Circular Manufacturing Systems

A development framework with analysis methods and tools for implementation

Farazee M. A. Asif

KTH Royal Institute of Technology
School of Industrial Engineering and Management
Department of Production Engineering
SE -100 44 Stockholm, Sweden

TRITA-IIP-17-05
ISSN: 1650-1888
ISBN: 978-91-7729-403-0

Akademisk avhandling som med tillstånd av KTH i Stockholm framlägges till offentlig granskning för avläggande av teknisk doktorsexamen torsdagen den 8 juni kl. 10:00 i Brinellsalen M311, KTH, Brinellvägen 68, 10044 Stockholm.

Abstract

The society today lives on the philosophy of ‘take-make-use-dispose.’ In the long run, this is not sustainable as the natural resources and the waste carrying capacity of the earth are limited. Therefore, it is essential to reduce dependency on the natural resources by decoupling the growth from the consumption. In this venture, both the society and the manufacturing industry have a vital role to play. The society needs to shift towards Circular Economy that rests upon the philosophy of ‘take-make-use-reuse’ and the manufacturing industry has to be a major stakeholder in this shift. Despite being proven to be both economically and environmentally beneficial, successful examples of circular systems are few today. This is primarily due to two reasons; firstly, there is a lack of systemic and systematic approach to guide industries and secondly, there is a lack of analysis methods and tools that are capable of assessing different aspects of circular manufacturing systems. Taking on to these challenges, the objective of this research is to bring forward a framework with methods and decision support tools that are essential to implement circular manufacturing systems. The initial conceptual framework with the systemic approach is developed based on extensive review and analysis of research, which is further adapted for industrial implementation. Systematic analysis methods, decision support and implementation tools are developed to facilitate this adaptation. This development has been supported by four cases from diverse manufacturing sectors. Behind each decision support tool, there are analysis methods built upon mainly system dynamics principles. These tools are based on simulation platforms called Stella and Anylogic. Among other things, these tools are capable of assessing the performance of closed-loop supply chains, consequences of resource scarcity, potential gains from resource conservation and overall economic and environmental performance of circular manufacturing systems.

Keywords: Circular economy, circular manufacturing systems, resource conservative manufacturing, ResCoM, system dynamics.

Acknowledgements

Acknowledgements are due to all those who have directly and indirectly supported the work presented in this dissertation and made this entire journey pleasant. I show my deepest gratitude to my main supervisor Associate Prof. Amir Rashid who not only has supported me in technical matters in carrying out the research but also given my research a purpose by involving me in the ResCoM project. The career path that I am travelling today with joy may look completely different without the guidance of my former supervisor Prof. Mihai Nicolescu. He guided me all the way from being his student to become a teacher and a researcher. Thanks to my co-supervisor Associate Prof. Daniel Tesfamariam Semere for all the meaningful discussions that encouraged me to think critically. I highly appreciate the support of my colleague Tech. Lic. Michael Lieder, who has made teamwork effective as well as development and implementation of new ideas efficient. I would also like to thank my colleague Dr. Ove Bayard who has always been there to support me in education management activities during the time when I was busy with my research.

I show my sincere gratitude to all my colleagues at the department of production engineering for making my everyday work pleasant.

Finally, thanks to my family for their unconditional love and support. This journey would have been much harder if my wife Fiza and daughter Arushi have not been always beside me.

This work has been financed through the ResCoM project that has received funding from the European Union's Seventh Programmes for research, technological development and demonstration under grant agreement No 603843.

Contents

List of figures

List of tables

Definition of critical terms

This section defines all the critical terms that are used in this work. These terms are not commonly used and often the definition and the use context of these terms may differ if compared with the same/similar terms used in other research areas. Therefore, it is important to introduce these terms and understand their use context as described below.

ResCoM stands for Resource Conservative Manufacturing, a term introduced by a group of researchers belonging to the department of Production Engineering at KTH Royal Institute of Technology. The term was first published in 2011 [1].

ResCoM initiative was adopted in 2010 as a focus area for research with the vision to conserve resources in the context of manufacturing systems.

ResCoM project is a European Commission (EC) funded 4-year research project started in 2013 with the title "Resource Conservative Manufacturing- transforming waste into high value resource through closed-loop product systems" [2].

ResCoM-framework was developed during the period 2010-2013 with the aim to guide industries in implementing circular manufacturing systems. The initial conceptual framework was first published in 2013 [3]. ***Framework*** in this context refers to a systemic approach with a set of guidelines, analysis methods and decision support tools as well as implementation tools that are necessary for developing and implementing circular manufacturing systems.

Analysis method and decision support tool **refers** to a collection of developments intended to support manufacturing industries in assessing different aspects of circular manufacturing systems. Behind each tool, there is a unique ***analysis method*** developed using single or multiple methods/approaches. For example, an analysis method (as described in paper D and in section 3.2 and 4.4) is developed which comprises System Dynamics, Agent-Based and Product Design Index approaches. Based on this analysis method, a simulation based generic ***decision support tool*** is developed which is capable of measuring the economic and the environmental performance of circular manufacturing systems.

Resource in the context of ResCoM refers to materials, energy and manufacturing value added. Labour, plant and equipment related overheads that are used for value addition in a product during manufacturing processes are included in the manufacturing value added. ***Resource conservation*** in this context means direct conservation of the above-mentioned resources which indirectly conserves other natural capitals such as land usage, air and water.

Circular manufacturing system is a system that is designed intentionally for closing the loop of products/components preferably in their original form, through multiple lifecycles. This is a value management approach which includes the phases, value creation, delivery, use, recovery and reuse in a systemic perspective. This term is used in this dissertation and proposed to be adopted in ResCoM replacing formerly used (in the same context) terms, such as ***closed-loop manufacturing system, closed-loop product system, circular product system, product multiple lifecycles*** and ***ResCoM product system***. The main purpose of adopting a new term is to introduce a term that is as holistic as the term (linear) 'manufacturing system.'

It is to be noted that the terms ***closed-loop system*** [4] and ***closed-loop supply chain*** [5] are also commonly used in literature referring to value recovery through product reusing, remanufacturing and material recycling. However, their context is the conventional manufacturing paradigm, where collection of products and value recovery mostly happens as a consequence of unplanned end-of-use/end-of-life scenarios. Furthermore, these value recovery activities are mainly motivated by the waste management and material recovery principles with limited business cases of remanufacturing.

Product multiple lifecycles is a concept that proposes the notion of predefined lifecycles, encompassing manufacturing, distribution, use, return, recover, remanufacture and reuse of the product. In this approach, the entire life of the product is divided into multiple lives of predetermined period (time or performance). After each designed lifecycle, the product is taken back for remanufacturing to the original performance specifications or upgrading to new specifications [3].

Circular economy 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. [6]

Remanufacturing is the process of restoring a non-functional, discarded, or traded-in product to a like-new condition [7]. In this process components of the used products are reused and/or upgraded and combined with newly manufactured components.

ResCoM-framework defines four organisational areas: ***business model, product design, supply chain*** and ***technology*** as the main pillars for implementation of circular manufacturing systems. T*echnology* in the context of the ResCoM-framework refers to manufacturing, remanufacturing and Information and Communication Technology (ICT).

Economic and environmental viability is proposed as a measure to identify the reference point when implementation of circular manufacturing systems should be questioned. For example, if there is a chance that the proposed circular manufacturing systems may either cost more or harm the environment more than the current practices (business as usual), the solutions should be carefully assessed. In cases when it may both cost more and harm the environment more than the current practices, the solutions should be completely abandoned and new solutions should be sought.

1. INTRODUCTION

It all started with an idea of conserving resources that manufacturing industries are consuming in their everyday activities. Since then the idea evolved and took the form of the research that is being carried out today. This chapter introduces the research topic and its evolution, the research motivation and the scope of the research covered in this dissertation.

Resource Conservative Manufacturing (ResCoM) is a research initiative that has evolved at the department of Production Engineering, KTH. One of the aims of this initiative is to develop a framework to support manufacturing industries in resource conservation through implementing circular manufacturing systems. In 2013, this initiative received funding from the European Union's Seventh Framework Programme for research, technological development and implementation. The research work presented in this dissertation is part of this initiative as well as the research project; both have the acronym ResCoM.

1.1 Research motivation

The society today lives on the philosophy of 'take-make-use-dispose'. In the long run, this is not sustainable as at one end resources are finite, meaning that we will not be able to 'take' as we wish or need. At the other end, the waste carrying capacity of the earth is also finite, meaning that we will not be able to 'dispose' as we wish or need. So, one side of the challenge is resource scarcity and the other side is wastes. With the boom in world population and increasing prosperity, these problems are becoming critical as the consumption of resources, generation of wastes and emissions are increasing in a proportional manner.

Although efficient usage of resources is a continuous effort in the manufacturing environment, in a conventional manufacturing company, this effort is limited only to manufacturing processes to minimise costs and wastes. A considerable amount of resources that manufactured products are often carrying at their end-of-use/end-of-life (EoU/EoL) is not a concern of manufacturers to conserve or recover. Research and industrial practices such as remanufacturing have shown that there is an enormous economic and environmental potential in the value recovery from products at their EoU/EoL, which is currently not being tapped by most of the manufacturers.

Motivated by the facts discussed above, this research investigated the possibilities of adopting circular manufacturing systems, in which profitability and environmental sustainability can be maintained at the same time without any trade-offs.

1.2 Research scope

As mentioned in the previous section, the core motivation of this research comes from the idea of resource conservation where economic performance and environmental sustainability is mutually inclusive. Being in the production engineering area, our natural interest has been manufacturing industries and the focus is extended from manufacturing processes to the systems. To be more specific, while endorsing recovery of materials through recycling, the primary interest has been in closing the loop of products/components through reusing and remanufacturing at an industrial scale. Due to this focus, the preliminary investigation started in the area of remanufacturing and conventional closed-loop supply chains. It is soon realised that in most cases the efforts for closing the loop of products/components at their EoU/EoL are made standing on the conventional manufacturing paradigm, where neither the products nor the manufacturing systems are designed to close the loop. As a result, except few pioneers in this field, most of the remanufacturers are struggling with classic barriers of remanufacturing including uncertainty in quality, quantity and timing of returning products. The greatest irony, however, is that most of the researchers and the practitioners in these fields are maintaining a conservative attitude and trying to solve the problems based on conventional thinking without appreciating the need for a paradigm shift. As the combined effect of the above-mentioned issues, remanufacturing is not becoming a mainstream business despite its sound benefits highlighted by researchers and industrial practices.

A major issue here is a lack of systemic view where the challenges of implementing circular manufacturing systems are seen as the effects of miss-alignments in different activities within the conventional (re) manufacturing systems. It is also important to appreciate that when a systemic view is under consideration, a systematic implementation and analysis approach becomes necessary. Based on this primary research a conceptual framework, addressed as the ResCoM-framework, has been developed which maintains a systemic view and takes a systematic approach towards the implementation of circular manufacturing systems.

However, from the development of a conceptual framework to actual adoption of this in an industrial environment is a long way. Such an adaptation demands that the framework is supported by systematic analysis, decision support and implementation tools, developed in relevance to real industrial cases. With this in mind, the ResCoM project started with four industrial case studies from different manufacturing sectors. Having said that, the research in ResCoM can be divided into four major categories as shown in Figure 1.

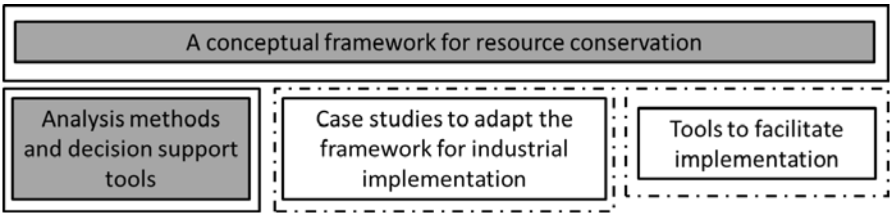

Figure 1: A schematic overview of the scope of the research within the ResCoM initiative, the EU project and the research covered in this dissertation.

The framework is the main body of knowledge which is continuously evolving as new insights are gained, problems are encountered and solutions are developed. Along the way, the framework itself or parts of it needs to be analysed and tested in order to ensure that the framework is ready for industrial implementation, for which case studies are being used. A framework like ResCoM challenges conventional manufacturing paradigm and proposes to bring changes in several core areas of a manufacturing organisation. Such radical changes can only gain traction in practice if proper analysis methods and decision support tools are available for trying out things before actual implementation. Furthermore, specific tools are also needed to facilitate implementation of the specific elements of the framework. My research contributions cover all these areas. Nevertheless, the main coverage of this dissertation is the development of the ResCoM-framework and development of analysis methods and decision support tools (marked with grey boxes and solid lines in Figure 1).

1.3 Problem statements, objectives and the research questions

The discussions above can be summarised in two main problem statements:

1. *Attempts to close the loop of the products/components at their end-of-life/end-of-use are carried out using conventional manufacturing thinking where neither the products nor the manufacturing systems are designed to close the loop. There is also a lack of systemic and systematic approach that can guide industries in implementing circular manufacturing systems.*

2. *Analysis methods and decision support tools are missing which can aid the implementation process by analysis the systemic dependencies among critical aspects that influence circular manufacturing systems.*

Having these problems as the background, one of the main objectives of the ResCoM initiative is to *"develop and test a framework to support industries in implementing circular manufacturing systems."* This development is an iterative process and this initiative is estimated to last for a time horizon of several decades, whereas, the research presented in this dissertation is the initial but significantly vital steps to support this long-term research. Besides contributing in developing the framework, an additional objective of my research is to *"develop analysis methods and decision support tools that can aid the implementation process of circular manufacturing systems."*

To address the problems and fulfil the objectives mentioned above, following research questions are answered as part of this research:

- *Research question 1: What elements are essential in order to implement circular manufacturing systems and why are those essential?*

- *Research question 2: How resource scarcity may influence manufacturing industries and how this influence can be incorporated in decision making to motivate implementation of circular manufacturing systems?*

- *Research question 3: What are the important characteristics of a closed-loop supply chain that is essential for implementing circular manufacturing systems and how can its performance be measured?*

- *Research question 4: How can the economic and environmental performance of circular manufacturing systems as proposed in ResCoM be measured?*

Section 4 and four papers appended to this dissertation answer these four questions respectively.

1.4 Research method

Research is a systematic process of collecting, analysing, and interpreting information (data) in order to increase our understanding of a phenomenon about which we are interested or concerned [8]. The research presented in this dissertation can be best ascribed as the applied research which aims at finding a solution for an emerging problem faced by a society or an industrial/business organisation [9].

Research is also a cyclic process that starts with a problem and/or a question and ends with the resolution of the problem or the tentative answer of the question [8]. In this process, several problems and/or questions may arise which also need to be solved and/or answered. As mentioned earlier, the ResCoM initiative is addressing problems that have a wider scope. On the other hand, the research presented in this dissertation addresses the subproblems of the ResCoM initiative which follows its own cyclic process. As apparent from the cyclic process in Figure 2, in order to solve the problems that the ResCoM initiative addresses, the subproblems must be solved with great cautions.

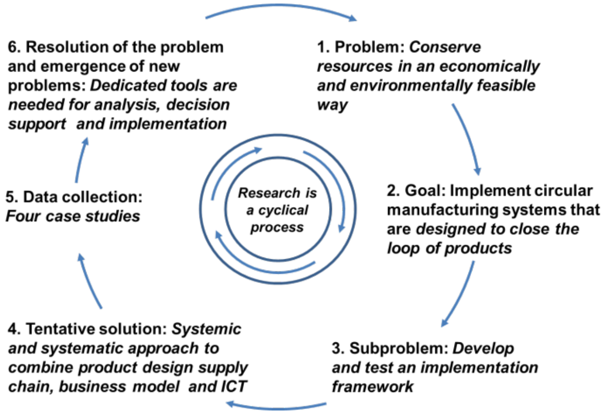

Figure 2: A six-step research process that is driving the ResCoM initiative (adapted from [8]).

