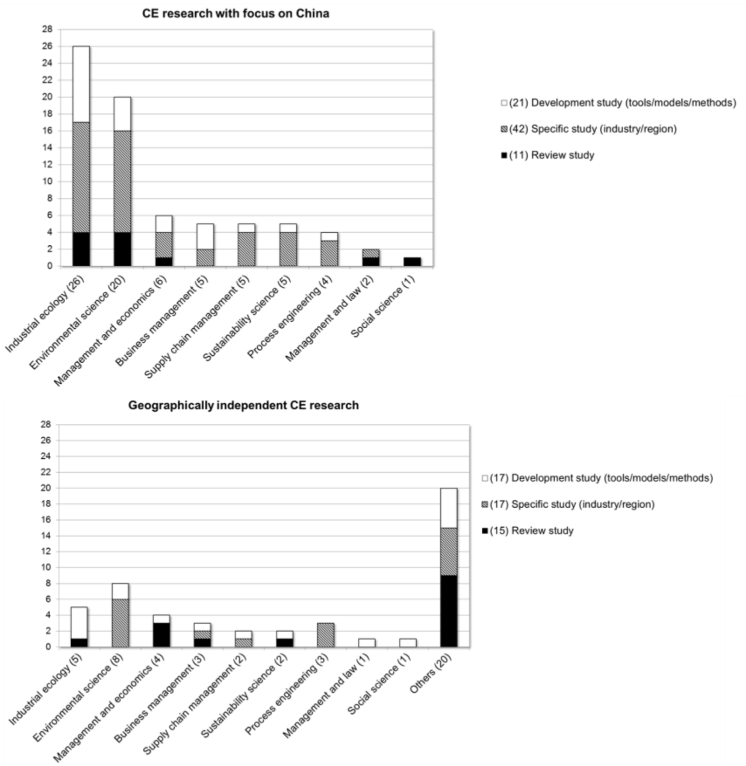


Figure 29: Number of research articles with explicit focus on China and geographically independent CE research, categorized into research field and type of research

Geographically independent CE research in this context stands for research which is not linked to a strategy of a particular geographic region. Figure 29 provides an overview of the literature analysis. The largest share of CE research has been done with focus on China in the fields of industrial ecology and environmental science. Especially, case studies of Chinese regions or industries are relatively high in number. In comparison, geographically independent CE research is by far more diverse and hence more challenging to characterize since it does not align with an overall formalized strategy as in the case of CE research in China. Consequently, the identified research is spread over a broader range of research fields as indicated in Figure 29. Moreover, geographically independent research includes further research fields summarized under “others”. These additional research fields are diverse and comprise material science, chemical engineering, industrial design, ecology, education, waste management, information and communication technology, applied physics and mathematics as well as architecture.

During the course of the review further related areas linked to CE-thinking have been identified and grouped to the following themes (detailed descriptions can be found in paper B):

- Transformation of economic structures and business rationales
- Regenerative design and critical materials
- Industrial ecology
- Remanufacturing and closed-loop supply chains
- Resource conservative manufacturing
- Governmental CE initiatives

Critical discussion of the state of the art research

From state-of-the-art review it can be concluded that a growing amount of research holds the concept of CE as accepted and desired to be implemented. Assuming lasting interest in the field of CE in China as well as in the global research community, it can be expected that the number of CE-related research articles will continue growing (Figure 27). Even if research shows that the comprehensive CE perspectives of resource scarcity, environmental impact and economic benefits are covered two major results can be highlighted:

- the coverage of the investigated CE research landscape is fragmented
- the level of discussion is highly granular and rarely touching implementation level

Most relevant, analyses and discussions about CE and towards CE development are to the largest extent done from a resource scarcity and environmental impact perspective. Economic benefits for industrial actors are in general weakly represented and remain missing on single company level. This shortcoming in the parent CE research landscape is critical considering the fact that manufacturing in general strive after gaining economic benefits. CE-relevant functions, such as business models, product design, supply chain design and choice of material are in control and hence finally determined by manufacturing companies. These activities are essential for successful CE implementation and require alignment to ensure economic viability. However, as these aspects have not been highlighted much in research it is likely that a transition towards the CE will not appear favorable for manufacturing companies since it will be perceived as constraint to industrial activities rather than an opportunity for sustainable business and growth.

There are few research efforts and frameworks that have included economic benefits or competitive advantages. On operational level often these issues are addressed by conventional closed-loop supply chains where products are neither designed nor manufacture to facilitate loop-closure by intent. Moreover, stakeholders identified usually remain the governmental bodies excluding manufacturing industry.

In summary, the prevailing CE research highlights elements of the three comprehensive CE perspectives resource scarcity, environmental impact and economic benefits. However, given the aforementioned arguments the current CE research horizon cannot yet be described as comprehensive, thus requiring a framework necessary to facilitate a successful transition from linear to CE. The comprehensive CE perspectives involve an environment where all interests of stakeholders and motivation are equal and where businesses, natural resources as well as waste and environmental aspects are considered including their dynamic relationships.

Comprehensive CE framework

In order to deal with the lack of a framework the comprehensive CE perspective emphasizes a combined view on resource scarcity, environmental impact and economic benefits. Figure 30 illustrates a comprehensive framework for CE based on these three perspectives including their relationships.

- Economic benefits in CE: Each individual company strives for gaining economic benefits in order to secure profitability and a competitive edge. This requires an integrative approach towards business models, product design, supply chain design and choice of materials.

- Resource scarcity in CE: Social prosperity depends on planet earth's finite resource supplies which makes regenerative use of resources mandatory for CE realization. The underlying factors in this context concern circularity of resources, material criticality and volatility of resources in wake of globally increasing prosperity and thus number of industrial activities.

- Environmental impact in CE: A society with minimum environmental impacts is an essentially desired status of nations, governmental bodies and individuals around the globe. CE aims at reducing waste, landfills and emissions through activities such as reuse, remanufacturing and/or recycling.

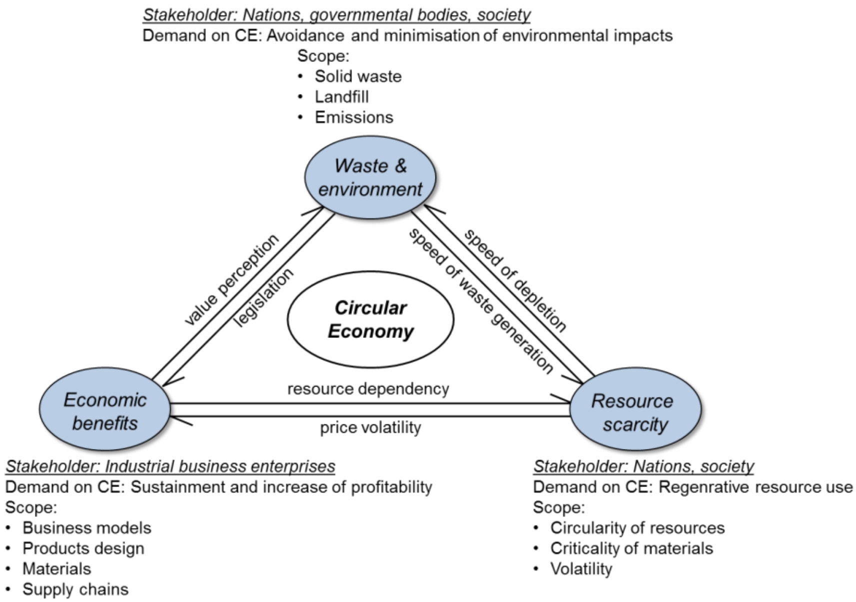


Figure 30: A comprehensive CE framework

Resource scarcity, environmental impact and economic benefits cover short-term as well as long-term objectives and are seamlessly linked in this CE framework. As each of the three perspectives has a systemic view with specific boundaries the relationships among the perspectives need to be described.

To gain economic benefits industrial activity fundamentally depends on resources necessary to perform manufacturing operations and transform raw materials into products and services. As a result, resource price volatility and supply risks have direct influence on the competitive edge of companies and their capability of performing their industrial activity in a sustainable and profitable manner.

At the same time, while pursuing economic benefits, industrial activity influences the natural environment, as e.g. through waste generation in a linear system. Perceiving end-of-life products/materials as resources rather than waste involves management of resource value as part of standard business operations. The approach of resource value management stands in contrast to the conventional “waste management” approach in the prevailing linear economy and does not differentiate between “waste” and “resources” (as nature does not distinguish between these two either). In response to waste generation the connotation is rather negative resulting in restricting legislation to reduce environmental impacts, thus affecting competitiveness. On the other hand, value management suggests an industrially driven connotation as resources are managed based on value maximization.

In a CE the speed of resource depletion and waste generation are reduced. In a rapidly growing population the speed of resource depletion and waste generation will be swelling in a linear economy.

Practical implementation strategy for CE

In order to give a practical way forward on how to implement CE at large scale Figure 31 suggests a concurrent approach which operates through public institutions from top-down and through industry from bottom-up. The motive for proposing a concurrent top-down and bottom-up approach contains the assumption that inverse motivations exist among the stakeholders of CE which need to be aligned and converged. Governmental bodies and policy makers advocate a collective consciousness about environmental issues as well as societal benefit of industrial activities. Hence, there is a notion of minimizing environmental impact by strict control of industrial businesses. On the contrary, manufacturing companies possess awareness about environmental impacts of their industrial activities. However, due to competitive pressure environmental impacts will most likely remain secondary consideration as primary focus is put on economic benefits and growth. Given the scenario that industrial businesses do not see (economic) advantages, the concept of CE will result in reluctance when it comes to pursuing CE-initiatives. This scenario makes a concurrent process obligatory to converge and compromise interests of public institutions (top) and multiple industrials actors (bottom). Prioritization of economic growth at the expense of the environment as well as compromising economic gains for lower environmental impact needs to be averted. Ultimate objective is the achievement of the CE, i.e. an economy which is environmentally and economically regenerative. Figure

31 conceptually illustrates the collective nexus which stands for convergence of all relevant stakeholders.