Since the research in ResCoM is multidisciplinary, the 'mixed methods procedures' that combine qualitative and quantitative data in a study is used [10]. The foundation of the research work is laid based on research review where both scientific literature and industrial examples are reviewed following Creswell's (2002 [11]) five-step review process and synthesised following narrative synthesis process described by Denyer and Tranfield's, (2006 [12]). Figure 3 shows an overview of the research methods used in this research. Literature review and analysis is the primary method used in developing the conceptual ResCoM-framework (described in paper A) which is adapted using the case study approach. In paper B, C and D, system dynamics principles are used to develop analysis methods and decision support tools that are essential to support the implementation of circular manufacturing systems. The tools are developed on the platform called Stella and Anylogic, which simulate different aspects of circular manufacturing systems. To develop the analysis methods and decision support tools both qualitative and quantitative research approaches are used. Firstly, review of research is conducted to establish conceptual models (also known as causal loop diagram) based on qualitative approach and secondly, relationships among variables in models addressing different phenomena are mathematically defined based on quantitative approach. The analysis method and the generic tool that is described in paper D and in section 3.2 and 4.4 further adapted using the case study approach.

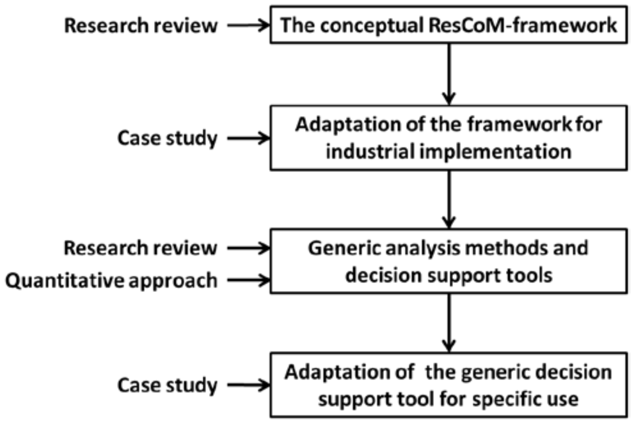

Figure 3: An overview of the research methods used in this work.

In conducting this research a large amount of information and data is collected and analysed. Depending on the type of information and data needed and the purposes of use, different data collection and analysis methods are used. As shown in the figure above, to develop the conceptual framework and the tools for analysis and decision support, review of research is carried out. Books, scientific publications in journals and conference proceedings, dissertations, technical reports and web-based sources are reviewed in this process. Google, Google Scholar, Primo (KTH library provided search engine) and Web of science are used as search engines. Different keywords are used depending on the objectives of the review. However, most commonly used keywords are remanufacturing, closed-loop supply chain, circular economy, system dynamics and resource conservation, etc. Information gathered from the above-mentioned sources are sorted and analysed as per the relevance and the objectives of the research. Relevant phenomena, evidence, facts and conclusions are documented using narrative synthesis approach. This process has resulted in outlining and describing the ResCoM-framework and formulating the conceptual models used in developing the analysis methods. These conceptual models are systematically analysed and given quantitative characteristics by mathematically representing them. This process is further described in chapter 3.

In addition to the thorough review of research, documented information and experience-based information is gathered from four case companies. In this process, internal documents of the companies are assessed and relevant people are interviewed. The process has resulted in several compiled documents that include information about the case studies and the case products. The documents also included information regarding the current ways of doing businesses, designing products, operating supply chains and managing product lifecycle information by the case companies. This process has also resulted in compiling requirements that the case companies have identified as important to be fulfilled in order to implement circular manufacturing system in their environments.

For data collection, roughly one week is spent at each company to interview several representatives. The interview sessions were organised according to four organisational areas, that is marketing/business model, product design, supply chain and information and communication technology. People representing these areas in each company were interviewed by a group of researchers from the relevant areas. Semi-structured interviews were used to collect information and gather experiences. The information gathered through the interviews was documented and all sessions were audio-recorded as well, which were eventually transcribed and added to the final documents. Each document was then reviewed and the information is analysed by both the research team and the respective company for accuracy and relevance of the information. In addition to the above-mentioned interview sessions, the case companies were contacted on numerous other occasions to collect information and data through questionnaires and informal interviews.

During the analysis method and tool development process focus group interviews were organised where representatives from each company were invited to experience partially completed methods and tools. They were also introduced to the ideas and the assumptions that are used to develop the methods and the tools to get feedback. Collected feedback is used in improving/adapting the analysis methods and tools further.

1.5 Overview of the dissertation

Followed by the introductory chapter, chapter 2 summarises the ResCoM initiative, project and framework with respect to other initiatives and industrial practices. Chapter 3 summarises the process of modelling complex systems. Chapter 4 summarises the research contributions in the form of answering the four research questions in brief. Chapter 5 briefly describes the process of implementing the generic decision support tool in industrial cases. Finally, chapter 6 includes final remarks, self-critiques and sets the directions for the future work. In addition to these four chapters, four papers are appended which answer the research questions in more details. Table 1 indicates which paper and section of this dissertation refer to the respective research questions.

Table 1: An overview of the relevance of research questions, papers and sections in this dissertation.

Research question no.	Paper no.	Section no.
1	A	4.1
2	B	4.2
3	C	4.3
4	D	4.3

The papers appended in this dissertation are listed below in the order of their appearance:

A. Rashid, Amir; Asif, Farazee M. A.; Krajnik, Peter & Nicolescu, Cornel M. (2013). Resource Conservative Manufacturing: An essential change in business and technology paradigm for sustainable manufacturing." **Journal of Cleaner Production**, 57, 166–177.

B. Asif, Farazee M. A.; Rashid, Amir; Bianchi, Carmine & Nicolescu, Cornel M. (2015). System dynamics models for decision making in product multiple lifecycles, **Resources, Conservation and Recycling**, 101, 20-33.

C. Asif, Farazee M. A.; Bianchi, Carmine; Rashid, Amir & Nicolescu, Cornel M. (2012). Performance Analysis of the Closed Loop Supply Chain, **Journal of Remanufacturing**, 2:4.

D. Asif, Farazee M. A.; Lieder, Michael & Rashid, Amir (2016). Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems, **Journal of Cleaner Production**, 139, 1261-1281.

Other papers in the order of publication year

1. M. Lieder, Farazee M. A. Asif and Amir Rashid, "Towards Circular Economy Implementation: An agent-based simulation approach for business model changes" **Autonomous Agents and Multi-Agent Systems**, 2017. DOI: 10.1007/s10458-017-9365-9
2. Michael Lieder, Ruud de Bruijckere, Farazee Asif, Mattias Löfstrand, Amir Rashid (2016). An IT-platform prototype as enabler for service-based business models in manufacturing industry, Proceedings of The 7th International Swedish Production Symposium 2016, Lund, Sweden.
3. Xu, Z.; Asif, Farazee M. A.; Löfstrand, M; Rashid, A. & Tymoshenko, S. (2014), Information Requirements and Management for Service Based Business Models, Proceedings of The 6th International Swedish Production Symposium 2014, paper no. 63, 16-18 September 2014, Gothenburg, Sweden.
4. Adane, Tigist F., Nafisi, M., Asif, Farazee M. A., Semere, Daniel T., Nicolescu, Cornel M. (2012). System Dynamics Analysis of Energy Usage: Case Studies in Automotive Manufacturing. Proceeding of the 5th International Swedish Production Symposium, 6th – 8th of November 2012, Linköping, Sweden.
5. Rashid, A., Asif, Farazee M. A., Krajnik, P.& Nicolescu, Cornel M. (2012). Multiple Life Cycles Product Systems: Redefining the Manufacturing Paradigm for Resource Efficient Production and Consumption, CIRP 10th Global Conference on Sustainable Manufacturing, 31st October- 2nd November 2012, Istanbul, Turkey.

6. Asif, Farazee M. A. (2011). Resource Conservative Manufacturing: a new generation of manufacturing, Licentiate thesis in Production Engineering, KTH Royal Institute of Technology, September 2011, 978-91-7501-112-7.
7. Asif, Farazee M. A. & Nicolescu, C. M., (2010). Minimizing Uncertainty Involved in Designing the Closed-loop Supply Network for Multiple-lifecycle of Products, Proceeding of the 21st DAAAM World Symposium, October 2010, University of Zadar, Zadar, Croatia.
8. Asif, Farazee M. A.; Semere, D. T.; Nicolescu, C. M. & Haumann, M., (2010). Methods Analysis of Remanufacturing Options for Repeated Lifecycle of Starters and Alternators. The Proceeding of the 7th International DAAAM Baltic Conference, "Industrial Engineering," Kyttner, B (Ed)., pp 340-345, ISBN-978-9985-59-982-2.
9. Asif, Farazee M. A.; Semere, D. T.& Nicolescu, C. M. (2009).A Novel Concept for the End-of-life Vehicle (ELV).The Proceeding of the International 3rd Swedish Production Symposium, 2-3 December 2009, Göteborg, Sweden.

Under review

10. M. Lieder, Farazee M. A. Asif, Amir Rashid Aleš Mihelič and Simon Kotnik, "A conjoint analysis of circular economy value propositions for consumers: using "washing machines in Stockholm" as a case study," **Journal of Cleaner Production**, 2017.
11. M. Lieder, Farazee M. A. Asif, Amir Rashid Aleš Mihelič and Simon Kotnik, "Towards circular economy implementation in manufacturing systems using a multi-method simulation approach to link design and business strategy," **The International Journal of Advanced Manufacturing Technology**, 2017.

2. RESOURCE CONSERVATION IN PRACTICE AND THEORY

This chapter introduces the ResCoM initiative and the framework. The chapter also discusses their relevance to other initiatives and industrial practices.

With the continuous growth of population that is estimated to reach 8.5 billion by 2030 [13], consumption of natural resources and generation of wastes are expected to rise in a similar manner. Although manufacturing activities are essential for the economic growth and account for 30.4% of the world GDP [14], manufacturing activities also raise concerns due to overwhelming consumption of natural resources and generation of a lot of wastes. As the economic growth and the consumption are the two sides of the same coin, it is not anymore an option to favour one over the other. For sustainable development, it has become essential to make attempts to reduce dependency on natural resources ([15] [16]) by decoupling the growth from the consumption [17] [18].

Furthermore, in last three decades, the household consumption expenditure per capita has increased by almost 36% [19]. One of the main drivers of this significant increase is the ‘take-make-use-dispose’ approach of consumers, which in many cases results in the residual value of products not being fully exploited. It has been claimed that in many cases products at their EoU/EoL retain up to 91% of the value [20] [21], pointing towards a huge economic opportunity currently not being tapped by the manufacturing industry. In this respect, it is also reasonable to assume that value recovery at a certain level from products at their EoU/EoL will also result in conservation of resources and reduction of wastes at a similar level, and eventually can decouple the growth from the consumption.

Having outlined the necessity of conserving resources in the discussions above, this chapter discusses practices and theories around resource conservation including a brief summary of the ResCoM initiative and the framework.

2.1 Resource conservation in practice

As mentioned earlier, in the context of the ResCoM-framework, reusing and remanufacturing of products/components is considered as the most viable option for resource conservation. Although historically remanufacturing activities are associated with lack of resources faced during the post WW2 time [22], the remanufacturing industry today is mainly run like any other business sectors with primary intention to make profits. De Brito *et al.* (2005) [23] reported a collection of case studies on remanufacturing highlighting that economic interests are the main business drivers in this sector. It is only in the cases when Original Equipment Manufacturers (OEMs) are performing remanufacturing, strategic issues such as green image, market protection and customer relations, etc. are being mentioned beside economic interests. This means, in the current context, the remanufacturing industry does not consider resource conservation as a mandate or a driver. In most cases, especially for 3rd party remanufacturers, it is just another business area that comes with additional challenges unique to this business [24] [25][1]. Despite challenges, both OEMs and 3rd party remanufacturers in different sectors are running successful remanufacturing businesses indicating that it is both strategically viable and technologically possible to overcome these challenges and remanufacture a wide range of products.

Furthermore, currently remanufacturing intensity (which is defined as the ratio of the value of production shipments of remanufactured goods to total sales of all products within a given industry sector) is still rather low, which is estimated to be only 2% in the US [26] and 1.9% in Europe [27].

[1] Remanufacturing Networks summarized as set of key barriers for remanufacturing from Guidat (2015) which is compilation of a number of research work.

This indicates that in order to make remanufacturing a key enabler for resource conservation, the current individual remanufacturing activities need to be scaled up to a level that is comparable to the activities in the conventional manufacturing industry.

2.2 Resource conservation in theory

Two aspects became vividly apparent during this research. Firstly, in most cases efforts to close the loop of products through remanufacturing are done following the conventional manufacturing paradigm. Secondly, there is no framework that suggests a systemic approach and a paradigm shift to support the implementation of circular manufacturing systems.

Many challenges that the remanufacturing industry is facing are classic and inherent to the fact that neither the products nor the manufacturing systems are designed for closing the loop. For example, uncertainty in quality, quantity and timing of returning products (usually address as “cores”) is considered as the key issue hindering remanufacturing businesses. With a closer look, it became obvious that if a viable business model is not in place products will return at random quantities at a random time. Moreover, if products are not designed to be remanufactured and knowledge about product usage is missing, quality of returning products becomes an issue. Solving these classic problems that have been in place for decades, demand a systemic approach to the problems and a paradigm shift.

Furthermore, the body of research work that suggests solutions to overcoming these challenges is quite fragmented and often concentrated on one specific aspect. For example, only designing products for remanufacturing, designing and optimising reverse supply chain networks for efficient recovery of products or increasing customers’ acceptance to promote remanufacturing, etc. may solve one or few of the problems, but the overall situation will remain unchanged for the remanufacturing industry. So, for a paradigm shift, a framework that takes systemic and systematic approach is essential.

Based on these initial findings, the ResCoM-framework outlines some fundamental requirements which need to be fulfilled in order to implement circular manufacturing systems:

- Look at the challenges from a system perspective. This means that business model, product design, supply chain or technological solutions such as ICT solutions individually cannot solve the problems as these areas are interlinked.
- An appropriate business model with clear value propositions is in place and rest of the activities should follow the business model.
- Forward and reverse supply chains are integrated.
- Predefined EoU/EoL strategies are in place.
- OEMs that own the final product are the major stakeholders in such business and preferably it should be steered by them. First tier suppliers can also be in the leading role if their supplied products are a major part of the final product.
- Closing the loop of products should be both economically and environmentally viable.

The ResCoM-framework is developed to support industries to implement circular manufacturing systems. Yet the framework is unique and at the conceptual level, and for its acceptance, empirical data from case studies is needed. With this in mind, the ResCoM project has been initiated with the funding from the EC. The project brought together experts from the fields of manufacturing, business, product design, supply chain, remanufacturing and ICT in order to further adapt and test the ResCoM-framework. For the first time, the research team started to look at all the challenges not in isolation but as the interacting elements of a complex system. The project aimed at several outcomes with the major ones listed below:

- Test the ResCoM-framework using four case studies collected from the consumer electronics, white goods, automotive parts and lifestyle products manufacturing sector.

- Develop a collaborative IT-platform that supports industries to understand and manage interlinks that exist among business model, product design, supply chain and ICT aspects.
- Develop methods and tools to facilitate decision support and analysis of different aspects such as the economic and environmental performance of implementing circular manufacturing systems.
- Develop methods and tools that help in solving particular issues related to the implementation. For example, develop a method to design products for multiple lifecycles with predefined EoU/EoL strategies.

2.3 ResCoM vs Circular Economy initiative

Although the introduction of the core principles of 'Circular Economy' (CE) [28], [22] and the introduction the term dates back to mid-60s and early-90s [29] respectively, the successful rebirth of CE has happened in 2013 through the Ellen MacArthur Foundation (EMF) in the UK. Since then the discussions and initiatives around CE started to boom in a similar fashion as sustainability boomed in last two decades. Most of these discussions emphasise mainly the needs for a paradigm shift and drivers at a higher level.

Furthermore, most of the CE reports and work so far discuss mainly the necessity, pros and cons as well as challenges of CE and rarely touching implementation aspects [22] such as how to implement CE concepts in industries. While discussions about these dimensions of the CE initiative should continue in parallel, emphasis should be given on the implementation approaches. This is extremely important in order to ensure that the value of the CE initiative does not get lost in the similar way as many of the sustainability initiatives lost their value in the past. Similarly, more and more companies (the EMF's CE 100 network is such an example) are appearing as successful adaptors of the CE concepts, claiming to have benefited by implementing CE. Although many of those examples are promising, there is hardly any case that shares details of the implementation process for others to gain knowledge.

The ResCoM initiative, on the other hand, shares the same vision as the CE initiative, which is resources conservation by design but emphasises the implementation. ResCoM provides a framework and sets the manufacturing industry as the boundary. ResCoM is in the process of testing the framework and aims to spread the learning from the case studies to relevant industries. ResCoM also plans to develop methods and tools as well as outline a collaborative platform, and share those with a wider audience.

2.4 Realising the systemic approach

Both the ResCoM and the CE initiatives are highlighting the need for a systemic and systematic approach. In ResCoM, business model, product design, supply chain and ICT aspects are included in this system approach. It also considers that business model, product design, supply chain and ICT aspects that are relevant for implementing circular manufacturing systems are interacting and influencing each other. Therefore, all developments in ResCoM are aimed at systemic approach considering the dynamics of space and time. For example, ResCoM collaborative IT-platform aims at understanding and managing interlinks that exist between business model, product design, supply chain and ICT aspects. Similar is the case for the analysis methods and tools that are developed where the systemic approach is the focus. Therefore, part of the research in ResCoM proposes a multi-method approach that includes different well established modelling methods such as System Dynamics (SD), Agent-Based (AB), and Discrete Event (DE) for developing the analysis methods. Based on these analysis methods, decision support tools are developed for the implementation of circular manufacturing systems. Furthermore, new methods are also developed to support the multi-method approach, where necessary. For example, Product Design Index (PDI) is a method developed to incorporate in the multi-method approach. In this dissertation, SD has been used as the main method for modelling different phenomena described in paper B, C and D. In paper

D, the AB and the PDI method has been used in addition to the SD method.

SD is an established method acknowledged for its ability to model and help in understanding complex systems with feedback across time and space [30]. SD was first used to model supply chain by Forrester (Forrester, 1958) in the 1950s and since then it has been widely used to model supply chains for different applications including closed-loop supply chains [31] [32]. AB method is also used in modelling complex systems that emerge from interactions between social networks of actors and physical networks of technical artefacts, where actors are often individuals [33]. Applications of the AB models for describing and understanding consumer behaviour and consumer decision-making, considering individual consumer characteristics, have just recently received attention. Research in this area focuses on the market diffusion of newly introduced products [34] [35], consumer multichannel choice behaviour [36] [37], consumer habits [38], consumer motivations [39] and public pressure (including customers) on environmental behaviour of firms [40]. All these examples indicate the compatibility of the AB method in modelling business models. However, there is no method available that is compatible to incorporate design aspects that are relevant for implementing circular manufacturing systems. Therefore, PDI method is a novel development in this work.

In summary, the three methods, i.e. AB, PDI and SD are considered appropriate to model the aspects of the business model, product design and supply chain respectively. Furthermore, a combination of these methods and their inherent characteristics of managing complex interactions also contributed in realising the ResCoM vision of the systemic approach.

3. MODELLING OF COMPLEX SYSTEMS

Relating to the discussions in section 2.4, this chapter describes the basic principles of system dynamics and the mechanisms of developing analysis method based on system dynamics. This chapter also describes how the analysis method is used in developing a generic decision support tool capable of measuring the economic and environmental performance of circular manufacturing systems.

3.1 System dynamics basics

In the process of decision making, we tend to think linear, meaning that we see a problem, decide on an action and expect that our action will resolve the problem as expected. This open loop impression of the world is shown in Figure 4.

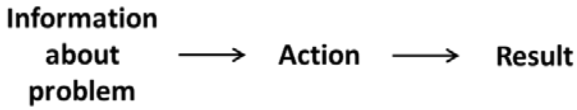

Figure 4: Open loop impression of the world [41].

In reality, a problem leads to an action and the action produces a result that may create further problems or alter the nature of the initial problem. As soon as the nature of the problem changes or new problems appear, the initial action does not remain relevant anymore. This demands that the initial action is changed or a new action is endorsed. This closed-loop structure of the world or a system is shown in Figure 5.

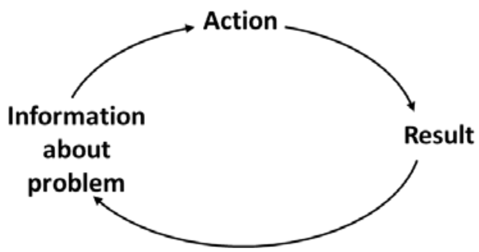

Figure 5: Closed-loop structure of the world [41].

In the decision making process, we seldom realise the existence of these feedback loops that change over time. In dedicated situations, decision makers do consider the existence of the feedback loops, but often fail to appreciate the existence of other sub-systems or considerable time delays that may exist between when actions are taken and the results are obtained. As a result, although decision makers may have the impression of non-linear and closed-loop structure of the given systems, the final outcomes may turn out to be completely different than anticipated. As illustrated in Figure 6, a decision maker may extrapolate the performance of a given system based on his/her perception of the system but can end up getting completely different outcomes if feedback from other sub-systems and delays in the system are ignored. As it can be imagined, more feedback from the sub-systems and/or the delays (and longer the delays) in the systems are considered more complex and unpredictable the final outcomes of that system becomes.

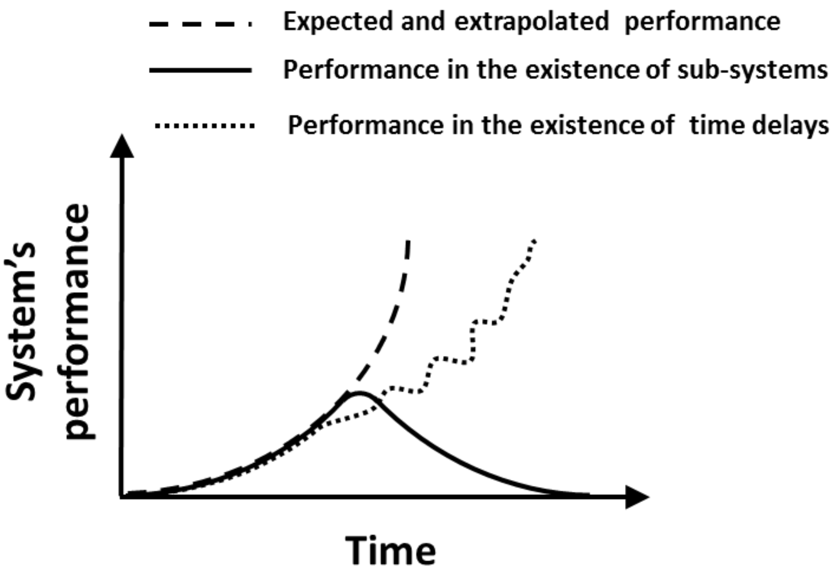

Figure 6: An example of system's performance over time illustrating different outcomes that may result from consideration of feedback loops and time delays.

In reality, a system can have either a positive or a negative feedback loop. A positive feedback loop which is also known as self-reinforcing feedback loop exhibits exponential growth or decay behaviour. A negative feedback loop which is also known as balancing feedback loop exhibits goal seeking behaviour. A negative feedback loop in the presence of time delays shows oscillating behaviour. A combination of a positive and a negative feedback loop create a system behaviour which is known as the s-shaped growth (behaviour). A system can consist of many different sub-systems of positive and negative feedback loops with many short and long time delays. A combination of these will determine how a system will behave over time. The primary interest, however, is not only to create models to observe the behaviour of the systems but also to use the models to find ways to create the system behaviours that are most desirable. For example, if a system exhibits exponential growth while the expectation is to obtain a goal seeking behaviour, the model can assist in finding the critical variables that dominate the behaviour and thereby, aid in controlling the system's behaviour by manipulating those critical variables. This leads to the discussion regarding how systems are modelled using system dynamics principles and how to use these models to improve the behaviours of systems which is further elaborated below.

In system dynamics the above-discussed principles are applied in the form of articulated problems, for instance, maintaining the level of inventory in a manufacturing system. The problems are then represented using mental models, also known as Causal Loop Diagram (CLD) as shown in Figure 7. CLDs are used in order to identify the system's internal feedback loops and the connection points with other active feedback loops that affect the problem at hand.

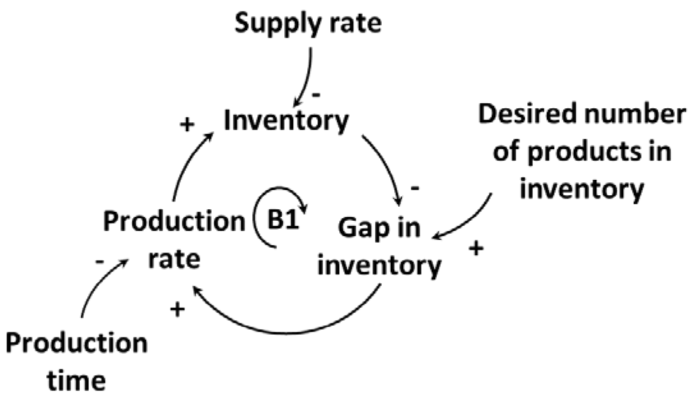

Figure 7: An example of a causal loop diagram to represent a problem.

The mental models are then mathematically expressed considering the interactions and feedback loops among different elements (variables) of the system. Following mathematical expressions are valid for the example discussed above,

$$Inventory(t) = \int_{t_0}^{t} [Production\ rate\ (s) - Supply\ rate\ (s)]\, ds + Inventory(t_0)$$

where, $Production\ rate\ (s)$ represents the value of the production rate at any time s between the initial time t_0 and the current time t.

$$Gap\ in\ invetory = Desired\ number\ of\ products\ \ in\ invetory - Inventory$$

$$production\ rate = \frac{Gap\ in\ invetory}{Production\ time}$$

These mathematical expressions are then coded in computer simulations for further elaboration and visualisation. The computer simulation models are represented with three elements known as stock, flow and variable that connect all model elements as shown in Figure 8.

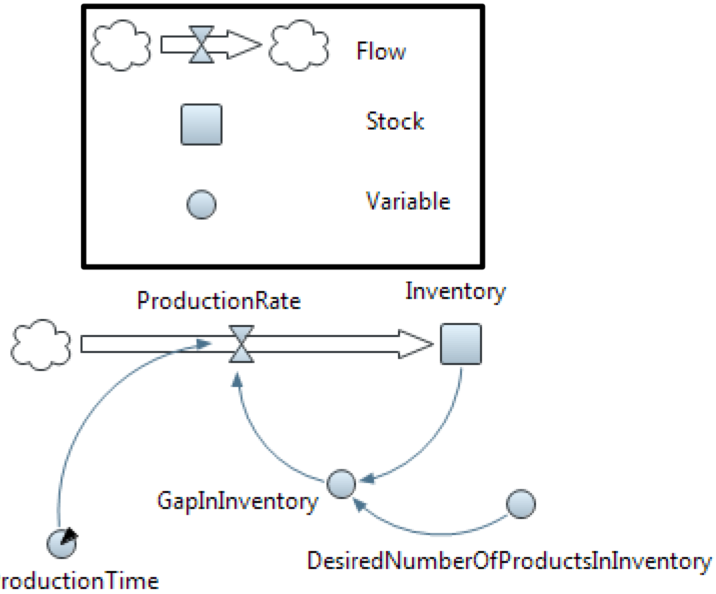

Figure 8: A screenshot from the Anylogic simulation platform showing different symbols that represent the CLD and the mathematical expressions of the example discussed above.

In system dynamics, each of these elements has its distinct characteristics, where a flow is expressed by a differential equation and a stock is expressed by an integral equation. A variable (also addressed as the auxiliary variable) creates a mathematical equation of its own which is mainly used for the ease of communication and clarity.

To summarise, complex modelling starts with an articulated problem that defines the issues to be addressed. Then the purposes of the model are defined and the time horizon under which the behaviour of the system will be analysed is set. Once the problem is defined, the theory that supports the problem is also developed. After that several sub-steps are taken which include defining the model boundaries, outlining the sub-system diagrams and developing the CLDs. After that simulation model is created by converting the CLDs to a stock and flow diagram. This is done by defining the mathematical relations and coding them in computer simulation software. After that, the model is tested and the results are evaluated.

A complete model may consist of many feedback loops interacting with each other and may have several stocks, flows and variables, which means a lot of mathematical relations to take care. To give an example, the generic analysis method and tool presented in paper D and described in section 3.2 is developed using 17 stocks, 17 flows, 9 delays and 32 input and auxiliary variables resulting in several complex relations and interactions. The following section provides an overview of this development.

3.2 Implementing complex modelling techniques in developing the analysis method and generic decision support tool

A relevant question concerning the implementation of circular manufacturing systems is whether it will be economically and environmentally feasible or not. In other words, how the economic and the environmental performance of a circular manufacturing system will behave compared to the current conventional manufacturing system over time. This is one of the key questions that all the four case companies are seeking an answer. However, each case company has its own vision of the circular manufacturing system, comprising its own business model, product design and supply chain aspects. For example, one case company wants to implement the leasing model together with their conventional sales model. The idea is to sell and lease products through the same supply chain channels. When the first leasing period is over, the products will be brought back and remanufacturing operations will be performed. After remanufacturing, products will be leased again to new customers.

After the second leasing period is over, the products will be brought back and remanufacturing operations will be performed again. After remanufacturing is performed for the second time, the products will be sold on the 2nd-hand market. All these activities are to be performed in specific locations in Europe and products will be manufactured in a location in Asia. Similarly, other case companies have their own circular manufacturing systems with different requirements to explore. As part of this research, four decision support tools are developed for the four case companies fitting to their needs. Each of these tools consists of a SD based supply chain model, a AB market (business) model and a PDI based product design model. In this process, first a SD based supply chain model fitting to a generic circular manufacturing system is created. This model includes all relevant critical factors of business model, product design and supply chain. These critical factors are identified by combining state-of-the-art research review, industrial practices and input from the case companies. The process of developing the SD based supply chain model includes developing the conceptual models, the logics, converting the logics to mathematical relations and coding the mathematical relations in the simulation software. This process also includes connecting SD based supply chain model with inputs from the AB models and the PDI models to create a complete analysis method and the generic tool for decision making. To make the modelling approach effective a modular approach is used, that is creating small modules of the models and put them together to make one complete model. This entire development process starting from the conceptual model to the executable computer simulation is described step-by-step in the section below. Note here that, in this process, one of the main contributions has been to develop the SD based supply chain model. Therefore, the discussions below only cover the supply chain model and exclude the AB model. Furthermore, the PDI method is also one of the major contributions, but the generic tool only takes the outputs of the PDI model and uses those as one-time input. Therefore, detailed discussions on how the concepts, logics and mathematical relations are used to develop the PDI method is not a relevant discussion for this section. The details of the PDI method are described in paper D.

As mentioned earlier, the purpose of all the tools developed for the case companies is to measure the economic and environmental performance of their circular manufacturing systems. In other words, the purpose is to 'study the behaviour of the economic and environmental performance of the circular manufacturing system.' Although the purpose of the generic method and tool is also the same, the circular manufacturing system in this context includes leasing model in addition to the conventional sales model. The assumptions of this generic method and tool are given below.

Assumption: Within the leasing model, new products are leased for certain duration and after the first leasing, the products are brought back and remanufactured. After remanufacturing the products are leased again. When the second leasing period is over, the products are brought back again and recycling for material recovery is performed.

Assumption: As more products are leased to the market more products will return and more products will be remanufactured.

Assumption: If remanufacturing costs less and causes less emission, more products remanufacturing (as an alternative of new product manufacturing) means overall costs and CO_2 emissions will be reduced.

Assumption: If manufacturing cost is lower, the manufacturer will have the possibility to reduce the price of the leasing offer, which will increase attractiveness and therefore, generate more demand for leasing.