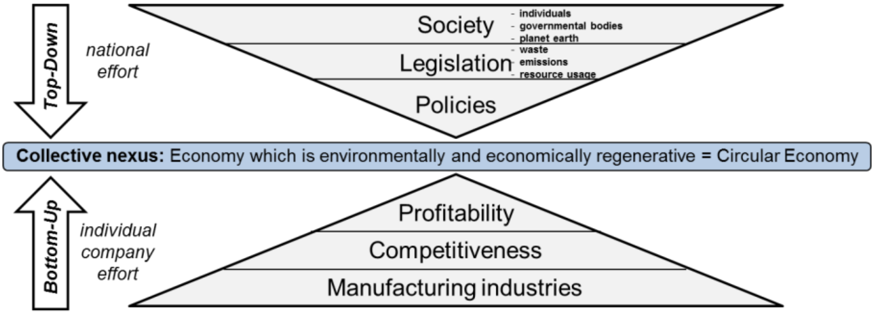


Figure 31: Proposed CE implementation strategy applying top-down and bottom-up approach

Feasibility of such CE implementation strategy is related to the following areas which are supportive in highlighting future research.

Top-Down:
- Legislation and policy
- Support infrastructure
- Social awareness

Bottom-Up:
- Collaborative business models
- Product design
- Supply chain
- Information and communication technology (ICT)

The developments in the following sections focus on the bottom-up approach for manufacturing industry.

3.3. Response to research question 3

How can customer behavior be assessed and determined on whether introductions of new (circular) business models will be accepted/rejected considering that customers are perceived as integral part of the circular manufacturing enterprise?

As indicated in the previous section, most of the CE relevant research has been carried out from the perspectives of waste generation, resource use and environmental impact while leaving business and economic perspectives aside. To reminder the reader, in industrial practice a transition from a linear (take-make-dispose) to a circular manufacturing system (considering reuse/remanufacturing/recycling) requires the change of value propositions. In doing so focus of the value proposition switches from selling a physical product to providing access to functionality through business innovation. It is particularly challenging to understand what complexity a new concept like CE brings to established businesses, where the success and failure of business is dependent on customer's acceptance of new value propositions. As a consequence, CE business transitions bring manufacturing companies to an uncertain situation since the effects of business model changes are unknown. This scenario also poses the risk of inhibiting CE implementation as advantages for industry are not explicit.

In this context two distinct studies have been carried out in this research work. The first study is based on the development of an AB simulation tool to enable assessment of customer behavior as a consequence of business model innovation (paper D). This AB has been developed and implemented based on the rational presented in section 2.3. The second study is an empirical market study to explore the perception of circular business approaches using the method of conjoint analysis (paper F). Both studies use a washing machine case as practical example.

In order to ensure alignment with business thinking and to motivate manufacturing companies to consider new (circular) business models, some fundamental assumptions are made in case of both studies:

1) It is assumed that manufacturing companies consider providing access to function rather than ownership. Thus, washing machines are offered with different prices and payment schemes since customers pay for the access. This may for example be a fee “per use” as alternative to acquiring ownership through product purchases. However, it is necessary to consider the possibility that a share of customers might perceive ownership as positive product attribute, thus resulting in an overall rejection of service-oriented offers.

2) Furthermore, the products are returned to the manufacturing companies after use for the purpose of value recovery and reuse. Key steps of remanufacturing as an industrial process are defined as disassembly, cleaning, inspection and sorting, reconditioning and reassembly (Steinhilper 1998). Durable products (like washing machines) are restored to a new-like condition through these processes. Hence, remanufactured products provide the same functionality (same electricity and water consumption) and same quality as a new product or better.

3) As a consequence of giving washing machines another life instead of manufacturing them with virgin materials results in lower environmental impact. The resulting environmental benefits in the form of, for example, less CO_2 emissions or materials saved are part of the new value proposition and considered in marketing activities to increase customer preferences for the product.

4) Moreover, the shift from conventional sales towards service-oriented offers allows manufacturing companies to explore and offer additional service elements, such as free maintenance or free upgrades. This is assumed as part of a service innovation process where manufacturing companies need to develop their abilities to build relationships with customers and focus on the service-related value of their offerings with the objective to advance a dynamic service offering portfolio that is adaptive to changing customer needs (Kindström 2010).

In summary, the CE value propositions of industrial interest are composed of attributes including *price and payment scheme*, *environmental friendliness* and *service level*. Based on the adoption/rejection of these attributes the business potential and risks of circular approaches are evaluated in both papers. The attribute service-level implies “convenience” for customers as it is not necessary for the customer to pay a large lump sum before utilizing the product or to provide storage space for the product after the use phase. On the contrary it needs to be considered that a share of customers might perceive ownership as a positive product attribute, thus resulting in an overall rejection of service-oriented offers such as pay-per-use.

Agent-based customer model

In order to bring forward a development in the form of an ABM, which considers the CE perspective, a conceptualization of purchase decision-making processes on individual customer level is necessary. On the left-hand side of Figure 32 a purchase decision-making process is shown, which has been adapted from section 2.3. To recall, this decision-making process in purchase of commodities can be commonly described as a cognitive process of five stages including:

1) Need recognition, which can be triggered by internal as well as external stimuli
2) Search for information in order to find a solution for the identified need
3) Evaluation of different solutions on the basis of varying product attributes
4) Purchase decision where the actual purchasing transaction takes place
5) Post purchase behavior in which products are compared with expectations resulting in satisfied or unsatisfied customers

This process, as illustrated in Figure 32 forms the basis for the tool development. In this context, there are three fundamental stimuli affecting purchase decisions:

Internal stimulus:

- Individual preferences as a result of socio-demographic factors, such as income, age, geographical location, education, etc.

External stimulus:

- Interaction with company information such as price or through, for example advertisement
- Interaction with other customers in an individual social network, for example through word-of-mouth

For a comprehensive model the given concept needs to be extended in order to account for underlying factors and influences. These underlying factors and influences constitute submodels of the ABM, which are modeled and described independently (section 2.3.2). Figure 32 provides an overview of all underlying factors and influences included in the ABM.

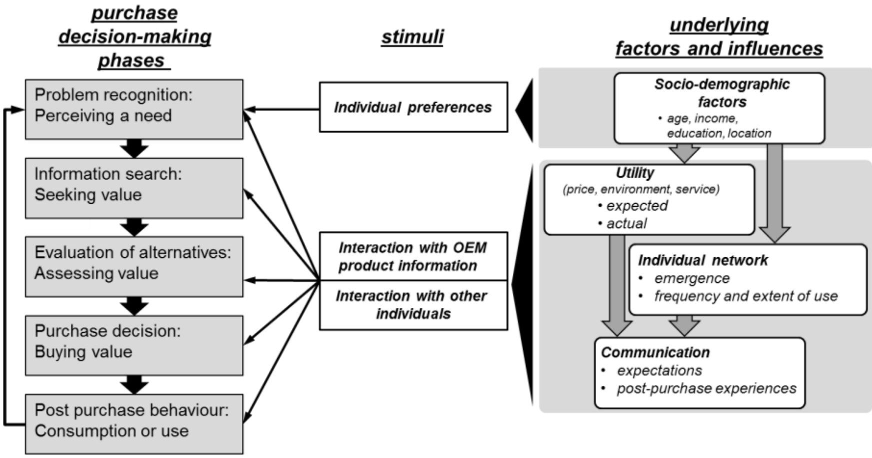


Figure 32: A schematic customer purchase decision model including three stimuli and underlying factors and influences

In summary, each single customer is repeatedly passing through the purchase decision-making phases (left side in Figure 32). In doing so, expectations about offers are updated after purchase and use as well as information is exchanged over time with other customers. All underlying factors and influences have continuous effect on the stimuli which make the purchase decision-making process highly dynamic and complex.

For the given boundary of the model, the assumptions and initial data used (listed in paper D) in the tool creates different demand streams for different products on the market. The simulation time encompasses 20 years in total. Starting from an initial linear scenario, which represents a business-as-usual case, a competitive market is assumed and represented by one conventional sales offer and one competitive sales offer. One of three scenarios tested in paper D is presented below. In this scenario a pay-per-use offer is introduced at year 5 (t = 1827 days) of the simulation run. Table 3 provides an overview of product offers and corresponding constellation of attribute values.

Table 3: Product offers and their attribute value for washing machines (WMs)

Attribute	*Conventional sales*	*Competitor sales*	*Pay-per-use*
Price & payment scheme	12000 SEK/WM (use phase 7 years)	8000 SEK/WM (use phase 5 years)	300 SEK/month (use phase 30 days)
Environmental friendly	no	no	yes
Service level	no service	no service	1) full maintenance 2) flexibility to change WM

Figure 33 shows market share, customer satisfaction, diffusion of attributes and communication occurrences of the simulation run. Launching the pay-per-use offer at t=1827 with the attributes price, environmental friendliness and service-orientation demonstrates a rapid diffusion of the price attribute (Figure 33 (c)). The attributes, service level and environmental friendliness, diffuse rather gradually and seem less relevant. Diffusion and communication about the attributes environmental friendliness and service level show greater variation during several simulation runs. The variations are caused by different network structures which are newly created at the start of every simulation run. In addition, the pay-per-use offers are re-evaluated by the customers every 30 days. This leads to more frequent updates of experiences and communication subjects over time and a more spread and less controllable diffusion compared to the offers with longer use phases.