Assumption: If reduction of CO_2 emission is communicated to the customers appropriately, this will improve the environmental image of the leasing offer causing the demand for leasing to rise.

The overall conceptual models that are used to create the generic tool are shown in Figure 9 and Figure 10.

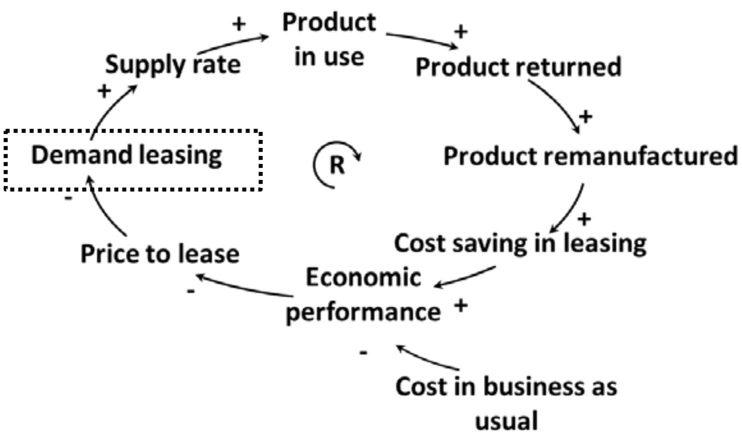

Figure 9: CLD of economic performance of a circular manufacturing system.

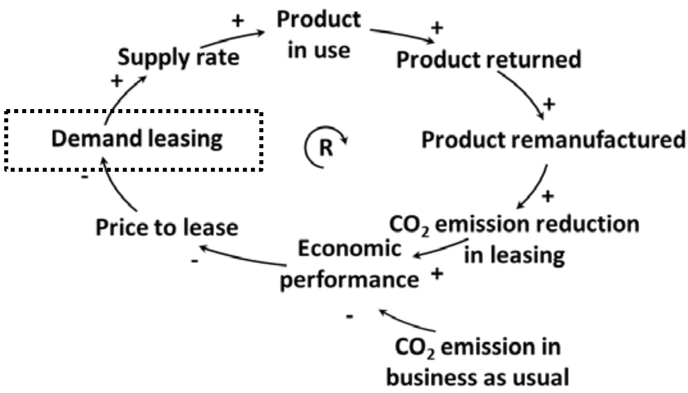

Figure 10: CLD of environmental performance of a circular manufacturing system.

The CLDs shown above consider only one business model, which is leasing. For additional business models, more feedback loops need to be included. Note also that in the CLDs how many times a product will be remanufactured is not mentioned. To include additional remanufacturing stages, additional stages of material flows need to be considered in the simulation model. Now, in order to identify the feedback that is relevant let us zoom in one of the elements of the CLDs, that is 'demand leasing' (highlighted with a broken-lined rectangle in Figure 9 and Figure 10). The feedback loop that is highly relevant for this element is shown in Figure 11.

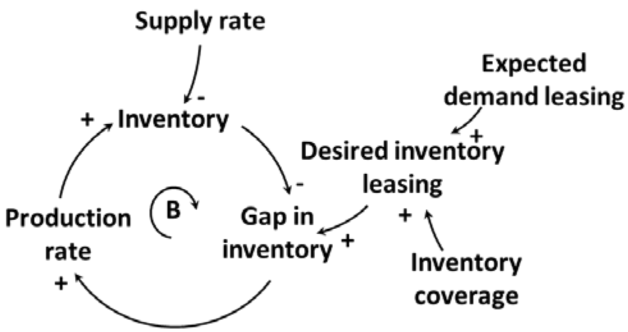

Figure 11: CLD of inventory control mechanism.

The CLD shown above can be expressed by following mathematical equations assuming that inventory is a stock and production rate, as well as supply rate, is a flow. Rest of the variables are input and auxiliary variables.

$$Inventory\ (t) = Inventory(t - dt) + (Production\ rate - Supply\ rate) * dt$$

$$Desired\ inventory\ leasing = Expected\ demand\ leasing * Inventory\ coverage$$

<u>Assumption:</u> There is no capacity constraint in production rate. This means that the production rate adapts instantly with the increase or decrease of the gap in inventory.

As mentioned earlier, in the context of the generic tool the circular manufacturing system consists of a combination of leasing and conventional sales model that uses a common supply channel. This means in order to control the inventory, the demand for sales has to be considered as well. So, the updated CLD will look like as shown in Figure 12.

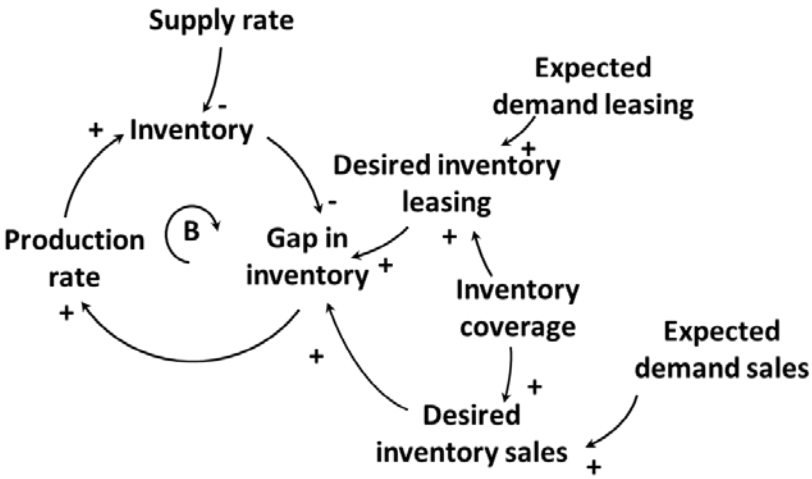

Figure 12: CLD of inventory control mechanism combining leasing and sales model.

The CLD shown above can be expressed by the following mathematical equations,

$$Inventory\ (t) = Inventory(t - dt) + (Production\ rate - Supply\ rate) * dt)$$

$$Gap\ in\ inventory = (Desired\ inventory\ leasing + Desired\ inventory\ sales - Inventory)$$

$$Desired\ inventory\ leasing = Expected\ demand\ leasing * Inventory\ coverage$$

$$Desired\ inventory\ sales = Expected\ demand\ sales * Inventory\ coverage$$

As also mentioned earlier, in the context of the generic method and tool, products are leased twice by performing remanufacturing at the end of each leasing period addressing them as multiple lifecycle products. From here on let us address respectively 1st life products, 2nd life products and .....nth life products when new products, one-time remanufactured and .... (n-1)th-time remanufactured products are leased. As products are leased several times, this requires a more complex inventory control mechanism than what is shown in Figure 12. At this point, a new assumption (which is confirmed by all case companies) is made.

Assumption: In leasing, if the products are designed for several lifecycles, then the latest lifecycle products will be prioritised to fulfil the demand.

This means, if the products are designed for two lifecycles where the products will return once and remanufactured once, an OEM will try to fulfil the demand by supplying the 2nd life products first and if 2nd life products are not available then demand will be fulfilled by supplying newly manufactured products. This mechanism of fulfilling the demand is shown in Figure 13. Continuing further with this assumption, the updated CLD of the inventory control mechanism combining leasing and sales model with two lifecycle products look like as shown in Figure 14.

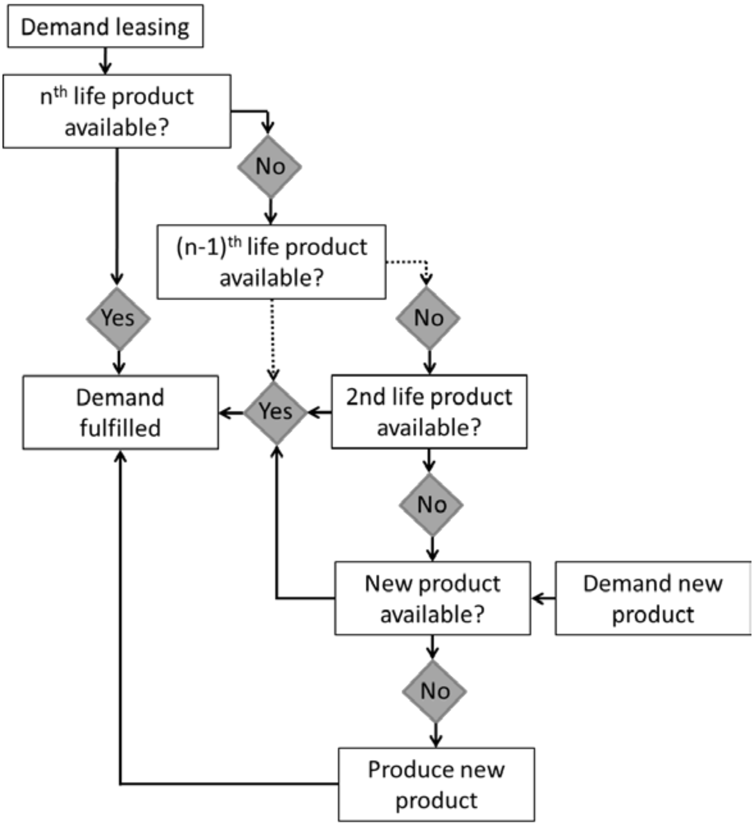

Figure 13: The mechanism of fulfilling the demands in case of multiple lifecycle products with conventional sales and leasing model.

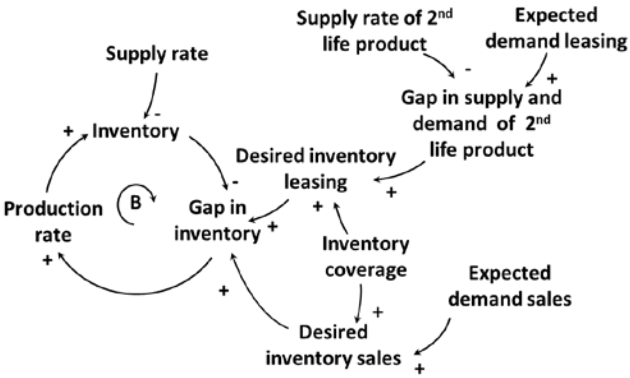

Figure 14: CLD of inventory control mechanism combining conventional sales and leasing model with two lifecycle products

The CLD shown above can be expressed by the following mathematical equations,

$$Inventory\ (t) = Inventory(t - dt) + (Production\ rate - Supply\ rate) * dt)$$

$$Gap\ in\ inventory = (Desired\ inventory\ leasing + Desired\ inventory\ sales - Inventory)$$

$$Desired\ inventory\ leasing = Gap\ in\ supply\ and\ demand\ of\ 2^{nd} life\ product * Inventory\ coverage$$

$$Gap\ in\ supply\ and\ demand\ of\ 2^{nd} life\ product = Expected\ demand\ leasing - supply\ rate\ of\ 2^{nd} life\ product$$

$$Desired\ inventory\ sales = Expected\ demand\ sales * Inventory\ coverage$$

Up to this point the logics of only one part of the generic analysis method and tool is described with an example. To accommodate all the above-mentioned assumptions the supply chain of the circular manufacturing system is created with production, use (two times), return (two times), remanufacturing and recovery (two times) stages as shown in Figure 15 and Figure 16. The following section describes how all the logics (CLDs) and the mathematical expressions/equations (including the ones described above) are implemented to create a complete executable computer simulation[2].

[2] The name of the variables used from this point forward slightly differs from the name of the variables mentioned in the section above. The reason of this difference is, to code the logics, mathematical expressions/equations in the computer simulation platform the names needed to be adapted accordingly in order to fit the requirements of the simulation platform.

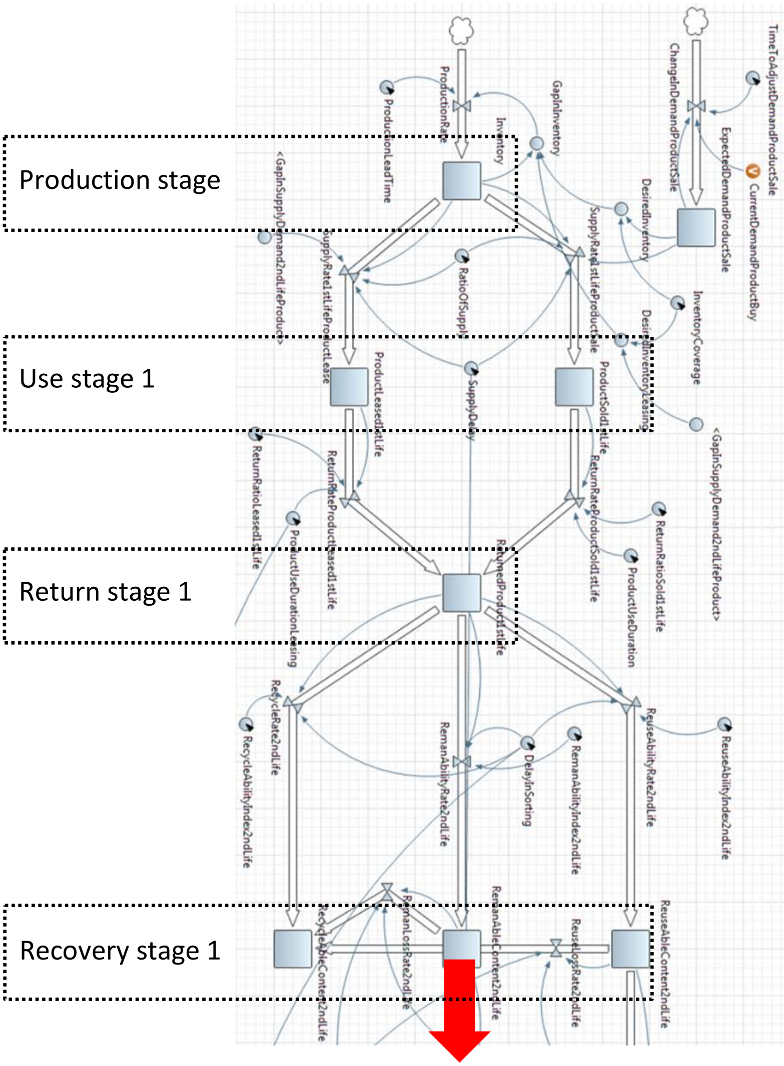

Figure 15: Stock and flow diagram of the supply chain (to increase the readability the diagram is split at the arrow).

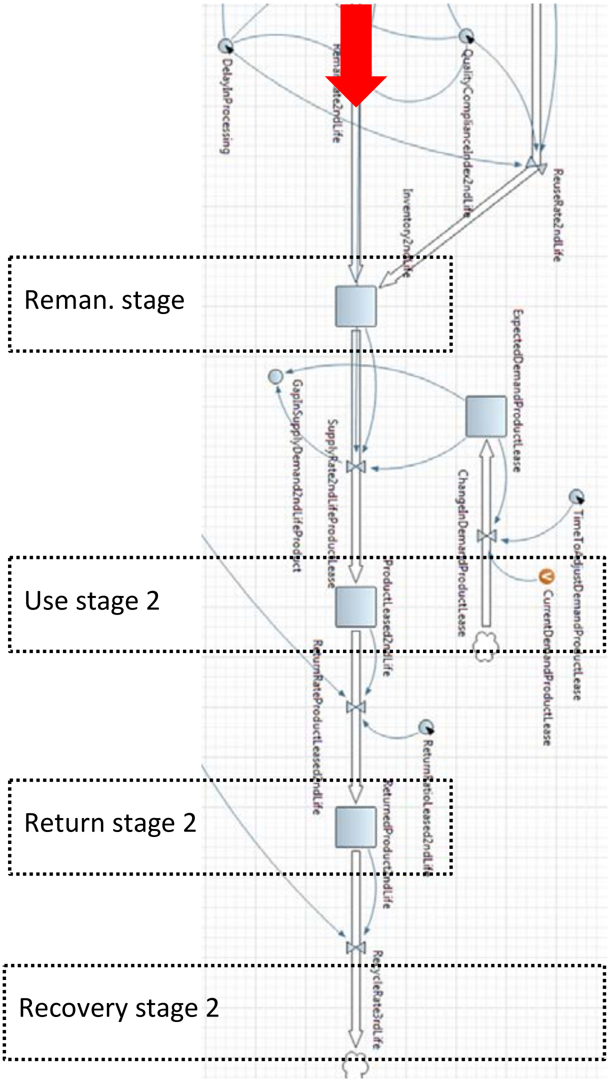

Figure 16: Stock and flow diagram of the supply chain (continued; to increase the readability the diagram is split at the arrow).

The demand fulfilling mechanism described above and shown in Figure 13 is implemented in the simulation platform as shown in Figure 17.

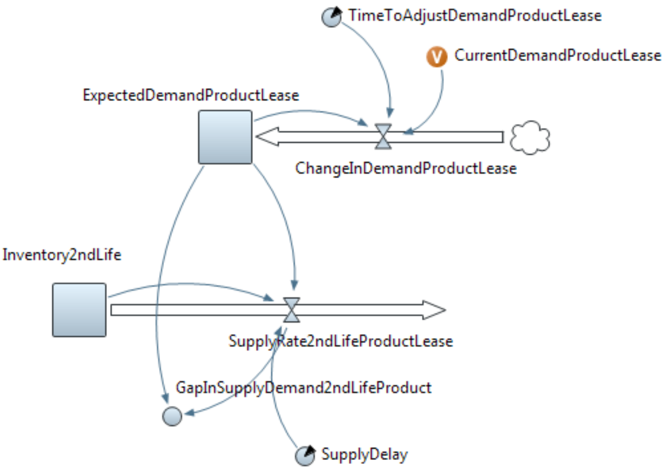

Figure 17: Stock and flow diagram of the supply and the demand for leasing of the 2nd life products.

The figure shown above illustrates that the supply chain is triggered by the demand coming from the market in the form of *CurrentDemandProducLease*[3].

Assumption: There is usually an information delay in updating information about the demand and synchronising that information with the internal production planning. Therefore, a variable called *ExpectedDemandProductLease* is added.

[3] The words written in *Italic* font from this point forward are the terms used in the computer simulation. The definition of these terms and detailed mathematical equations are included in the appendix of Paper D.

The mathematical equations used here are,

$$ExpectedDemandProductLease\ (t) = ExpectedDemandProductLease\ (t - dt) + (ChangeInDemandProductLease) * dt$$

If there are enough products in the *Inventory2ndLife*, the leasing demand is met by supplying products from the inventory, for which the following equation is used. Here, the minimum function is used in order to make sure that no products are supplied when products are not available in the *Inventory2ndLife* (this is also to make sure that the inventory does not generate any negative values).

$$SupplyRate2ndLifeProductLease = min((Inventory2ndLife / SupplyDelay), ExpectedDemandProductLease)$$

If there are not enough products in the *Inventory2ndLife*, a variable called *GapInSupplyDemand2ndLifeProduct* is created which is expressed as,

$$GapInSupplyDemand2ndLifeProduct = (ExpectedDemandProductLease - SupplyRate2ndLifeProductLease)$$

This gap is then used as feedback to the inventory of the new products and thereby, the demand is fulfilled by supplying new products. This mechanism is shown in Figure 18.

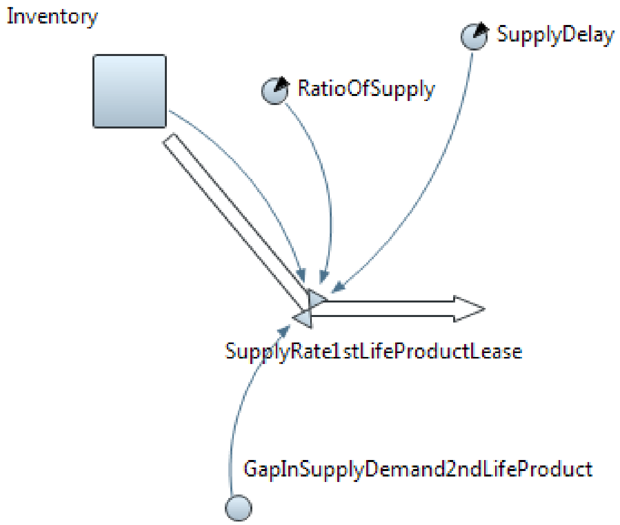

Figure 18: Demand fed back to the inventory of new products to fulfil the demand and thereby, reduce the *GapInSupplyDemand2ndLifeProduct.*

The equation is expressed as,

$$SupplyRate1stLifeProductLease = min((Inventory/SupplyDelay) * (1 - RatioOfSupply)), GapInSupplyDemand2ndLifeProduct)$$

Here, the *RatioOfSupply* is an input variable used with the intention that in case there are more demands (combining both demands for buying and leasing) than the number of products available in the *Inventory*, the products are equally distributed to partially fulfil the demands for buying and leasing.

The market demand for selling products is handled as shown in Figure 19 and described below.

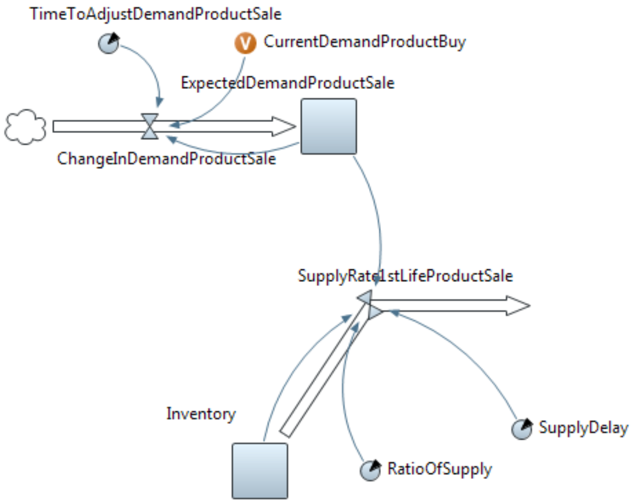

Figure 19: Stock and flow diagram of supply and demand for buying of 1st life products (new products).

The figure shown above illustrates that the supply chain is triggered by the demand coming from the market in the form of $CurrentDemandProducSale$. The corresponding equations are,

$$ExpectedDemandProductSale(t) = ExpectedDemandProductSale\,(t - dt) + (ChangeInDemandProductSale) * dt$$

$$SupplyRate1stLifeProductSale = min(((Inventory/SupplyDelay) * RatioOfSupply), ExpectedDemandProductSale)$$

Combining the demand fulfilling mechanism of both the demands for leasing (shown in Figure 17 and Figure 18) and buying (Figure 19) the inventory control mechanism is modelled as shown in Figure 20

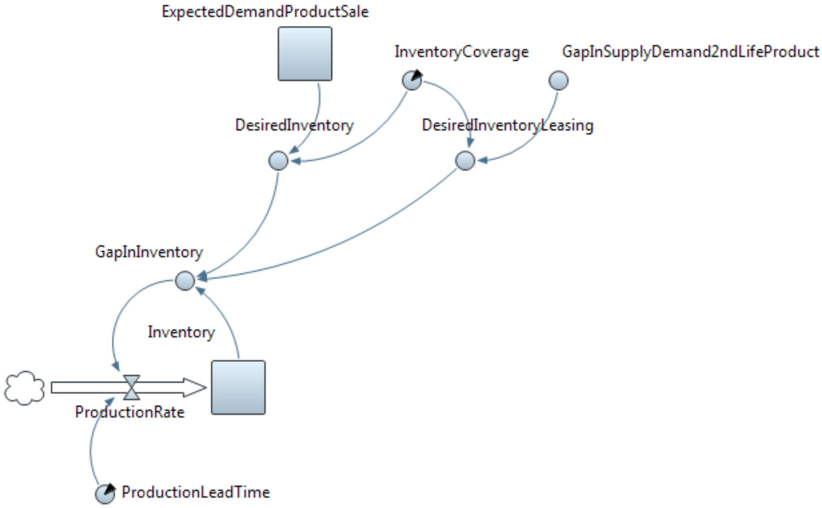

Figure 20: Stock and flow diagram of the inventory control mechanism combining the demand fulfilling mechanism of both demand for leasing and buying.

The corresponding equations are,

$$DesiredInventory = ExpectedDemandProductSale * InventoryCoverage$$

$$DesiredInventoryLeasing = GapInSupplyDemand2ndLifeProduct * InventoryCoverage$$

$$GapInInventory = (DesiredInventory + DesiredInventoryLeasing) - Inventory$$

$$ProductionRate = (GapInInventory / ProductionLeadTime) > 0?\,(GapInInventory / ProductionLeadTime): 0$$

In the equation above, >=0? :0 function (which is same as the 'IF-THEN-ELSE' function. This means IF a value of a variable is greater than zero THEN take the value ELSE take zero) is used to avoid having negative value for the production rate.

Up to this point, the demand fulfilling and the inventory control mechanism of the circular manufacturing systems is described. These mechanisms are important for two main reasons. Firstly, these mechanisms make sure that the demand for leasing is always met despite remanufactured (2^{nd} life) products are available or not. If not enough remanufactured products are available demands are met by supplying newly manufactured (1^{st} life) products. Secondly, the inventory level is maintained and the production rate is controlled considering both demands for buying and leasing. These are extremely important for reducing the uncertainty that conventional closed-loop supply chains suffer from.

In the coming section remaining all stages of the supply chain are described that combine different product design attributes. As mentioned earlier, the products move from the production stage to the use stage through two flows, i.e. *SupplyRate1stLifeProductSale* and *SupplyRate1stLifeProductLease*. After being in the use stage for a certain duration, products enter the return stage through the *ReturnRateProductSold1stLife and ReturnRateProductLeased1stLife* as shown in Figure 21.

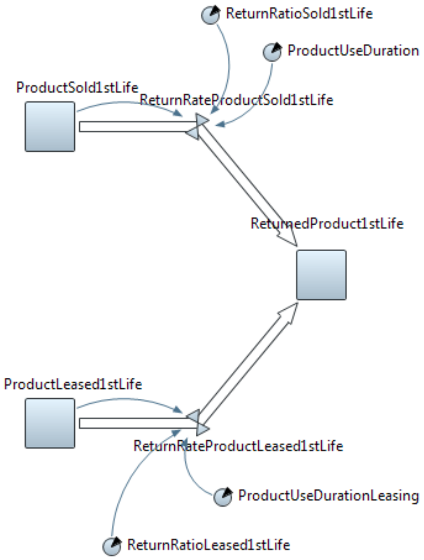

Figure 21: Stock and flow diagram showing products moving from the use stage to the return stage.

The corresponding equations are,

$$ReturnRateProductSold1stLife = (ProductSold1stLife/ProductUseDuration) * ReturnRatioSold1stLife$$

$$ReturnRateProductLeased1stLife = (ProductLeased1stLife/ProductUseDurationLeasing) * ReturnRatioLeased1stLife$$

The return ratios, in this case, are the variables that determine how many products will return from the market. The ratio can have any value between 0 and 1, where o means no products and 1 means all products will return. From the return stage, products move to the recovery and the remanufacturing stage where recycling and remanufacturing is performed as shown in Figure 22.

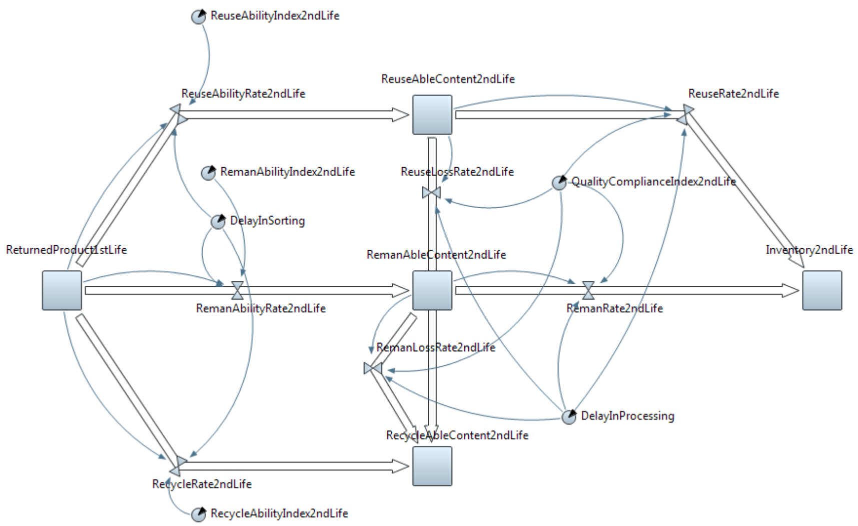

Figure 22: Stock and flow diagram showing products moving from the return stage to the recovery and remanufacturing stage.

The corresponding equations are,

$$ReuseAbilityRate2ndLife = (ReturnedProduct1stLife/DelayInSorting) * ReuseAbilityIndex2ndLife$$

$$RemanAbilityRate2ndLife = (ReturnedProduct1stLife/DelayInSorting) * RemanAbilityIndex2ndLife$$

$$RecycleRate2ndLife = (ReturnedProduct1stLife/DelayInSorting) * RecycleAbilityIndex2ndLife$$

$$ReuseLossRate2ndLife = (ReuseAbleContent2ndLife/DelayInProcessing) * (1 - QualityComplianceIndex2ndLife)$$

$$RemanLossRate2ndLife = (RemanAbleContent2ndLife/DelayInProcessing) * (1 - QualityComplianceIndex2ndLife)$$

$$ReuseAbilityRate2ndLife = (ReturnedProduct1stLife/DelayInSorting) * ReuseAbilityIndex2ndLife$$

$$RemanRate2ndLife = (RemanAbleContent2ndLife/DelayInProcessing) * QualityComplianceIndex2ndLife$$

ReuseAbilityIndex2ndLife, *RemanAbilityIndex2ndLife and RecycleAbilityIndex2ndLife* are the design indices indicating the ratio 0f the components (or equivalent mass) of a product being designed for reusing, remanufacturing and recycling. These indices are the outputs of the PDI method described in paper D. Index, in this case, is a ratio that can have any value between 0 and 1. This means that if a product is designed with the *ReuseAbility, RemanAbility and RecycleAbility* index of 0.4, 0.4 and 0.2 respectively, in an ideal case 40%, 40% and 20% of the component/mass of that product will be reused, remanufactured and recycled at the EoL. Note also that the indices can be expressed at mass or component level whichever is relevant in a particular product design case. However, when this information is included in the generic tool, it is assumed that indices at component/mass level have the same weight at the product level. This means, if *ReuseAbility* index at the component level is 0.4, it is assumed that 40% of the products that will return from the market will be reused. This is a necessary conversion as the generic tool is created at the product level.

Furthermore, *QualityComplianceIndex2ndLife* is another ratio that is introduced to define the system's loss. For example, even if a product is designed with a certain index of *ReuseAbility and RemanAbility* in reality when the product will return some of the components (or equivalent mass) of that product will not be re-useable or remanufacture-able as planned due to quality issues. This is in-line with the classic challenge in the conventional remanufacturing or closed-loop supply chains, which refers to the uncertainty in quality of the returning products. From this stage, the remanufactured products moved to the use stage 2 and products are leased for another lifecycle. After the products are being leased for the 2nd time, products are brought back and recycling is performed as shown in Figure 23.

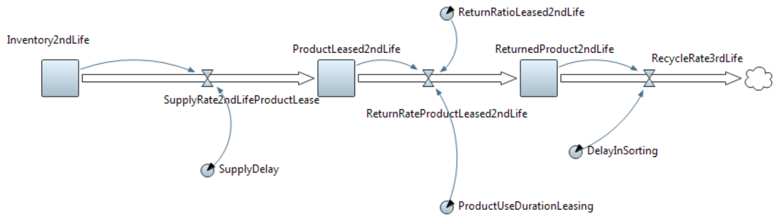

Figure 23: Stock and flow diagram showing products moving from the remanufacturing stage to the 2^{nd} use stage and eventually returning back (return stage 2) and being recycled (recovery stage 2).