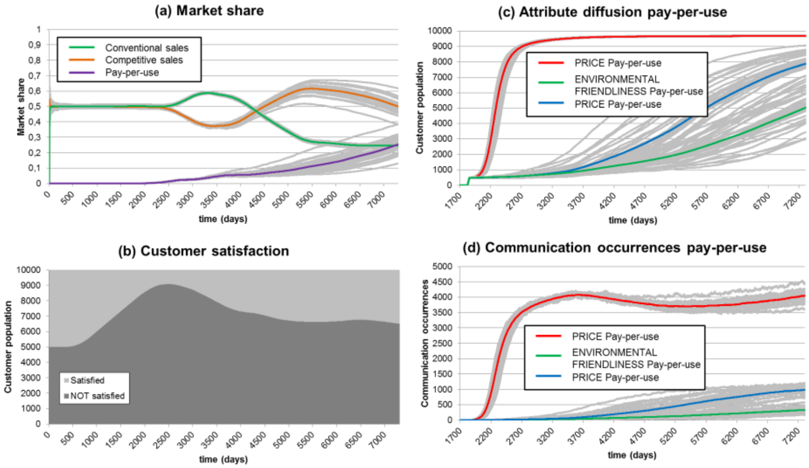


Figure 33: Average simulation results after 30 replications (in grey) for pay-per-use scenario with launch at t=1827 days (5 years) including market share (a), customer satisfaction (b), diffusion of product attributes (c) and communication occurrences per product attribute (d)

Apart from visualizing diffusion rates, communication events, customer satisfaction and market share, the tool serves as decision support capable of identifying proper CE marketing and pricing strategies in order to obtain best fit demand behavior. This tool is unique and relevant in facilitating the transition from linear to circular manufacturing systems as the business potential and risks can be quantified.

To conclude, paper D presents an AB simulation tool which is able to fill the gap between diffusion-based penetration of information, resulting in social behavior in the form of product-purchase decisions. In doing so, AB models provide more objective results when describing social systems (in this case customers/users of products and their social network, and the overall behavior resulting from their mutual interactions). This significantly reduces subjectivity when describing effects on technical systems such as manufacturing systems and leads to an improved understanding of complex adaptive systems and usefulness of ABM in industrial dynamics.

Conjoint analysis with CE value propositions

In order to investigate value propositions of a circular business approach a conjoint study has been carried out, which includes acquisition and analysis of empirical market data.

Conjoint analysis is a quantitative marketing research method and deals with estimating the structure of customer preferences and uses statistical design as well as parameter estimation models. As per definition conjoint measurement *"is concerned with determining the joint effect of levels of two or more attributes of stimuli on the total evaluative judgement of a set of stimuli [...]. The objective is to decompose the total evaluation into component scores, imputable to each attributes level or combination of attribute levels"* (Rao 2014).

The purpose of this conjoint study is to investigate value propositions of a circular business approach to gain objective insights on customer perception. This would support manufacturers in estimating market potentials in a quantified manner. Furthermore, the reaction of customers in terms of choice-process and trade-offs can be analyzed when exposing them to CE value propositions.

In this study a choice-based conjoint analysis (CBCA) has been applied, which belongs to the family of discrete choice analysis methods and is probably the most widely used approach in practice. The advantage of using CBCA is that respondents are presented a set of offers from which they are supposed to choose their most preferred one. In doing so, a hypothetical market place scenario is mimicked where customers are exposed to different offers and need to pick their favorite choice. In this perspective CBCA is considered as more realistic compared to conjoint approaches where respondents are asked to rank or rate alternatives. In a CBCA statistical analysis is performed involving the development of a choice-model which is tested for statistical validity.

Based on the discussion above, attributes and their levels for washing machines in a circular business scenario have been discussed and decided in collaboration with Gorenje d.d. A summary of the attributes and their levels are listed in Table 4. As can be seen only a limited number of attributes and levels are included in the CBCA in order to keep the number of possible profiles to a relatively low number. A profile is a single product offer based on a distinct combination of attribute levels. Based on the resulting number of profiles that need to be tested, choice sets are developed and made part of a questionnaire for the purpose of data collection. Choice sets contain a number of profiles from which the respondent can choose the most preferred constellation. The data collection process in a CBCA typically involves filling out the questionnaire either online or as print out. Details on the background, experimental setup, respondent sample and statistical analysis of the CBCA can be found in paper F.

Table 4: Summary of attributes and their levels for B2C survey

Attributes	Levels
Price and payment scheme	Purchase for 10.000 SEK
	Rent for a monthly fee of 130 SEK
	Pay-per-wash for 5 SEK
Environmental friendliness	0% CO_2 reduction (not remanufactured)
	30% CO_2 reduction (1x remanufactured)
	50% CO_2 reduction (2x remanufactured)
Service level	5-year warranty
	5-year warranty & free maintenance
	5-year warranty & free maintenance and installation & upgradeability

In total data from 141 respondents was obtained, each answering nine choice sets which resulted in a total of 1269 discrete choices for the conjoint study. Figure 34 shows customer choice probabilities for all 27 washing machine profiles resulting from combining levels from Table 4. The reference profile is the purchase of a new washing machine (0% CO_2 emission reduction with a 5-year warranty).

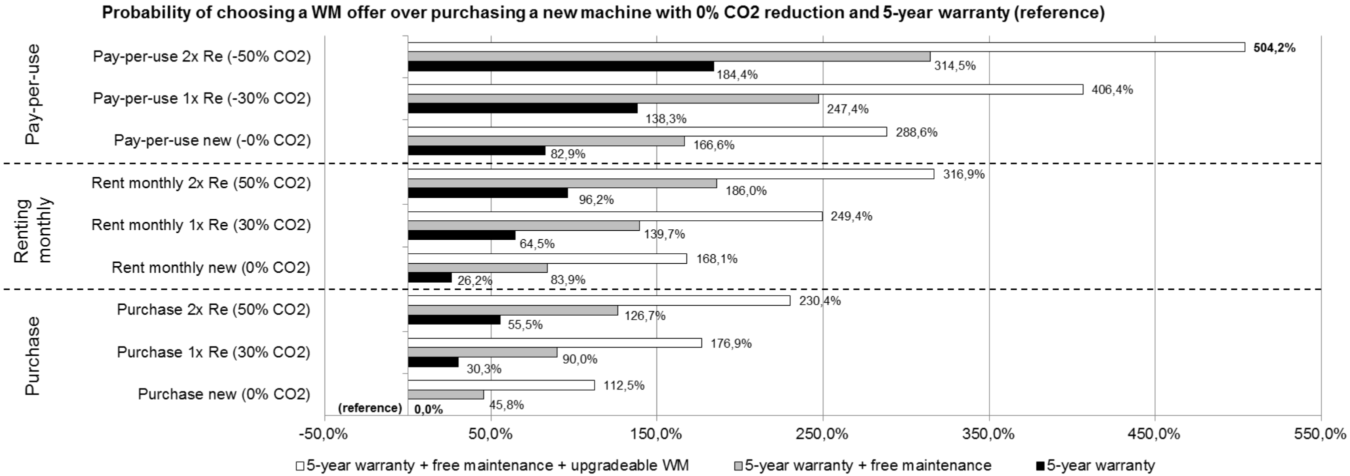


Figure 34: Customer choice probabilities for different washing machine (WM) profiles taking purchase of a new WM with a 5-year warranty as reference

As can be seen individual customers are five times more likely to choose a pay-per-use offer with a two-time remanufactured washing machine which includes a 5-year warranty, free maintenance and possibility to upgrade over the reference case. At the same time the reference case, which is today's most common practice, has the lowest choice probability. Hence, there seems to be customer empathy towards environmental friendly products as well as preference of access over ownership and different service levels in general. However, considering the limited sample size of 141 individuals the result of this CBCA can be considered suggestive and more market studies are necessary to reinforce the specificity of the findings.

In summary, the paper F demonstrates how preferences for CE value propositions based on price and payment scheme, environmental friendliness and service level can be effectively investigated using a choice-based conjoint approach. As a quantitative research method CBCA seems helpful in logically breaking down the CE value propositions making the evaluation more tangible when it comes to identifying to what extent service-related and product-related attributes contribute to overall customer utility.

3.4. Response to research question 4

How can economic and environmental impact of different circular manufacturing systems be quantified and assessed considering different business models, design strategies and supply chains?

Post-use design strategies like reuse, remanufacturing and recycling become highly relevant for the CE implementation process as they practically enable loop closure and influence cost and emissions of value recovery operations. There are sophisticated tools available for designers which provide decision support during the design process in terms of cost estimates, lifecycle assessment and material criticality. However, most of these tools are limited to the scope of linear production, i.e. the product is used by one user for one life neglecting recovery activities. In this scenario, it becomes enormously challenging for designers and decision makers to estimate economic and environmental benefits of design options in an expanded and unexplored CE view. Most importantly, potentials of product design in combination with new (circular) business models remain undetermined for industry, thus impeding successful implementation of circular manufacturing systems.

Considering the systems perspective as envisaged by ResCoM Figure 35 illustrates explorative and optimization approaches. The explorative approach assumes that there is not any pre-knowledge available. Starting point is therefore the designer who is capable of allocating different end-of-life strategies to components. At this point there are not any constraints on the product design since the business model and associated supply chain is not determined. In order to narrow down the number of design options the additional design effort in terms of cost or CO_2 emissions to realize the design option can be specified. Finally, the business models through which the product or service may be delivered need to be decided. As a consequence, different design and business model constellations require to be explored systematically for their design and business potentials. The other way around the best fitting design strategy for one particular circular business model can be supported by optimization approaches. If the relevant business model has been chosen and the maximum additional design effort (e.g. budget) decided, it is possible to obtain the best fitting (e.g. cost-minimum) allocation of EoL strategies on component level.