The corresponding equations are,

$$SupplyRate2ndLifeProductLease = min((Inventory2ndLife / SupplyDelay), ExpectedDemandProductLease)$$

$$ReturnRateProductLeased2ndLife = (ProductLeased2ndLife / ProductUseDurationLeasing) * ReturnRatioLeased2ndLife$$

$$RecycleRate3rdLife = ReturnedProduct2ndLife/DelayInSorting$$

With this, the supply chain of the product flows end. However, as mentioned earlier, this model is created using a modular approach which makes it easier to extend the model to include additional business models and lifecycle stages if need. Up to this point, the model is capable of measuring the total demand severed by supplying remanufactured and newly manufactured products. It can also measure how many products are returned after each leasing period and how many products are recycled after each leasing period. This information is used to create the supply chain extension model that measures the economic and environmental performance as shown in Figure 24.

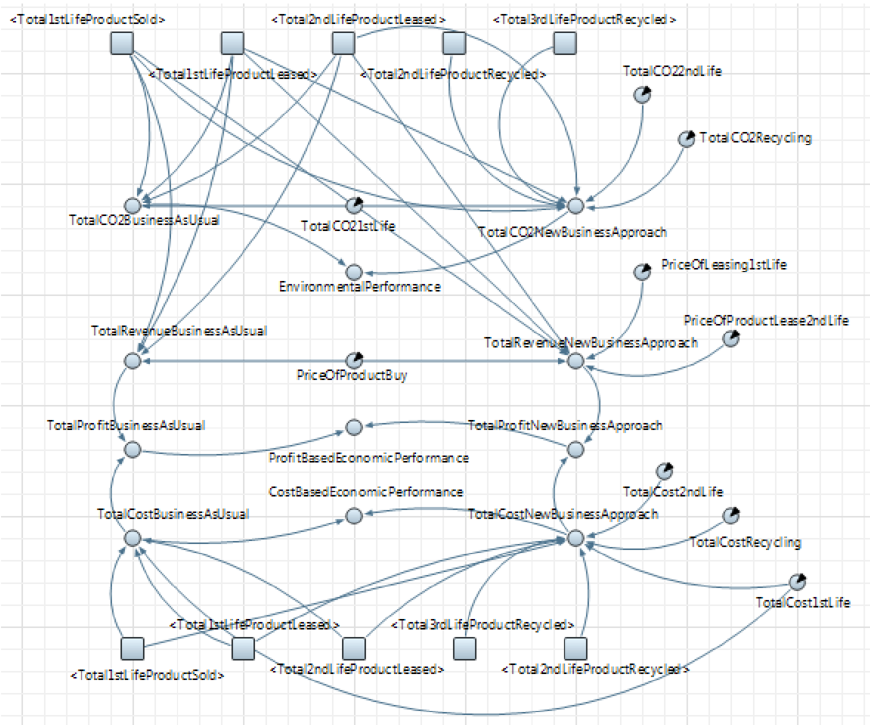

Figure 24: Stock and flow diagram of the supply chain extension model that measures the economic and environmental performance.

Assumption: In this context, the economic performance is measured based on cost and profit and the environmental performance is measured based on carbon emission (kg CO_2 eq.). In both cases, the performance of a circular manufacturing system is a ratio that is measured against the performance of the conventional manufacturing system (i.e. the business as usual).

For example, to measure the environmental performance, total CO_2 emission in all stages of the circular manufacturing system is measured and compared to the business as usual system. To clarify this further, let us assume that in a circular manufacturing system 30 customers are served by selling 10 new products, leasing 10 new products and leasing 10 remanufactured products. Assume also that all these activities together emitted 30 kg of CO_2 equivalent. Now to measure the environmental performance, the total amount of CO_2 emission that would have resulted if 30 customers would have been served by selling 30 new products in the business as usual system is measured. Assume that in the business as usual system this would have emitted 40 kg of CO_2 equivalent. Combining this would give the environmental performance, which is 40/30= 1.333.

Similarly, assume that the total cost incurred in a circular manufacturing system is 20 Euro. Assume also that, if these 30 customers would have been served by selling 30 new products in the business as usual system, the cost would have been 30 Euro. Combining this would give a cost based performance, which is 30/20= 1.5. In a similar way, assume that the total profit gained in a circular manufacturing system is 30 Euro. Assume also that, if these 30 customers would have been served by selling 30 new products in the business as usual system, the profit would have been 40 Euro. Combining this would give a profit based performance, which is 30/40= 0.75.It is important to note that in the case of measuring the profit based economic performance the numerator and the denominator of the equation are altered. As one of the main objectives has been to generate a positive numerical value (greater than 1) to indicate better/higher performance and vice versa, this alteration is necessary. As the result of this alteration, a lower total profit in a circular manufacturing system (compared to the total profit in the business as usual system) will create a numerical value smaller than '1'.

Figure 25 shows the mechanism how the environmental performance is measured.

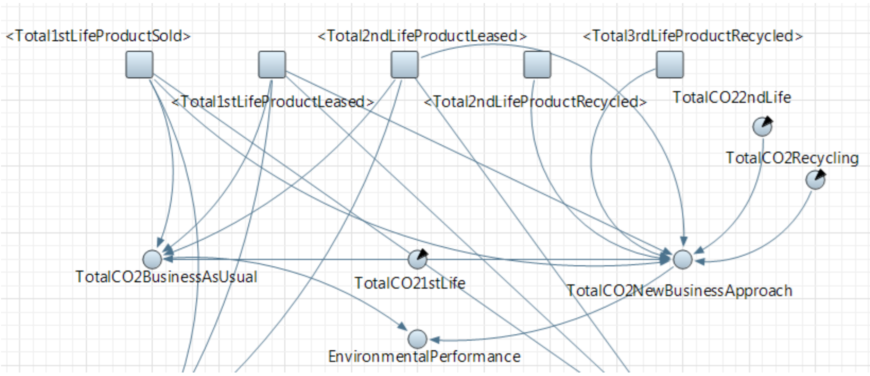

Figure 25: Stock and flow diagram of the supply chain extension model that measures the environmental performance.

The corresponding equations are,

$$EnvironmentalPerformance = TotalCO2BusinessAsUsual / TotalCO2NewBusinessApproach$$

$$TotalCO2BusinessAsUsual = (Total1stLifeProductSold + Total1stLifeProductLeased + Total2ndLifeProductLeased) * TotalCO21stLife$$

$$TotalCO2NewBusinessApproach = (Total1stLifeProductSold + Total1stLifeProductLeased) * TotalCO21stLife + Total2ndLifeProductLeased * TotalCO22ndLife + (Total2ndLifeProductRecycled + Total3rdLifeProductRecycled) * TotalCO2Recycling$$

Similarly, Figure 26 shows the mechanism used to measure the economic performance.

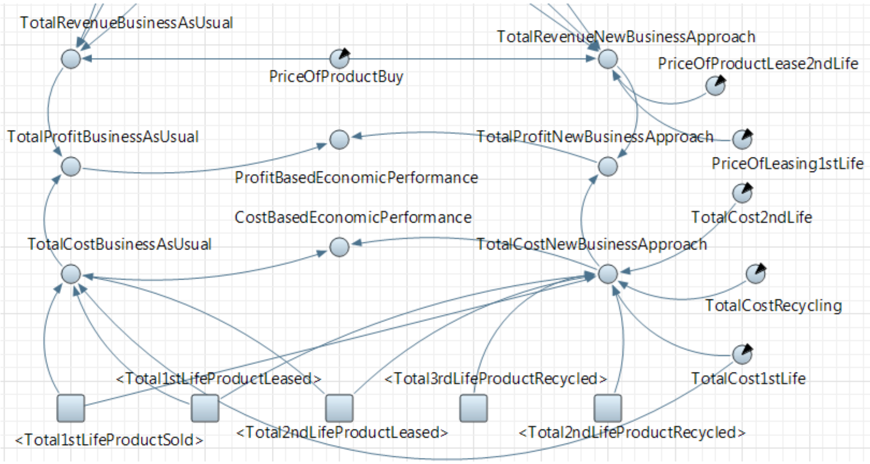

Figure 26: Stock and flow diagram of the supply chain extension model that measures the profit and cost based economic performance.

The corresponding equations for measuring the cost based economic performance are,

$$CostBasedEconomicPerformance = TotalCostBusinessAsUsual / TotalCostNewBusinessApproach$$

$$TotalCostNewBusinessApproach = (Total1stLifeProductSold + Total1stLifeProductLeased) * TotalCost1stLife + Total2ndLifeProductLeased * TotalCost2ndLife + (Total3rdLifeProductRecycled + Total2ndLifeProductRecycled) * TotalCostRecycling$$

$$TotalCostBusinessAsUsual = (Total1stLifeProductSold + Total1stLifeProductLeased + Total2ndLifeProductLeased) * TotalCost1stLife$$

The corresponding equations for measuring the profit based economic performance are,

$$ProfitBasedEconomicPerformance = TotalProfitNewBusinessApproach / TotalProfitBusinessAsUsual$$

$$TotalProfitNewBusinessApproach = TotalRevenueNewBusinessApproach - TotalCostNewBusinessApproach$$

$$TotalRevenueNewBusinessApproach = (Total1stLifeProductSold * PriceOfProductBuy) + (Total1stLifeProductLeased * PriceOfProductLease2ndLife) + (Total2ndLifeProductLeased * PriceOfLeasing1stLife)$$

$$TotalProfitBusinessAsUsual = TotalRevenueBusinessAsUsual - TotalCostBusinessAsUsual$$

$$TotalRevenueBusinessAsUsual = (Total1stLifeProductSold + Total1stLifeProductLeased + Total2ndLifeProductLeased) * PriceOfProductBuy$$

It should be noted that in this case the cost and the CO_2 emission related inputs are included in an aggregated form and if needed, these input variables can be broken down to make the scope of the estimation wider and the estimation more accurate. For example, currently, *TotalCO21stLife* is an aggregation of the CO_2 emission that includes all activities in the 1st lifecycle which for example, can be split in CO_2 production, CO_2 transportation and CO_2 recycling (at EoL), etc.

Concluding here the explanation on how the analysis method and generic tool is developed. This generic tool is the core, which is adapted to develop four case company specific decision support tools. Section 5 describes some generic aspects of these case specific tools and how those are used to analyse the circular manufacturing systems envisaged by the case companies.

4. RESEARCH CONTRIBUTIONS

This chapter summarises the research contributions in relation to the appended papers and in the form of answering the research questions mentioned in section 1.3.

In section 1.5 a list of all the papers published during the research is included, from which 4 most recent and relevant papers are selected for this dissertation. The main reasons for excluding some of the papers are, either the papers have already been used in the Licentiate dissertation or the papers are not directly within the scope of the research work presented in this dissertation.

In the following sections, all four research questions mentioned in section 1.3 are answered briefly by summarising the contents of the appended papers. A detailed answer to each question is available in the appended papers.

4.1 Answer to the research question 1

What elements are essential in order to implement circular manufacturing systems and why are those essential?

As defined earlier, the ResCoM-framework is developed to guide industries in implementing circular manufacturing systems. In developing this framework the conventional remanufacturing and the closed-loop supply chain paradigm is challenged with five major interventions as discussed below.

New approach to resource flows

Referring to the hierarchy of the EoU/EoL strategies of products, it is generally acknowledged that reusing and remanufacturing are the most preferred strategies from the economic and environmental perspective

[42] [43] [44]. Therefore, ResCoM aims at keeping the loop of products/components closed in their original form and for a longer period as long as they are economically and environmentally viable.

In general, the conventional manufacturing systems are entirely dependent on 'take-make-use-dispose' approach with material recycling as the best EoU/EoL strategy. Although from the economic and the environmental perspective recycling is a preferred strategy over disposal and incineration, it is still in the bottom part of the hierarchy of EoU/EoL strategies in terms of resource conservation. Furthermore, in this approach recovery of manufacturing value added from a product is low and product is generally intended to be used for one lifecycle.

In the case of the conventional remanufacturing systems, the level of resource conservation through remanufacturing is relatively higher as compared to recycling only, but the overall benefits that may be achieved are not optimum due to not having any control over products from the first lifecycle to the second. Although in such approach products have two lifecycles, the overall gains are low as the remanufacturing activities are not supported by appropriate business models, product design and supply chains. With this, the conventional remanufacturing systems run into the problem of uncertainty in quality, quantity and timing of the returning products.

Unlike the conventional manufacturing and remanufacturing systems, in ResCoM as shown in Figure 27, products are aimed to be used multiple times where reusing and remanufacturing strategies are designed as an integrated part of the manufacturing systems. In doing so, a product or its components are only considered for recycling to recover materials, when they cannot be reused or remanufactured in an economically and environmentally viable way.

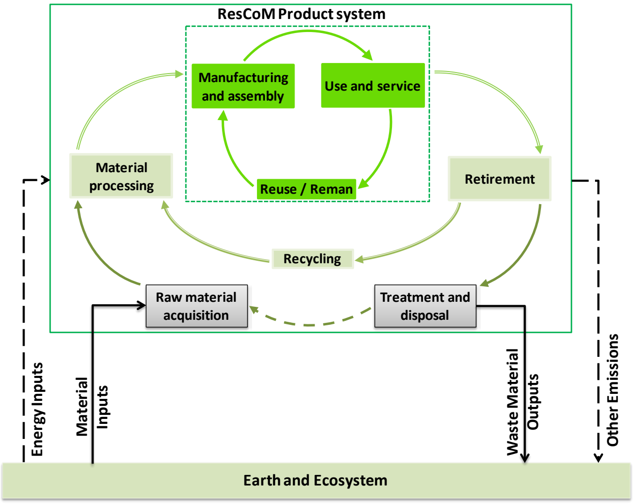

Figure 27: Concept of product system with closed-loop of material flows as envisaged in ResCoM.

As it can be imagined, in such closed-loop approach the possibility of value recovery is higher due to multiple usages of the products and components in their original forms. However, to make this approach technically feasible and to optimise resource conservation, products need to be designed for multiple lifecycles with predefined lifecycle/end-of-life management strategies as described below.

New approach to product design

As shown in Figure 28, in conventional approach a product's performance drops over time which is kept to a desired level through maintenance. As time passes, the performance of the product continues to drop and eventually the product reaches to its EoL. This is the point in time when products are usually classed as waste and in almost all cases, this is the time when lifecycle of the prevailing remanufacturing products start, looking for a possibility of recovering value when it has literally failed to function. Being too late in the product lifecycle, this approach causes two serious problems: unreliable quality of the returned products and uncertainty in the timing of returning products. As a result of this, remanufacturing becomes challenging.

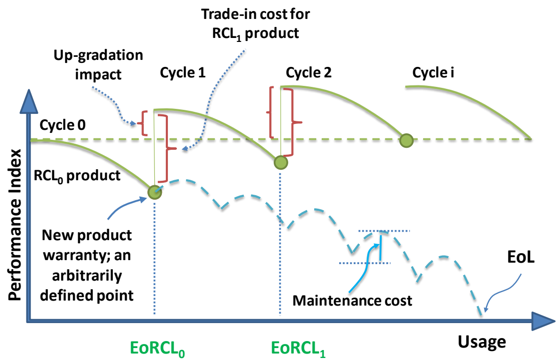

Figure 28: Comparison of the conventional lifecycle (blue- dotted curves) and the ResCoM lifecycle (green solid curves). The detail of the different notations in the figure is explained in paper A [3].

ResCoM design approach proposes the notion of predefined multiple lifecycles, encompassing the manufacturing, distribution, use, return, recover, remanufacture and reuse of the product. In this approach, the entire life of a product is divided into multiple lives of predetermined period (time or performance). After each designed lifecycle, the product is taken back for remanufacturing to the original performance specifications or upgrading to new specifications. With this approach, the problem of unreliable quality is partly solved as the quality of the returned products become relatively deterministic. This also solves the uncertainty in recovery time-frame to a great extent as products are planned to be returning on a specific time. However, product design alone cannot solve the quality issue completely, as the quality of returned products is often dependent on users' interactions with the products during the use phase.

Furthermore, such approach requires that there is a supply chain in place that can assure forward and reverse flow of products in multiple occasions, meaning that integration of forward and reverse manufacturing functions becomes vital. This also requires that the product and the lifecycle planning information is stored and communicated with relevant partners at the right time. In an advanced scenario, product usage and condition monitoring data can also be collected and made available during product collection, recovery and remanufacturing stages. Therefore, ResCoM design also emphasises on ICT, both internal and external to the products, to facilitate efficient management of multiple lifecycles.

New approach to closed-loop supply chain

A conventional closed-loop supply chain designed to collect EoU/EoL products and sell remanufactured products in a secondary market as a cheaper alternative to OEM-manufactured new products is not considered closed in the context of the ResCoM-framework. In fact, in most conventional cases remanufacturing activities are run as an open-loop supply chain with the illusion of a closed-loop supply chain. For example, for a 3rd party remanufacturer, the supply chain is always open which starts with collecting used products and ends with delivering the remanufactured products to a new market that is willing to accept a cheaper alternative to OEM-manufactured new products. All the activities performed by the 3rd party remanufacturers are typically done independently without involving OEMs. Such a strategy creates an open-loop supply chain (as shown in Figure 29) for a remanufacturer which is quite often addressed as a closed-loop supply chain in conventional thinking.

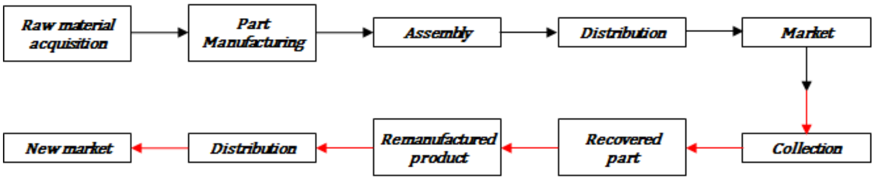

Figure 29: Remanufacturing is performed by the 3rd party and the products are distributed to a different market where two supply chains are operating in parallel, one for the manufacturer and the other for the remanufacturer (adapted from [1] [45]).

A relatively difficult to detect open-loop supply chain is formed when an OEM or an authorised 3rd party remanufacturer of behalf of the OEM runs the remanufacturing activities. As the collection, remanufacturing and re-distribution activities in such cases are done by the OEMs (or authorised 3rd party remanufacturers); this is often mistaken as the closed-loop supply chain. The main reason to avoid labelling this (as shown in Figure 30) as a closed-loop supply chain is, that the OEMs run remanufacturing as parallel to their manufacturing activities having no or very little connections with the new product manufacturing. Further confusion arises when an OEM uses the same distribution channels and sells the products to the same market as a cheaper alternative to their own products. As both manufacturing and remanufacturing functions are run independently often competing with each other, it creates an open-loop supply chain which is quite often misunderstood as a closed-loop supply chain.

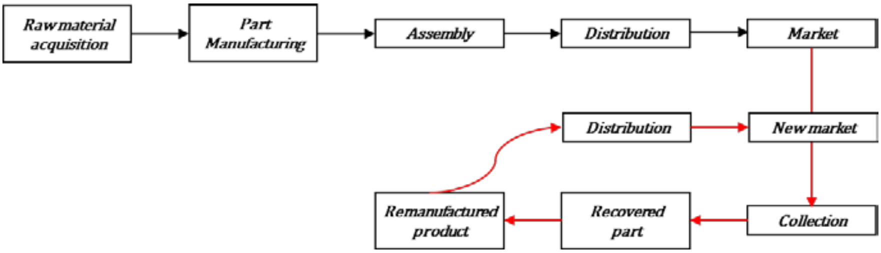

Figure 30: Remanufacturing is performed by an OEM or an authorised 3rd party remanufacturer, but the products are distributed through a different channel and to a different market. Here manufacturing and remanufacturing functions are run in parallel activities having no or very little connections, often mistaken as a closed-loop supply chain (adapted from [1] [45]).

Nevertheless, in both cases when remanufacturing is performed by independent 3rd party remanufacturers or OEMs, the supply chains suffer from its classic drawbacks that include uncertainty in quality, quantity and timing of returning products and mismatch between supply (of used products) and demand (of remanufactured products). In addition, when remanufacturing is performed by the OEMs, cannibalization is considered as a potential threat [46], [47]. Solutions to overcome these drawbacks lie in the integration of the forward and the reverse supply chain as proposed in the ResCoM-framework in order to create a closed-loop supply chain as shown in Figure 31.

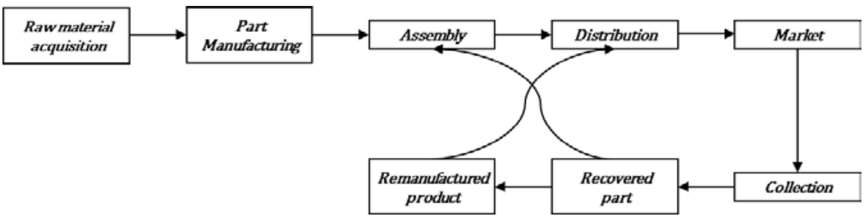

Figure 31: Remanufacturing is performed by an OEM or a 3rd party remanufacturer, but the products are distributed through the same channel and to the same market. The ResCoM-framework proposed closed-loop supply chain (adapted from [1] [45]).

In this approach, remanufacturing activities are an integrated part of the manufacturing functions where new and remanufactured products and components complement each other in fulfilling the market demand. The combination of the product design approach with predefined lifecycle strategies and a well-integrated supply chain means that the issues with quantity, quality and timing of the returning products are minimised. This also means a balance between supply-demand and fewer possibilities for cannibalization. However, this approach puts a lot of demand on customers in terms of accepting remanufactured/reused products/components and also returning the products. This means a sound relationship between OEMs and customers is fundamental for the success of this approach. Business model innovations can be a way to establish such relationships which are discussed below.

New approach to integrate customers in businesses

Although customers can play a vital role in supplying used products to solve some of the challenges faced by the remanufacturing sector, this opportunity is not fully tapped in conventional remanufacturing and closed-loop supply chain practices. In fact, in most cases, the collaboration between OEMs (or remanufacturers) and customers is completely missing or even weaker than in conventional manufacturing. There is no mechanism in place that obliges (except of few legislations such as 2002/96/EC on WEEE [48] and 2000/53/EC on vehicles [49] and 2005/64/EC on motor vehicles with regard to their re-usability, recyclability and recoverability [50] aimed at efficient management of wastes) or motivates customers to return products back to the OEMs or the 3rd party remanufacturers. Under the given circumstances, it is also not an interest of customers to better maintain products during the usage and help ensure a certain level of quality to make remanufacturing processes effective for OEMs. Furthermore, customers' acceptance of remanufactured products, despite assuring same quality and safety as well as providing the same guarantee as of a new product is rather low [51] [52]. As customers are both at receiving and providing end, their lack of involvement and motivation contributes to the uncertainty in quantity, quality and timing of returning products and leads to a mismatch between supply-demand.

The discussions above on integrating customers in businesses outlines that for any business models it is important for both OEMs and customers to understand the additional business value obtained through this integration. For an OEM that wants to implement circular manufacturing systems, the minimum and necessary business value is still profitability. In addition to this, through integrating the customers in the business, the OEM can obtain a certain level of reliability in their supply chains to ensure return of products in right quantity and quality at the right time. For a customer, the minimum business value is to obtain a product that fulfils the desired functions and the product is affordable in his/her perception. The customer may consider being part of the business if additional business values are provided. Furthermore, these additional business values must give the customer a feeling that the product is worth paying for and is better than obtaining a product in a conventional way.

To illustrate it further, let us assume that an OEM would like to increase the reliability in quantity, quality and timing of returning products. To increase the supply chain reliability, the OEM might need to invest in product design, supply chain networks and customer communication to increase their willingness to return products. This investment needs to be justified for the given level of reliability increase in the supply chain. This indicates that the OEM should be able to relate or measure the investment in relation to the supply chain reliability. Similarly, for the increased reliability in the supply chain, the customers need to be integrated rather strongly in the business. This means while ensuring the minimum business value, i.e. a product that fulfils the desired functions and is affordable, the OEM need to offer additional value propositions that can outperform any conventional offers. The value propositions can include competitive price, better payment schemes, flexibility to return/exchange products, higher service level and better environmental image, etc. Here also, both the OEM and the customers should be able to relate or measure the business value in relation to the supply chain reliability and level of integration of the customers in the business.

Considering these two sides of the business value, ResCoM proposes business model innovations that ensure a balance in the value for both OEMs and customers. To integrate customers with different levels of engagement fitting to the desired level of supply chain reliability and other business objectives, ResCoM suggests business models (but not limited to), ranging from buy-back to functional sales. For example, as shown in Figure 32, an OEM ready to work with the lowest level of supply chain reliability can adopt the buy-back model, where for the customers the value proposition is the monetary benefits received when products are returned. Similarly, an OEM accepting only the highest level of supply chain reliability can adopt the functional sales model, where the customers can receive service, maintenance, consumables, etc. included in the value propositions. These business models can be implemented as replacing or in a hybrid form and in parallel to the conventional product sales model.

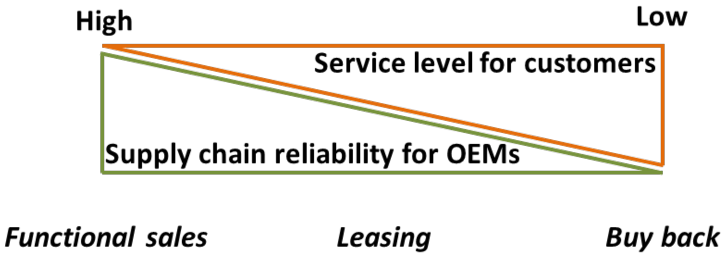

Figure 32: An example to illustrate balance in business value for OEMs and customers.

In order to integrate OEMs and customers in a ‘bottom-up’ approach using the business value as the instrument, there is also need for a ‘top-down’ approach. The ‘top-down’ approach includes social innovations that highlight environmental and societal benefits as a value proposition of circular manufacturing systems and legislative efforts to increase industry's uptake and customers' acceptance.

To summarise, four interventions of the state-of-the-art mentioned above, i.e. new approach to resource flows, product design, closed-loop supply chain and integrating customers are essential. They have evolved in a natural and logical way throughout the development of the ResCoM-framework. This indicates that these interventions are interlinked and interdependent. For example, adoption of the proposed new approach to the resource flows demands to rethink the product design in terms of pre-defined and pre-planned lifecycles. This also requires that an appropriate business model is adopted to integrate customers and a well-integrated closed-loop supply chain is in place. Such logical links and their interdependencies demand that the implementation of circular manufacturing systems takes a systemic and systematic approach, which is the fifth intervention of the state-of-the-art.

A systemic and systematic approach

One of the most significant contributions of the ResCoM-framework is to look at all the challenges from a system perspective and take a systematic approach to handle the challenges. Traditionally, the challenges that are encountered by the remanufacturing industry are inherent to the fact that aspects of business model, product design supply chain and ICT are driven in isolation without necessary consideration to their mutual dependencies and interactions. For example, design for disassembly and design for remanufacturing is proposed as a solution to increase the operational efficiency of remanufacturing activities. Ironically, those proposals do not consider the fact that, if there is no mechanism to recover and transport products from customers, there will be nothing to remanufacture. Furthermore, if customers are not willing to return products and accept remanufacturing products, solving the operational efficiency issues will not be able to balance the supply-demand issue. This means that business model, product design, supply chain and ICT aspects are interlinked and they should be treated that way. Table 2 presents a list of challenges that are typically faced by the remanufacturing industry with the mapping of the areas that should be worked on to solve the issues. As it is apparent, to deal with most of the challenges, work needs to be done in more than one area. For instance, to solve the challenge of 'uncertainties about the quality of the used products' (which is listed in the first row in Table 2), a remanufacturer needs to work with all four areas. This also means that to overcome all the challenges; there is no other option than the cross functional integration of all four areas.

Table 2: A list of typical barriers of remanufacturing (based on [24] and [25]). The right side columns show a mapping of the organisational areas that need to be worked on to overcome the state-of-the-art barriers in remanufacturing.

Barriers of remanufacturing	Organizational areas to be worked on →	Business model(Marketing and customer	Product design	supply chain	ICT
Relationship with core supplier	Uncertainties about the quality of the used product	x	x	x	x
	Uncertainties about the quantity of the used product	x		x	x
	Uncertainty about when the used product will return to the remanufacturing	x	x	x	x
	The enterprises have a high quantity of suppliers and the selection often only considers financial issues	x	x	x	
	The company does not have a close relationship with the final customer, when he is the supplier of raw material	x			
	High cost for the used product individual returns	x		x	
	When the customer is the supplier, he receives few incentives to return the product	x			
Reverse logistics issues	Excess of used products waiting to be remanufactured which increases the need for more space	x	x	x	x
	Geographical dispersion of the used products location	x		x	
	Products transportation to the warehouse or the factory for remanufacturing, yet the product is not able to be reused	x	x	x	x
	Need to structure reverse logistics	x	x	x	
	Parts that are inappropriate for remanufacturing that can hinder the access to those parts that have potential to be remanufactured		x		x
Remanufacturing operation	High cost of used product inspection		x		x
	Difficulty and lack of accuracy of the inspection stage		x		
	Complexity and variability of the cleaning stage		x		x
	Difficulties in the disassembly stage mainly due to the excess of fixation points in the products		x		x
	Low added value of the product and/or its parts to remanufacture	x	x		x
Remanufactured product selling	Low demand of remanufactured product	x	x		
	Unstable demand of remanufactured products	x			
	The remanufactured product can be unattractive when compared with the new one	x	x		
	Low customer acceptance	x	x		
	Customer uncertainty about the quality of the remanufactured products, making them suspicious of the purchase	x	x		
	The sales channel for remanufactured products is poorly structured and underdeveloped	x		x	
Design for remanufacturing	High diversity of products making difficult to standardize the processes of remanufacturing	x	x		
	Utilization of high variety of materials		x		
	Utilization of less durable materials	x	x		
	Low possibility of remanufacturing of most products because of the little concern in designing for remanufacturing	x	x		
	Immature technological products		x		
	Design aesthetic is much more predominant compared to functional design	x	x		
Information flow on remanufacturing system	Lack of communication within the remanufacturing value chain				x
	Information about the logic and sequence of the product assembly which could help in the disassembly stage are not available for remanufacturing actor		x		x
	Information required for the remanufacturing are available late in the value chain		x		x
	Lack of information about the product during its use phase	x	x		x
	Little information about the benefits and quality of remanufacturing which arrives at the customer	x	x		x

Based on this, the ResCoM-framework considers the implementation of the circular manufacturing systems as the cross functional integration of four areas where their mutual dependencies and interactions are considered and understood as shown in Figure 33.

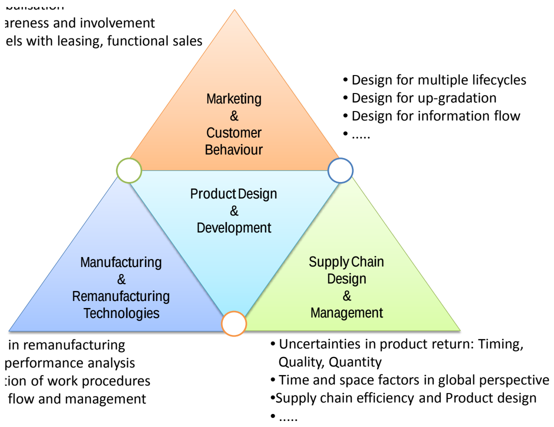

Figure 33: Cross-functional integration in the ResCoM-framework.

Once this is understood, requirements for implementing the circular manufacturing systems can be defined. For example, if an OEM decides to design a product for two lifecycles with one time remanufacturing in-between, they need to understand what sort of business models are appropriate to ensure integration of customers. Once a business model is defined, a supply chain can be designed to ensure both forward and reverse flows of products. To make the entire process efficient, necessary product and lifecycle information needs to be integrated and communicated with relevant partners. This system approach is not being considered currently in the conventional remanufacturing or closed-loop supply chain practices. As a result, the remanufacturing industry suffers from all classical problems of uncertainty, inefficiency and missing both economic and environmental opportunities.

4.2 Answer to the research question 2

How resource scarcity may influence manufacturing industries and how this influence can be incorporated in decision making to motivate implementation of circular manufacturing systems?