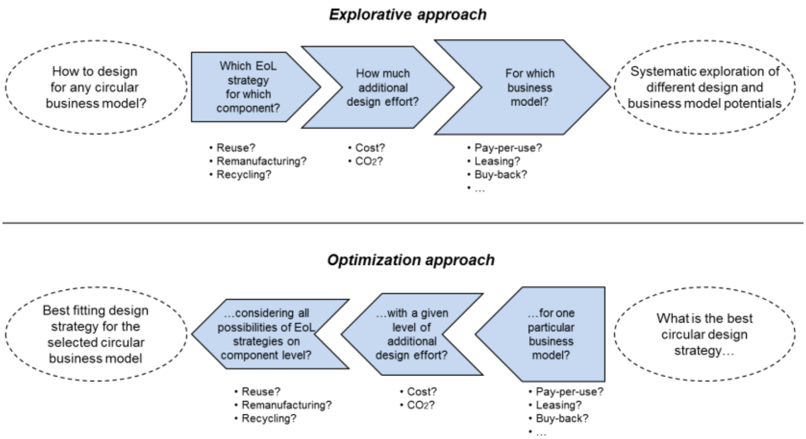


Figure 35: Explorative and optimization approach to connect design and business strategy in circular manufacturing systems

Both approaches connect design as well as business strategy and treat supply chain as implicit but central part. In paper E a multi-method simulation tool has been developed to enable exploration of various circular design strategies considering different circular business models, as well as identifying the optimum circular design strategy for a given circular business model and a given additional design effort. The elements on which this tool is based on consist of

- a method to systematically quantify design efforts for different circular design options
- an agent-based component model capable of tracing single components with different EoL strategies and different business scenarios
- a discrete event (circular) supply chain model including all relevant business process instances such as forward and reverse logistics as well as value recovery (reuse / remanufacturing / recycling)

Based on the concept of product design indices for EoL strategies in paper C and paper E design options of a product including reuse, remanufacturing and recycling can be quantified. Paper E furthermore extends product design indices to include estimations about additional design efforts when it comes to expand an existing linear design to include EoL strategies on component level. As a result, designers are able to define various EoL design options and estimate additional efforts for realizing these designs. Design efforts can include all monetary expenses and CO_2 emissions.

The ABM considers all single components as well as distinct states that a component can be in during its lifecycle. Reuse, remanufacturing, recycling and landfill are potential EoL strategies which may be considered after the use phase. Based on the designer's new design option each single component carries the EoL strategy that has been allocated to it. Moreover, additional component-specific information can be allocated and saved for each single component agent, such as material designation, component mass, process cost and CO_2 emission for each supply chain step.

The discrete event supply chain model considers all necessary business process instances of a circular manufacturing system. Its main sections consist of manufacturing and recovery phase, transport phase and use phase. During manufacturing component agents are merged and assembled to form a product agent. After assembly the product is delivered via forward transport to the customer where it stays as part of the use phase before it is transported back to the manufacturing company. After return products are disassembled to component level and processed according to their pre-defined EoL strategy. Components that ought to be reused or have been remanufactured will be delivered to a component inventory to be available for future assembly processes and another lifecycle. Figure 36 provides an overview how model elements are connected.

Starting from the left-hand side, individual components are represented by agents (one agent per component). If a component is requested during simulation by the supply chain a component agent is created considering design decisions and its corresponding parameter values, which have been provided as input. In the next step the component agent is inserted in the supply chain. The supply chain determines the movement of component agents based on the business process configuration (e.g. linear, buy-back, pay-per-use or other). More details regarding the model can be found in paper E.

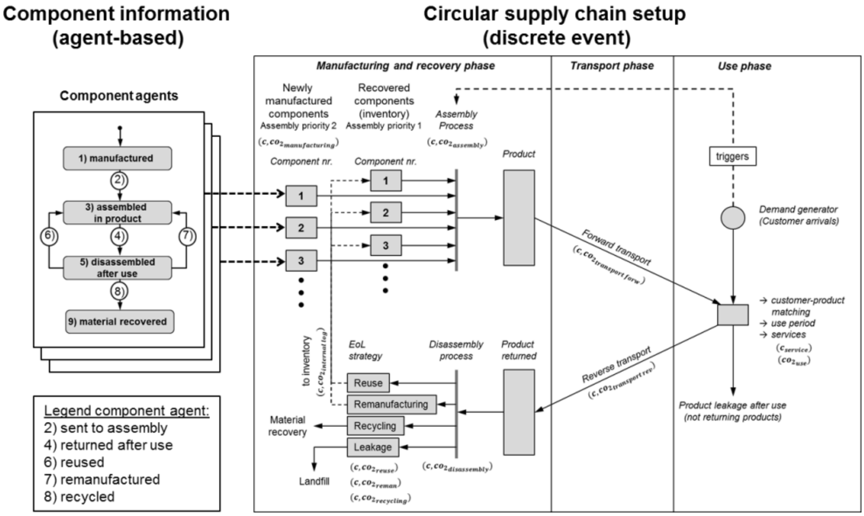


Figure 36: Overview and connection points of component-specific data, component agent and circular supply chain

Exploration of circular design strategies and business scenarios

Within the boundary of the presented multi-method tool, 3 different design options for a washing machine (see Table 5) have been tested in 3 business models, namely buy-back, leasing and pay-per-use.

Table 5: Washing machine design options considering different EoL strategies (based on number of components)

End-of-life strategy	*Design option 1*	*Design option 2*	*Design option 3*
Reuse (r_{reuse})	0,70	0,48	0,24
Remanufacturing (r_{reman})	0,24	0,39	0,58
Recycling ($r_{recycling}$)	0,06	0,12	0,18

The simulation runs are analyzed and compared to the linear case using the criteria: number of customers served per washing machine, overall cost and CO_2 emissions. The baseline is formed by a linear scenario where washing machines are manufactured and transported to the customer without the possibility of take-back. It is worthwhile to mention that direct cost and CO2 values are considered while fixed cost, such as remanufacturing facility or transport infrastructure, is not considered within the scope of the simulation.

Figure 37 shows the number of customers served per washing machine as well as aggregated lifecycle cost and impact of each design option in each of the business scenarios. Comparing only the 3 business scenarios in general it can be stated that the more service-oriented the business and supply chain setting, the more costly the business operations. However, taking the linear model into consideration, the buy-back and the leasing model are less cost-intensive. The pay-per-use model exceeds the linear setting with all of the 3 design options. On the other hand, the pay-per-use model serves more customers with a lower number of components. The number of customers served per washing machine is highest for design option 1 in the pay-per-use model, i.e. 1,70. This means that over the time of 15 years on average 1,70 customers have been served with the components of one single washing machine. The number of customers served per washing machine is highest for design option 1 in all 3 business model configurations. This is due to the fact that in design option 1 the largest number of components (94%) is planned to be reused and remanufactured compared to the other two design options.

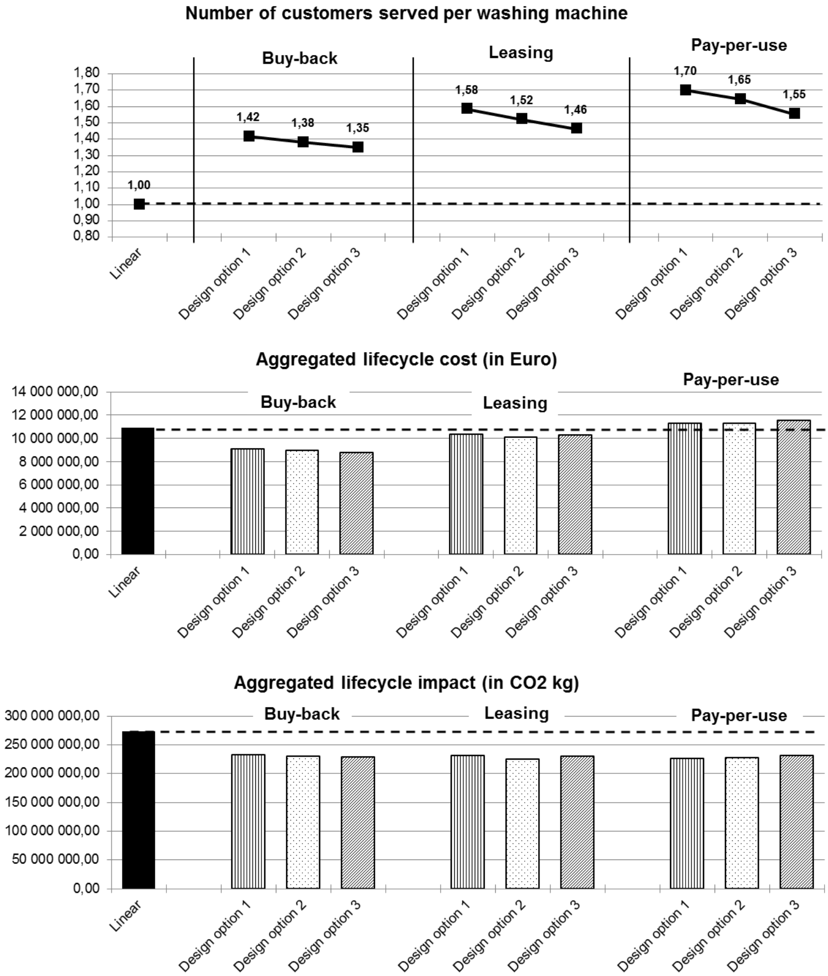


Figure 37: Number of customers served per washing machine, aggregated lifecycle cost and impact for distinct 3 design options and 3 supply chains in a 15 year scenario

Furthermore, the pay-per-use model has the most reliable time-to-recovery since timing and quantity of product returns are less uncertain, i.e. more predictable. This leads to a more steady reverse flow of components to be reused and remanufactured. As a result of both, larger share of components to be reused and remanufactured as well as more steady reverse flows, more components circulate through the closed-loop supply chain system and are made available for reassembly to serve new demand streams. However, under these circumstances more frequent transportation occurs which has a strong impact on cost and environment.

Results for the CO_2 emissions are rather similar for all combinations of design options and business models. Since the use phase has the highest CO_2-intensity compared to the other lifecycle phases of the washing machine (based on a fast track LCA), the reduction from 7 years in the linear scenario to roughly 4 years in any of the 3 alternative business models lowers the overall CO_2 emissions significantly. The increase of forward and reverse transport of all 3 alternative business models seems to be overcompensated by CO_2 savings resulting from the shortened use phases.

Optimization of circular design strategies

Given the results from the explorative study, the pay-per-use model in combination with design option 1 seems to deliver the most resource productive result since the largest number of customers can be served per washing machine. In addition, the same business setting performs environmentally better than the linear setting in terms of CO_2 emissions. However, from an aggregated lifecycle cost perspective design option 1 in combination with a pay-per-use model results in roughly 0,3 million euro more than the linear scenario. In the next step the same business setting of pay-per-use provides the basis for an optimization experiment with the aim to minimize the aggregated lifecycle cost.

The objective is to minimize the aggregated lifecycle cost under variation of different end-of-life strategies on component level while keeping the pay-per-use business setting. During this experiment the optimization engine runs numerous simulations while varying EoL strategies on component level from simulation run to simulation run to find the optimal (cost minimum) constellation in the pay-per-use setting. 2000 successive simulation runs have been performed. At the end of each of the 2000 runs the overall additional design effort of the respective EoL strategy on product level is compared to the design effort from design option 1 (Table 5). Simulation outcomes with a lower or equal design effort are marked as *feasible* while outcomes with a greater design effort are marked as *infeasible*. Based on the chosen design the corresponding additional design effort for including the EoL strategies reuse, remanufacturing and recycling is estimated and quantified after each simulation run. Paper E describes the underlying concept of product design indices and resulting design effort in detail. Figure 38 illustrates the results of the entire optimization experiment of 2000 runs.

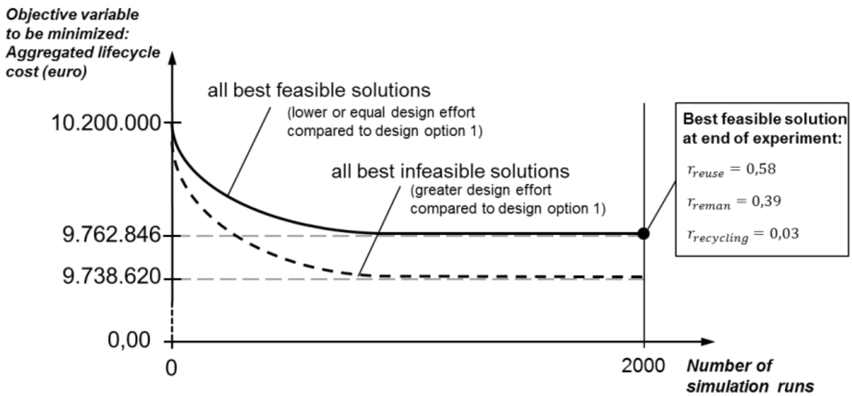


Figure 38: Results of cost optimization experiment for pay-per-use model (2000 consecutive simulation runs, 15 year scenario)

As can be seen in Figure 38, randomly starting in the range of 10,2 million euro the EoL strategies of all washing machine components could be optimized finally settling around 9,76 million euro. The best feasible solution has been achieved with the design of 0,58, 0,39 and 0,03 for the product design indices reuse (r_{reuse}), remanufacturing (r_{reman}) and recycling ($r_{recycling}$) respectively, while keeping the additional design effort lower or equal to the effort of design option 1. While maintaining business processes of a pay-per-use model, these design indices indicate the best end-of-life design strategy that should be adopted from the beginning in order to fulfill business objectives at minimum lifecycle cost.

Thus, it can be concluded that through variation of EoL strategies in a given pay-per-use setting and a maximum additional design effort of economic savings of roughly 1,1 million euro (equivalent to -10,4%) could be realized (comparing the best feasible result of 9.762.846 million euro in Figure 38 with 10.892.909 million euro in the pay-per-use setting for design option 1 in Figure 37). With the optimized EoL strategy the aggregated lifecycle cost can be reduced to a level below all of the 3 leasing models while still fulfilling the business objectives of a pay-per-use model.

As second level results component-specific data can be extracted from the component agents. All washing machine components have been summarized as a total of 33 components for this simulation experiment to simplify the case and avoid unnecessary details such as single screws and bolts. Figure 39 shows aggregated lifecycle cost per component number (1 through 33) for the duration of 15 years. Component lifecycle cost is compared for the cases linear, design option 1 and optimized pay-per-use design.

Similarly, in order to analyze environmental benefits component mass and material information have been extracted from the component agents. The data sets for the optimized design and the linear scenario have been compared. Figure 40 provides an overview about the saved mass of washing machine materials in the optimized design for the pay-per-use case. Roughly 326 tons of material could be saved in total in 15 years for a given number of customers served. This information is particularly useful when it comes to making design decisions in the light of resource scarcity and material criticality.

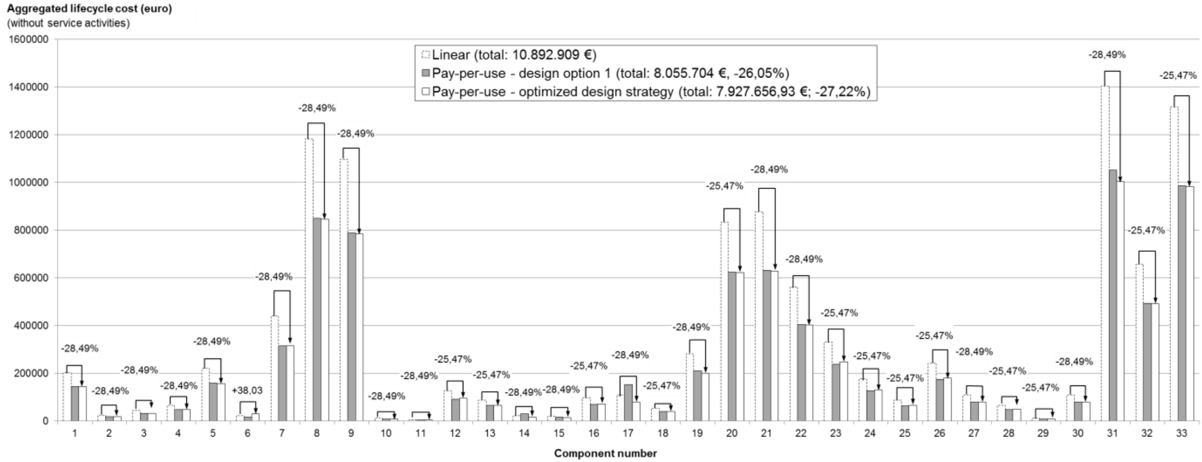


Figure 39: Comparison of aggregated lifecycle cost for 33 washing machine components in a 15 year scenario (cases: linear, design option 1, optimized pay-per-use design)

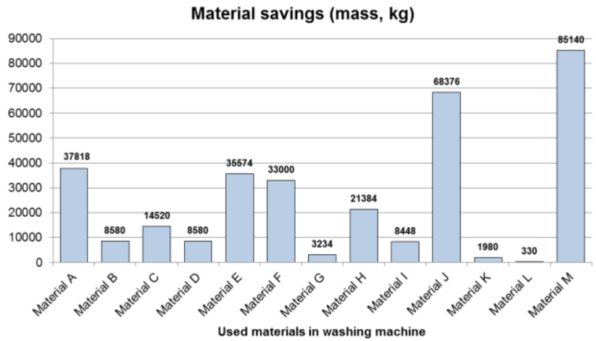


Figure 40: Material savings in kg of optimized design compared to linear scenario

To summarize, paper E provides researchers as well as practitioners with a quantitative analysis tool to explore various EoL design strategies in combination with circular business models. The tool is capable of optimizing design to fit to a model of preference or choice. Results can be delivered based on planned design efforts, chosen end-of-life strategies of components (i.e. reuse, remanufacturing, recycling) in different business and supply chain settings. The tool serves as decision-support at the intersection of product design, business model and supply chain and is capable of connecting EoL design with business strategy. The combination of agent-based and discrete event approach allows for connecting design on component level with business strategy. Consequences of different design choices in circular supply chains can be systematically investigated since components and their data are traceable throughout the entire simulation time. Circular manufacturing system settings allow for considering different degrees of quality, quantity and timing of product returns. As a result, cost, CO_2 and material saving effects over time can be quantified using agent-based product architectures and discrete event supply chains. This significantly reduces uncertainty when it comes to evaluating circular design and business approaches at early design stage and leads to improved decision making about circular manufacturing system implementation.

4. Implementation of decision-support tools

This chapter describes aspects of specific industrial cases in which the developed decision support tools have been applied to analyze circular manufacturing systems as envisaged by ResCoM.

Chapter 3 summarizes the research contributions as an answer to the research questions. These contributions are published in the form of scientific articles during the course of the research work. In addition to these contributions, a significant amount of research work is not publishable given its confidential nature. To give an example, the adaptation and simplification of the agent-based customer model to fit each of the four case companies in the ResCoM project resulted in four case-specific developments. The development activities around these cases include numerous discussions, data collection, iterations of model development, coding, model testing and debugging, user interface development, result analysis and reporting. Hence, this section highlights the capabilities for users in industry to implementing the solutions from research papers D and E. While avoiding sensitive company information the following sections summarize some of the additional research contributions.

4.1. Case company-specific circular manufacturing system

Four decision support tools have been developed for the four different industrial cases using a more simplified rationale than described in paper D. The agent-based customer model is connected to a system dynamics supply chain model and adapted to the case at hand considering alternative business models, product designs and supply chains. This section provides an overview of the tool and implementation example. The four case companies are named as company A, B, C and D.

Company A

Company A aims to investigate the potential of a leasing model in addition to their current business-as-usual practice. As part of the new leasing approach products are supposed to have multiple lifecycles. In between the leasing cycles products are refurbished, which requires central geographic collection point for the products before undergoing the refurbishment process. In an ideal case the product will be leased out for a pre-defined amount of time and brought back after to be refurbished. After refurbishment the product will be leased out for a second time. After the second return and refurbishment process the product is planned to be sold on the market. To facilitate the new leasing approach changes in product design are considered in order to ensure efficient reverse flows of products and refurbishment operations. This will allow company A to mix new and refurbished products in order to fulfill the leasing demand. Furthermore, this new leasing approach considers new activities, which require additional investments for the setup of new infrastructure, new pricing models and as a consequence different environmental impact at supply chain stages.

Company B
Company B investigates the potential of expanding its current remanufacturing business with two different options. Firstly, the buy-back of own products and, secondly, the purchase of used products from other brands in the market are explored. In both scenarios the returning products are planned to be remanufactured and sold. To facilitate the new remanufacturing case a change in product design of the own products is considered, which allows for more efficient reverse flow and remanufacturing activities. A remanufacturing facility has been geographically determined where all used products are supposed to be collected. Furthermore, expansion of the remanufacturing business considers new activities, which require additional investments for the setup of new infrastructure, new pricing models and as a consequence different environmental impact at supply chain stages. As a consequence the return on investment at different time periods is of particular interest.

Company C
Company C investigates the strategy of extending the product life through upgrades. In this strategy it is assumed that the customer will keep the product for a longer time (ideally double the use phase) if a major upgrade is performed at the end of the first use cycle. The potential of upgrades with more services/function-oriented features is supposed to be

explored as well. In doing so, the product becomes the platform for providing user experiences. This involves changes in the product design, forward supply chain as well as cost and revenue streams as part of a new service-oriented offer. This new business approach considers new activities, which require additional investments for the setup of service-related infrastructure, new pricing models and as a consequence different environmental impact at supply chain stages.

Company D

Company D has the ambition to introduce a service-oriented business model in which customers pay "per use". At the same time, company D plans to remanufacture the returning products. The plan is to give each product a maximum of three consecutive service lives, meaning that each product will be remanufactured twice. In doing so, the number of customers served per product is supposed to increase while increasing profits. To facilitate the service-oriented business approach changes in the product design are considered to facilitate remanufacturing operations. Also, the reverse supply chain is redesigned in order to increase efficiency of reverse flows. Company D plans to serve market demand with new as well as once and twice remanufactured products. This requires a balancing of forward and reverse supply chain flows. This new business approach considers new activities, which require additional investments for the setup of service-related infrastructure, new pricing models and as a consequence different environmental impact at supply chain stages.

As can be seen each case company covers a different scope for which the modelling developments needed adaptation. Particularly when it came to market-specific information, as required by the agent-based model, simplifications were necessary in all cases due to lack of information. Table 6 shows an overview, highlighting the differences in the scope for the case companies and the computer simulations.

Table 6: Differences of case-specific decision support tools

	Company A	Company B	Company C	Company D
Purpose of the decision support tool	Creation of different customer demand streams when changing from a linear to a circular business model			
Business model	• Business as usual • Leasing of new and refurbished products • Sales of refurbished products	• Business as usual • Sales of remanufac-tured products	• Business as usual • Sales of extended upgrades & service	• Business as usual • Service-oriented contracts (pay-per-use)
Strategy for multiple lifecycles	• Twice refurbishment	• Once remanufac-tured	• Product life extension with upgrade	• Twice remanufac-tured
Sources of used products	• Own products returning from leasing	• Own and other products bought on the market	• Own products	• Own products returning from service contracts
Generation of customer demand	Based on sensitivity to and offers of following value propositions: • Price • Environmental impact • Service level	• Demand streams as input	• Seasonal demand streams as input	Based on sensitivity to and offers of following value propositions: • Price • Environmental impact • Service level
Elements of the ABM on single agent level	• 12 states • 16 transitions • 39 input and auxiliary variables	• 20 states • 29 transitions	• 10 states • 15 transitions	• 13 states • 21 transitions • 38 input and auxiliary variables

4.2. Tool overview and implementation

The adapted models include numerous details. For the purpose of user-friendliness the direct interaction with elements from the agent-based and system dynamics model is minimized through the development of custom interfaces. Through these interfaces the user is able to provide quantitative input data, run the simulation and create analysis reports containing aggregated and visualized results.

The main input interface is provided in MS Excel as this is a commonly used program in industry. In this interfaces the input variables are categorized according to business model, product design and supply chain inputs. Once all relevant variables have been inserted the multi-method model is activated and the input data from the excel sheet is transferred to the simulation model.

In the next step, the simulation starts to run a scenario based on the input provided in the main interface. Throughout the simulation data is logged from the modelling elements per time unit and saved, thus resulting in large data sets per run. Once the simulation run has been completed, data is aggregated, visualized and summarized in an automatically generated report (PDF format). For example, customer agent decisions are counted to calculate and visualize market share over time or products produced and delivered are aggregated for total cost and CO_2 calculations. Similarly forward and reverse supply chain cost and CO_2 emissions are visualized. Figure 41 shows an overview of the user steps.

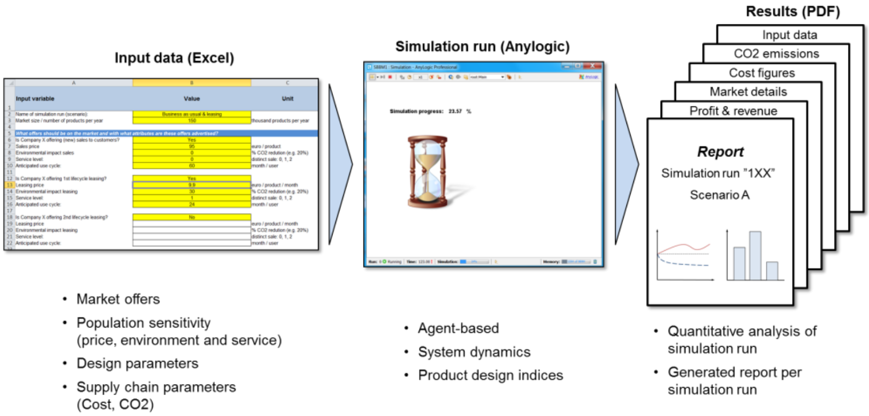


Figure 41: Overview of user steps from data input, simulation run to results

4.3. Exemplary scenario for exploring circular business approaches

By changing the input values and running the simulation, various circular business scenarios can be explored. To illustrate this further an exemplary scenario is created for company X. Following assumptions are made for the scenario:

- On the market a conventional sales offer from company X and from a competitor (business as usual scenario) exists. In addition to these two offers company X introduces a leasing offer.

- The products of the leasing offer are leased out twice. In between the leasing cycles the products are remanufactured once. After the second leasing cycle the products are sent to material recovery through recycling.
- The market size consists of 1 million products per year and the simulation runs for 10 years.
- The leasing price per month is 30% greater compared to the price of the conventional sales offer from company X, if the conventional sales prices is divided by two times the leasing use cycle.
- The willingness to pay for the product is distributed normally between zero and a maximum willingness to pay value in Euro per month.
- Leasing is associated with 30% of CO_2 reduction compared to the linear sales (due to remanufacturing practices).
- The customer population is sensitive to environmental friendly products.
- 15% of the customer population would never lease.
- There are not any additional services considered in the offer.
- Cost and CO_2 values of the forward and reverse supply chain activities are based on location Y.

The assumptions mentioned above result in graphs (Figure 42) describing the market details of that particular simulation run. The supply chain model which aims at fulfilling the emerging demand streams over time is described in paper C in detail, including all relevant supply chain performance criteria.

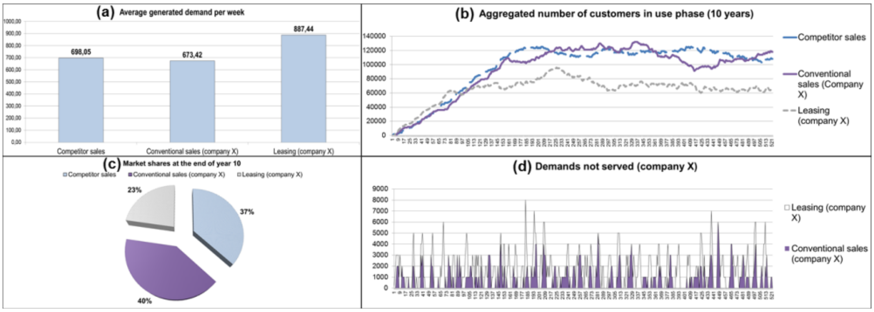


Figure 42: Report extract: Average generated demand per week (a), aggregated number of customers in use phase (b), market shares at the end of year 10 (c) and demands not served over time (d)

As can be seen in Figure 42 (a) the highest demand has emerged for the leasing offer on average. Since the use phase of a leasing offer is shorter compared to the conventional sales and competitive sales offer, the steady state of aggregated number of customers in the leasing use phase is lower than for the other two offers (b). The market share (snap-shot at the end of year 10) is lowest for the leasing offer, however serving the highest demand (a) with less resources since the leased products are remanufactured and not produced from virgin material. The supply chain is capable to serve all demand streams as there is not any accumulated demand (d).

4.4. Product-specific analysis for circular manufacturing systems

More specific analysis can be carried out on component level as indicated in paper E to identify best fit of EoL and business strategy. As a pre-requisite the entire product needs to be disassembled and analyzed with regard to its components. This leads to a detailed summary containing bill of material, life cycle assessment and life cycle cost estimations. As a supporting tool MS Excel may be used to capture and structure component-specific data in the necessary format, which is useful when linking and feeding data to the multi-method simulation model. In doing so, the effect of different design scenarios for components can be explored in any business and supply chain scenario. The other way around, the best fitting design strategies can be identified given a fixed business model and design invest. Figure 43 shows the steps of the detailed product analysis.

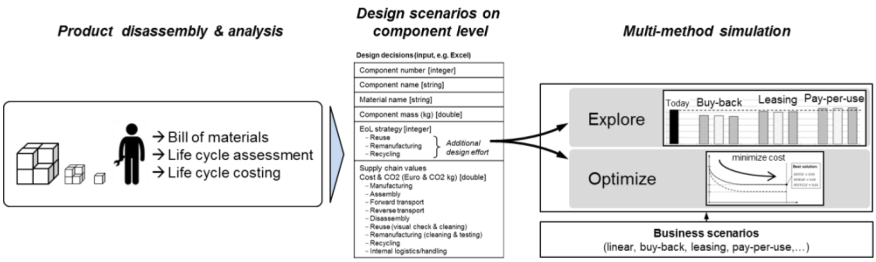


Figure 43: Procedure for in-depth product analysis for circular manufacturing systems

As a result of systematically exploring the potential of circular design and business model, strategic recommendations can be given. Assuming a company follows the policy of resource conservation while maximizing the number of customers served, a pay-per-use model with a service-oriented circular supply chain and a larger amount of reused components are needed. As a consequence, this requires a large investment into circular manufacturing infrastructure in case the company aims at performing all reverse transport and recovery activities by itself. As an alternative, collaborations with third parties can be sought to reduce the initial investment. Figure 44 shows a matrix containing exemplary strategic recommendations after explorative simulation studies.

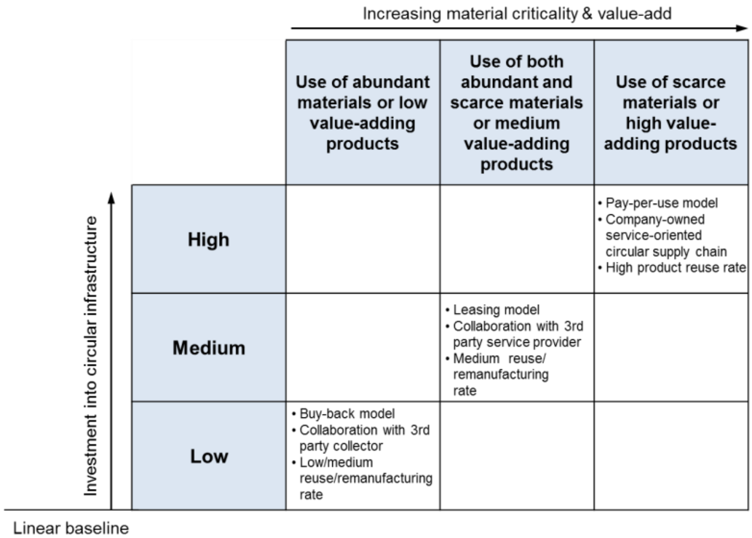


Figure 44: Exemplary strategic recommendations based on investment need, material criticality and value-add as a result of explorative simulation studies

When it comes to identifying the best design strategies on component level given a maximum of additional design effort and a fixed business and supply chain setting, optimization runs are performed with an objective function (e.g. minimization of cost in a period of 15 years). Table 7 shows cost minimum EoL strategies for one of the case companies using the example of a washing machine with 33 components. The optimization has been run in a pay-per-use business model scenario with corresponding process instances in the supply chain. The constraint has been that additional design effort (for example design invest in euro) may not be greater than 24,9% based on the current linear design approach.

Table 7: Overview of end-of-life strategies for 33 washing machine components for an optimized pay-per-use design

Component number	Material name	Manufacturing cost (euro)	Optimized pay-per-use design
1	Material A	12,76	Reuse
2	Material B	1,53	Reuse
3	Material C	2,77	Reuse
4	Material D	4,16	Reuse
5	Material D	13,87	Reuse
6	Material B	1,39	Recycle
7	Material C	27,75	Reuse
8	Material E	74,79	Reuse
9	Material F	69,37	Reuse
10	Material B	0,69	Reuse
11	Material B	0,28	Reuse
12	Material B	8,05	Reman
13	Material G	5,55	Reman
14	Material B	1,39	Reuse
15	Material G	1,25	Reuse
16	Material B	6,10	Reman
17	Material A	6,94	Reuse
18	Material H	3,33	Reman
19	Material I	17,76	Reuse
20	Material J	52,72	Reman
21	Material J	55,50	Reuse
22	Material J	35,52	Reuse
23	Material A	20,95	Reman
24	Material A	11,10	Reman
25	Material A	5,55	Reman
26	Material A	15,26	Reman
27	Material A	6,94	Reuse
28	Material K	4,16	Reman
29	Material L	0,69	Reman
30	Material M	6,94	Reuse
31	Material M	88,80	Reuse
32	Material H	41,62	Reman
33	Material M	83,25	Reman

The discussion above highlights the features of case-specific decision support tools and provides an overview of how different scenarios can be created, run and visualized. Once a specific product has been identified an in-depth analysis on component level can be performed to further systematically explore different designs and business model potentials. However, rather large amounts of data and pre-studies need to be carried out in advance in order to tailor the tools to the case at hand. Still, once carried out successfully strategic and quantified recommendations can be provided when it comes to implementation of circular manufacturing systems. Particularly the achieved level of detail in combination with simulation techniques capable of pressing several years into a few minutes reduces uncertainty at early design stage.

5. Discussions and conclusions

This chapter presents final remarks and criticism of the research. Future research steps are outlined at the end of this chapter.

Manufacturing industry is under pressure to maintain its economic growth and profitability as a strong societal backbone. At the same time environmental pressures due to emissions, waste generation and staggering resource consumption are increasing. In this scenario, the change from linear to circular manufacturing systems appears not only apposite but also inevitable to ensure sustainable development for manufacturing industry in future. Resource Conservative Manufacturing (ResCoM) is a development framework that proposes a systems perspective and simultaneously considers business models, product design, supply chain design and technology to support an industrially driven CE movement. In doing so, manufacturers are supposed to widen their view from resource efficiency efforts in production systems towards resource conservation in manufacturing systems where customers are perceived as integral part of the enterprise. This new perspective supports manufacturing businesses to gain control over quality, quantity and timing of product returns or reverse supplies, which is considered as one of the critical barriers in CE implementation.

The research contributions in this thesis cover a change in perspective to adopt the ResCoM view. Starting from resource efficiency improvements in production systems with focus on operational resources (material, energy, equipment, staff), the view is expanded to a systems perspective with focus on resource conservation in manufacturing systems as part of the ResCoM framework. The new systems perspective is explored and analysis methods and tools are developed to support decisions characteristic to the new scope. However, obstacles encountered during the process of development have been identified, which should be highlighted here as potential shortcomings.

To start with, as this research covers an evolving area the consistent use and understanding of terminology among stakeholders has been challenging. As the ResCoM framework relates to four areas simultaneously, while each of these areas constitutes a large field of knowledge and research, an enormous amount of terminology was brought together and needed to be streamlined over time. To give an example, the term *circular manufacturing system* has been used to align both the ResCoM and CE initiative, and furthermore encompasses terms as closed-loop (manufacturing) system, closed-loop product system, closed-loop supply chain, ResCoM product system and circular product system.

It has been challenging to decide which of the ResCoM-related areas need to be prioritized in the light of specific industrial cases. The scope of the ResCoM framework is broad and aims at providing specific solutions for industry at the same time. In order to bridge the gap between generic concepts and specific solutions, an analysis of the current state of a manufacturing company is necessary in practice, since each organization is unique in its operations, its management and its strategy. This requires preparatory steps in the form of interviews and data collection to create a baseline for analysis.

The process of validation for the modelling work presented in this research has been challenging since actual data about circular manufacturing systems implementation do not exist and are therefore only available after its real-world event. Sterman (Sterman 2000) argues that "no model can be verified or validated [...] because all models are wrong". Sterman further explains that "all models, mental or formal, are limited, simplified representations of the real world. They differ from the reality in ways large and small, infinite in number". Still, some level of validation is needed to increase the confidence that the models can generate reasonable results. When it comes to the multi-method models, the supply chain input parameters for cost and CO_2 could be obtained relatively easily since manufacturing companies can provide sound cost estimations and to an increasing extent also reasonable estimations on their environmental impact. As an alternative life cycle assessments and life cycle costing approaches can be performed to generate reasonable input data sets. However, when it comes to the customer agent-based models, the assumed empathy towards environmental friendly products, preferences of access over ownership and different service levels requires reinforcement. At this point the conjoint analysis validates the assumptions of positive perception of the attributes in general for the Stockholm market. However, more studies are needed to reinforce the specificity of the findings for particular markets or segments.

It is highly motivating that the appended papers in thesis have been cited 105 times until August 2017 in Google scholar. This can be interpreted as acknowledgement from the research community and that the research is considered as seminal and also that more knowledge in this field is the need of the hour.

There are various paths for continuing the work in future. Currently, the benefits for manufacturing companies are investigated from a bottom-up perspective. As indicated in Figure 31, the top-down perspective needs to be adjusted to facilitate industrial transition efforts of circular manufacturing system implementation. As part of support infrastructure, which materializes the benefits of policy and legislation, approaches and policy initiatives to instigate the CE movement seem missing around the globe, despite the large benefits that are predicted in this area. The movement in the field of social awareness is ongoing and educational programs, public campaigns and seminars have increased significantly during the past years. So far this movement has been supported by public institutions and gradually gaining support from industry. Still, the people's mind-set requires a change towards "fit-for-use" rather than ownership of products.

Benefits for manufacturing businesses and customers have been investigated in order to facilitate a changeover from linear to circular. Extending the concept of value propositions including relevant measures to other stakeholder in the value chain, such as suppliers, retailers or service organizations would allow for comprehensive analysis of potentials and benefits. Such a comprehensive and quantified stakeholder analysis can be a persuasive way for industrial businesses to join collaborative business models in CE context.

This research work demonstrates and quantifies the business potential of circular manufacturing systems. Based on the washing machine case, a pilot study would provide further valuable insights and strengthen the feasibility of a circular business change in the Stockholm city area. The experiences and lessons learned from such a pilots study would allow for further validation of assumptions and study results obtained so far, and provide insight on following challenges and implementation steps.

References

Asif, F.M. et al., 2012. Performance analysis of the closed loop supply chain. *Journal of Remanufacturing*, 2(1), p.4. Available at: http://www.journalofremanufacturing.com/content/2/1/4.

Asif, F.M.A., 2017. *Circular Manufacturing Systems: A development framework with analysis methods and tools for implementation*. KTH Royal Institute of Technology. Available at: http://kth.diva-portal.org/smash/record.jsf?pid=diva2:1096938&dswid=-378.

Bonabeau, E., 2002. Agent-based modeling: methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, 99(suppl. 3), pp.7280–7287. Available at: http://www.ncbi.nlm.nih.gov/pubmed/12011407.

Borshchev, A. & Filippov, A., 2004. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. In *22nd International Conference of the System Dynamics Society, 25-29 July 2004*. p. 45.

City municipality of Stockholm - Stockolm stad, 2014. Age distribution Stockholm 2014 (folkmängd, hela staden per 31 dec 2014). Available at: http://www.statistikomstockholm.se/index.php/detaljerad-statistik [Accessed March 21, 2016].

Dam, K.H. van, Nikolic, I. & Zofia Lukszo, 2013. *Agent-Based Modelling of Socio-Technical Systems* Volume 9. H. Deguchi, ed., Yokohama, Japan: Springer.

E. W. Anderson, 1998. Customer Satisfaction and Word of Mouth. *Journal of Service Research*, 1(1), pp.5–17.

Ellen Macarthur Foundation, 2013. *Towards a Circular Economy: Opportunities for the consumer goods sectors*, Available at: http://www.ingentaconnect.com/content/glbj/gmi/2005/00000200 5/00000050/art00004.

Ellen Macarthur Foundation, 2014. Towards the Circular Economy: Accelerating the scale-up across global supply chains. *World Economic Forum Reports*.

Engel, J.F., Blackwell, R.D. & Miniard, P.W., 1995. *Consumer Behavior*, Philadelphia: The Dryden Press.

European Parliament, 2017. Circular economy. Available at: http://www.europarl.europa.eu/thinktank/infographics/circulareconomy/public/index.html [Accessed April 26, 2017].

Giljum, S. et al., 2008. Modelling scenarios towards a sustainable use of natural resources in Europe. *Environmental Science and Policy*, 11(3), pp.204–216.

Grimm, V. et al., 2010. The ODD protocol: A review and first update. *Ecological Modelling*, 221(23), pp.2760–2768. Available at: http://dx.doi.org/10.1016/j.ecolmodel.2010.08.019.

Guide, V.D.R. & Van Wassenhove, L.N., 2009. The Evolution of Closed-Loop Supply Chain Research. *Operations Research*, 57(1), pp.10–18.

International Institution for Production Engineering Research, 2004. *CIRP Dictionary of Production Engineering* Vol. 3., Springer-Verlag Berlin Heidelberg.

Joshi, Y. & Rahman, Z., 2015. *Factors Affecting Green Purchase Behaviour and Future Research Directions*, Holy Spirit University of Kaslik. Available at: http://dx.doi.org/10.1016/j.ism.2015.04.001.

Kindström, D., 2010. Towards a service-based business model - Key aspects for future competitive advantage. *European Management Journal*, 28(6), pp.479–490.

Kuester, S., 2012. *MKT 301: Strategic Marketing & Marketing in Specific Industry Contexts*, University of Mannheim.

Lieder, M., 2011. *Development of a tool for consistent assessment of resource efficiency in small and medium-sized enterprises*. KTH Royal Institute of Technology. Available at: kth.diva-portal.org/smash/get/diva2:460084/FULLTEXT01.pdf.

Lieder, M., 2014. *Integrated evaluation of resource efficiency and cost effectiveness in production systems*. KTH Royal Institute of Technology. Available at: http://kth.diva-portal.org/smash/get/diva2:712671/FULLTEXT01.pdf.

Lundholm, T., Lieder, M. & Rumpel, G., 2012. Resource Efficiency Assessment System. *Leveraging Technology for a Sustainable World Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA, May 23 - 25, 2012*, pp.423–428.

Lyle Center, 2006. History of the Lyle Center. Available at: http://www.cpp.edu/~crs/history.html [Accessed June 30, 2015].

Martin, D., Gustafsson, A. & Choi, S., 2016. Service innovation, renewal, and adoption/rejection in dynamic global contexts. *Journal of Business Research*, 69(7), pp.2397–2400. Available at: http://dx.doi.org/10.1016/j.jbusres.2016.01.008.

Mcpherson, M., Smith-Lovin, L. & Cook, J., 2001. Birds of a Feather : Homophily in Social Networks. *Annual Review of Sociology*, 27(2001), pp.415–444.

Meadows, D.. et al., 1972. *The Limits to Growth*, Available at: http://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf.

Nasr, N. & Thurston, M., 2006. Remanufacturing : A Key Enabler to Sustainable Product Systems. *Proceedings of LCE*, pp.15–18.

Osterwalder, A. & Pigneur, Y., 2010. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*, New Jersey: John Wiley & Sons, Hoboken.

Paul D., J.E.L. & Ormrod, 2013. *Practical Research: Planning and Design*, New Jersey: Pearson Education, Inc.

Rao, V.R., 2014. *Applied conjoint analysis*, Springer-Verlag Berlin Heidelberg.

Rashid, A. et al., 2013. Resource conservative manufacturing: An essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner Production*, 57, pp.166–177. Available at: http://dx.doi.org/10.1016/j.jclepro.2013.06.012.

ResCoM consortium, 2013. ResCoM - From linear to closed-loop manufacturing. Available at: http://www.rescoms.eu/rescom

[Accessed June 30, 2015].

SCB Statistiska centralbyrån - Statistics Sweden, 2014a. Educational levels of the Stockholm population (befolkningens utbildning Stockholm). Available at: http://www.scb.se/sv_/Hitta-statistik/Statistik-efter-amne/Utbildning-och-forskning/Befolkningens-utbildning/Befolkningens-utbildning/#c_undefined [Accessed March 21, 2016].

SCB Statistiska centralbyrån - Statistics Sweden, 2014b. Income statistics Stockholm (sammanräknad förvärvsinkomst hela året). *Statistical database; Household finances*. Available at: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0110__HE0110A/SamForvInk1/?rxid=980ed2d5-4438-4ae4-aab8-c8d32ca550e3# [Accessed March 21, 2016].

SCB Statistiska centralbyrån - Statistics Sweden, 2012. Localities 2010, area, population and density in localities 2005 and 2010 and change in area and population. Available at: www.scb.se/Statistik/MI/MI0810/2010A01Z/01_Localities2010_land_area_pop_density_2005_2010.xls [Accessed March 21, 2016].

Siebers, P.O. et al., 2010. Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation*, 4(3), pp.204–210.

Slawik, S., 2012. *Determinanten und Optimierungsmethoden industrieller Ressourceneffizienz* 22nd ed., Bayreuth, Germany: Prof. Dr.-Ing. Frank Rieg und Prof. Dr.-Ing. Rolf Steinhilper. Available at: http://www.shaker.de/de/content/catalogue/index.asp?ID=8&ISBN=978-3-8440-1136-4.

Steinhilper, R., 1998. *Remanufacturing: The Ultimate Form of Recycling*,

Sterman, J.D., 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill Companies, USA.

Tangen & Stefan, 2005. Demystifying productivity and performance. *International Journal of Productivity and Performance Management*, 54(2005), pp.34–46.

The Standing Committee of the National People’s Congress China, 2008.

Circular Economy Promotion Law of the People's Republic of China. *online*. Available at: http://www.fdi.gov.cn/1800000121_39_597_0_7.html.

Tukker, A., 2004. Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment*, 13(4), pp.246–260.

UN Statistics Division, 2016. National Accounts Main Aggregate Database. Available at: https://unstats.un.org/unsd/snaama/dnlList.asp [Accessed March 24, 2017].

UN World Commission on Environment an Development, 1987. *Development and international economic co-operation: Environment*,

Wolf, I. et al., 2015. Changing minds about electric cars: An empirically grounded agent-based modeling approach. *Technological Forecasting & Social Change*, 94, pp.269–285. Available at: http://arxiv.org/abs/1405.6230.

Wooldridge, M. & Jennings, N.R., 1995. Intelligent Agents: Theory and Practice. *Knowledge Engineering Review*, 10(2), pp.115–152. Available at: http://journals.cambridge.org/production/action/cjoGetFulltext?fulltextid=4100132.

World Resource Forum, 2017. Natural Resources, what are they? Global resource use - Worldwide patterns of resource extraction. Available at: https://www.wrforum.org/publications-2/publications/ [Accessed July 12, 2016].

Zhang, T. & Zhang, D., 2007. Agent-based simulation of consumer purchase decision-making and the decoy effect. *Journal of Business Research*, 60(8), pp.912–922.