One of the main drivers for implementing circular manufacturing systems is to conserve resources. Conservation, in this case, is considered as a proactive approach to prepare for future resource scarcity, where the future could be anything from few years to several decades. Although resource scarcity is one of the most discussed issues of the recent times [53], [54], many manufacturing industries are not yet seeing the need to prioritise this in their strategic decision making. The reason is simple; manufacturing industries have more acute challenges to overcome in their everyday operations than the problem that may show up in decades. Unless consequences of resource scarcity are described from their perspective, their proactive measures are less likely and without their active participation, the resource conservation goals of ResCoM or CE initiative cannot be achieved.

Furthermore, often resource conservation, particularly in the case of materials, is measured in terms of the absolute quantity of materials (usually measured in kg/product) saved or reused without considering availability, criticality and possible future price volatility of materials. As a result, the decision whether to conserve materials or not is made based on comparing how much money one saves (assuming that the materials are always available and cost of materials will change at an extrapolated rate) by conserving materials over how much to invest. In this decision making process, it is seldom considered that when materials become unavailable for shorter or longer duration for any reasons, how it may affect a business. Therefore, it is important to understand that the gains through resource conservation are not only a matter of absolute quantity of materials saved but also to increase the robustness of businesses against vulnerability in case of material scarcity or material price volatility. This means that a comprehensive understanding of resource flows and their dynamics is needed to make better decisions. Dynamic models of resource use and flows should be developed by considering systemic effects, which should then be presented in a form that the decision makers can use to evaluate the influences of alternative scenarios.

The work presented in paper B introduces a system dynamics based method (model) and tool that helps in assessing and analysing potential gains in terms of conservation of material resources through implementation of circular manufacturing systems. In this work, a two-step analysis method is used by incorporating a two-level model described below,

1. The first step is to observe the global trend of the scarcity of a particular material (steel in this case), that is how the supply of that particular material would fluctuate and how the material reserves would eventually run out over time.
2. In the second step, the global trend of the material scarcity is fed into an enterprise level model in order to identify its influences on the enterprise that largely depends on the supply of that particular material. These influences are used as the basis to understand the potential gains of adopting the circular manufacturing systems.

The main underlying assumptions in the models are:

1. If the reserves of a particular material start to decrease due to consumption, this will increase the cost of material extraction due to difficulties in extracting and as a result material extraction will decrease. This assumption is based mainly on the fixed stock paradigm principles, where the influence of technological developments that may have on to increasing material production or to reduce the cost of material extraction has not been considered.

2. If material extraction decreases and demand for the material will start to increase. As a result, the countries that are controlling the reserves of the material will try to limit the supply to ensure their solo access in order to secure the survival of their own manufacturing industries.
3. As an effect of point 1 and 2, the worldwide supply of that particular material will drop which will increase the price of the material. Consequently, for an enterprise that uses that particular material as the main raw material for manufacturing, the cost of manufacturing will increase.
4. As the manufacturing cost increases, the products will become more expensive and as a result demand for the products will decrease. This will negatively affect that particular enterprise as the customers will lose interest to continue doing business with them.

For the given boundary of the model, the assumptions and the initial data used (listed in paper C), the model estimates that the material (steel, in this case) will completely exhaust in roughly 100 years as shown in Figure 34.

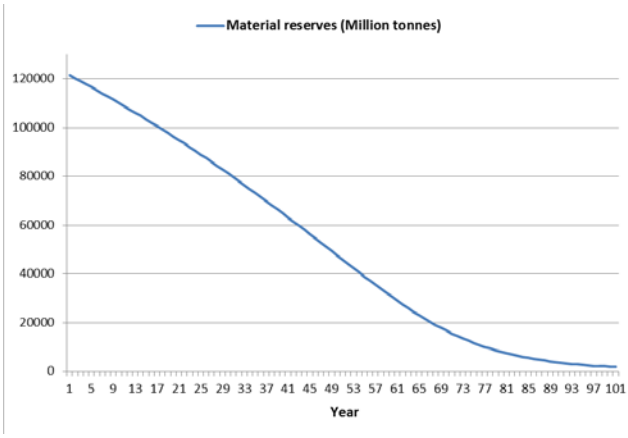

Figure 34: The behaviour of material reserves.

However, due to the geopolitical reasons, the crisis may hit earlier than estimated as shown in Figure 35.

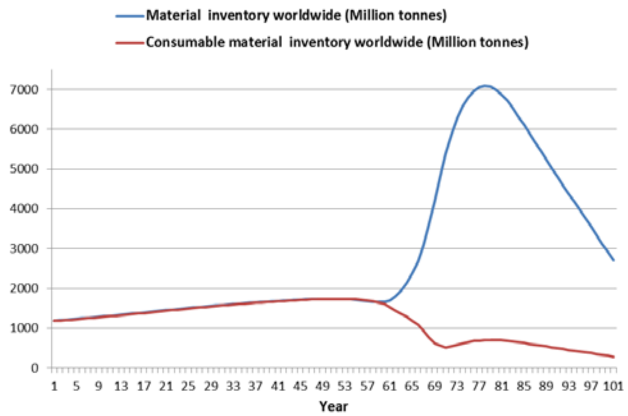

Figure 35: The behaviour of material inventory worldwide and consumable material inventory worldwide.

The graph in Figure 35 shows that at the beginning of simulation the nations that are holding the reserves of the material, are supplying the material as per the demand from rest of the world. As the time passes, the consumption of material increases which causes material producing nations to be more concerned about protecting the material for their own use. As a result, despite the physical availability of the material, access to the material becomes limited to rest of the world. As the access becomes limited, the price of the material will increase. Assuming that an enterprise uses this particular material as the main raw material for manufacturing, it can be expected that the manufacturing cost of that particular product will increase in proportion to the increase of the material cost. This will increase the price of the products which will have a negative impact on customers' willingness to buy products from that particular enterprise. As a result, the expected growth of the enterprise will stop as shown in Figure 36.

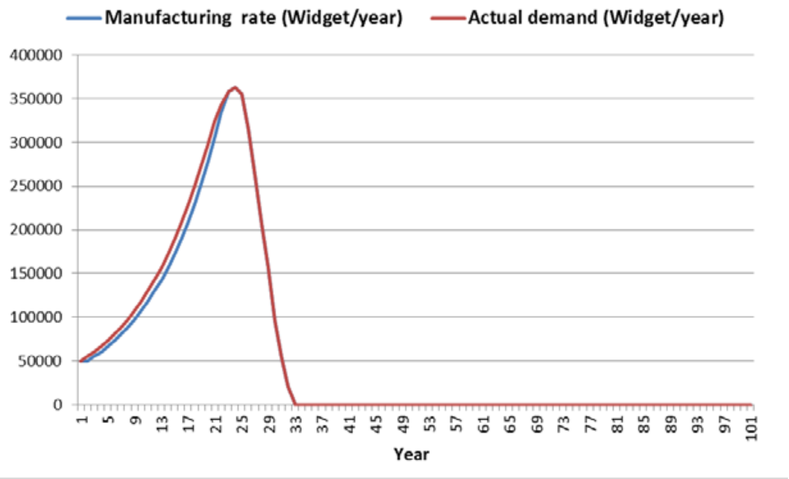

Figure 36: The behaviour of manufacturing rate in comparison with actual product demand. Here the main constraint is the price of products (adapted from [55])

The graph in Figure 36 shows the behaviour of the manufacturing rate in comparison to the actual product demand. This illustrates that growth of any enterprise will be threatened as the price of the product goes beyond a perceived level and customers decide not to buy the products anymore from the enterprise.

If the price increase is not an issue, meaning that customers are willing to buy products from the enterprise even if the price of the products is ridiculously high, the growth will be threatened by the availability of the material. In that case, there will be demand, but the enterprise will not be able to meet the demand due to lack of the material.

Given the combined effects of resource (material) scarcity due to consumption and supply uncertainty due to geopolitical reasons, it can be summarised that despite the physical availability of a certain material, its supply may be restricted. In such situation, an enterprise that largely depends on the supply of that particular material will have difficulties in operating its daily manufacturing activities. Therefore, to tackle such situation emphasis should be given on conservation of material resources. This strategy of resource conservation will not only save the value of the material in monetary terms but also make the businesses less vulnerable to the challenges related to resource scarcity. This makes a business robust against material supply and price volatility which is one of the advantages of circular manufacturing systems and which cannot be measured only in terms of kg of material or money saving.

4.3 Answer to the research question 3

What are the important characteristics of a closed-loop supply chain that is essential for implementing circular manufacturing systems and how can its performance be measured?

The difference between the conventional and the ResCoM proposed closed-loop supply chain is briefly discussed in section 4.1 and detailed in paper C. To summarise, the main features of the ResCoM closed-loop supply chain (which is shown in Figure 31 in section 4.1) are:

1. The used products are collected by the OEMs or the authorised 3rd party remanufacturers that act as the suppliers to OEMs.
2. The used products/components enter (and are reused) in the mainstream of the manufacturing forward material flows.
3. The remanufactured products are sold in the same way as the new products. This means remanufactured products are not considered a different product variant, and their order and supply are not handled separately.

The third point is the most important point to establish a circular manufacturing system and it is only possible when neither OEMs nor customers differentiate products as new or remanufactured for any reasons. Ideally, this means, if both a remanufactured and a new product assure same functionality, quality, safety and guarantee, etc., the customers will not have any problem in accepting either a remanufactured or a new product. This, however, is challenging to implement for two reasons. Firstly, as mentioned earlier, in general customers' attitudes towards remanufactured products are negative. Secondly, there are legislative implications that prevent remanufactured products to be declared as new or use old components in a new product [56]. This can be avoided in two ways; either by improving customers' acceptance (which is a long-term process requiring social innovation) or changing the value propositions in a way that the concept of newness become less important than the function that a product provides. Therefore, ResCoM proposes to adopt innovative business models to bring functionality on focus over newness. Furthermore, legislative measures that can prevent labelling products as new and remanufactured (old) can be of great support in changing customers' attitudes. A combination of appropriate value propositions and legislative push can act as the 'carrot' and 'stick' which will improve customers' acceptance faster.

A new value proposition may mean new ways of offering products while at the same time a better performing closed-loop supply chain is ensured for OEMs. To explain this further, let us assume that an OEM decides to implement circular manufacturing systems and offers to lease products in parallel to the conventional sales model. In leasing, demand can be fulfilled by supplying both new and remanufactured products. It is also assumed that the leasing offer brings certain additional value propositions, such as competitive price and additional maintenance services, etc. which make leasing attractive to the customers. Furthermore, the OEM also promises same functionality, safety and quality in leasing as if the customers would have bought the product in a conventional way. These value propositions will make the newness less relevant because the customers will evaluate the leasing offer as a whole, not as a new product against a remanufactured product. If this can be done a balance between supply (of old products)-demand (of remanufactured products) can be handled in a better way as described below and shown in Figure 37, and this will ensure a better performing closed-loop supply chain.

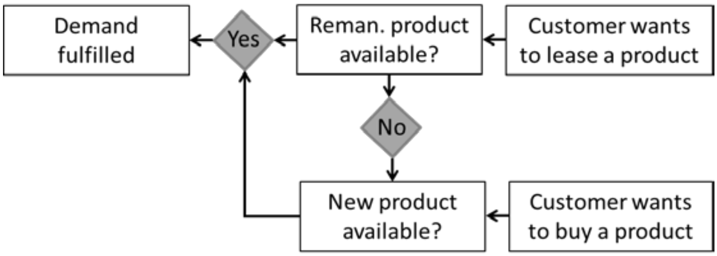

Figure 37: Illustration of a proposed demand fulfilling mechanism in ResCoM closed-loop supply chain.

As illustrated in the figure above, when a customer wants to lease a product, the OEM has the possibility to satisfy the demand either by supplying a remanufactured or a new product. This means that the customers' demand is always fulfilled. This makes an OEM less vulnerable to uncertain supply-demand and eventually creates a closed-loop supply chain which can perform better than the conventional closed-loop supply chain. The same mechanism can be implemented for several value propositions (different business models) and for products with several lifecycles, as described earlier in section 3.2 and also in paper D.

The whole purpose of improving customers' acceptance and integrating customers through new value propositions is to improve the performance of the closed-loop supply chain. This, however, raises two questions. Firstly, how to measure the performance of such closed-loop supply chains? Secondly, can the proposed demand fulfilling mechanism enhance the performance of the closed-loop supply chain?

To answer these questions, in paper C, system dynamics models are developed to represent a forward and a reverse supply chain, and then these two supply chains are combined to create both conventional and ResCoM proposed closed-loop supply chains. The main underlying assumptions in the models are as follows,

- In the case of conventional closed-loop supply chain used products are returning at different times at different rates and demand for remanufactured products is random.
- In the case of ResCoM closed-loop supply chain, used products are returning at a specific time at a specific rate and demand for the remanufactured products is constant.

The key performance indicators (KPIs) that are used to compare the supply chains are generic indicators commonly used in any supply chain management such as, rate of production/shipment, delivery delay, backlog, inventory and production capacity, etc. In the language of system dynamics, the performance of a supply chain is considered to be good if these KPIs remain within desired range over time. For example, if demand for a particular product increases, the delivery delay is expected to increase. Here, delivery delay is the duration that a customer needs to wait to receive a product after an order is placed. However, any OEM would like to maintain this delay to the desired level which can be standard for a given market or acceptable by the customers in that market. To maintain the delivery delay to the desired level the production capacity of that particular product has to increase to adjust this increased demand, given that there is a certain level of flexibility in the production capacity to adjust. As a result of the adjustment of the production capacity, the delivery delay will settle back to its desired level. This adaptation is due to the system's internal feedback that exists between the supply and the demand of products in the supply chain.

Having said that, the main objective of paper C is to measure and compare KPIs in conventional and ResCoM proposed closed-loop supply chain to observe how well the KPIs match their desired level. For the given boundary of the model, the assumptions and the initial data used, the KPIs reach to the desired level over time in case of the forward supply chain. In the case of the reverse supply chain, the KPIs experience difficulties in reaching to the desired level. This is an indication that, due to the inherent characteristics of the reverse supply chain related to uncertain in quality, quantity and timing of returning products, the KPIs do not reach their desired level. As soon as the forward and reverse supply chain is connected to create a (conventional) closed-loop supply chain, these inherent uncertainties affect the supply chain performance and make the entire closed-loop supply chain unstable. After the closed-loop supply chain is reformed to fit the ResCoM proposed closed-loop supply chain, it becomes relatively stable. To illustrate it further, the same outputs are displayed in Figure 38 and Figure 39 for the conventional and the ResCoM proposed closed-loop supply chain.

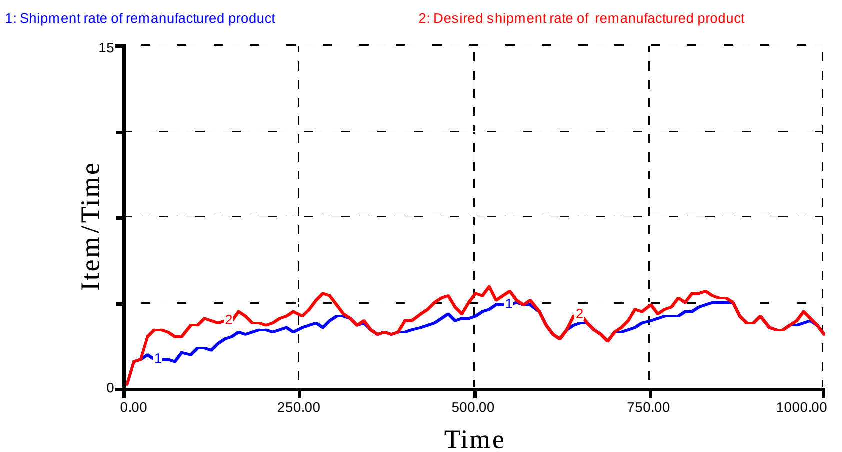

Figure 38: Behaviour of the actual and desired shipment rate of remanufacturing products in the conventional closed-loop supply chain (adapted from [1] [45]).

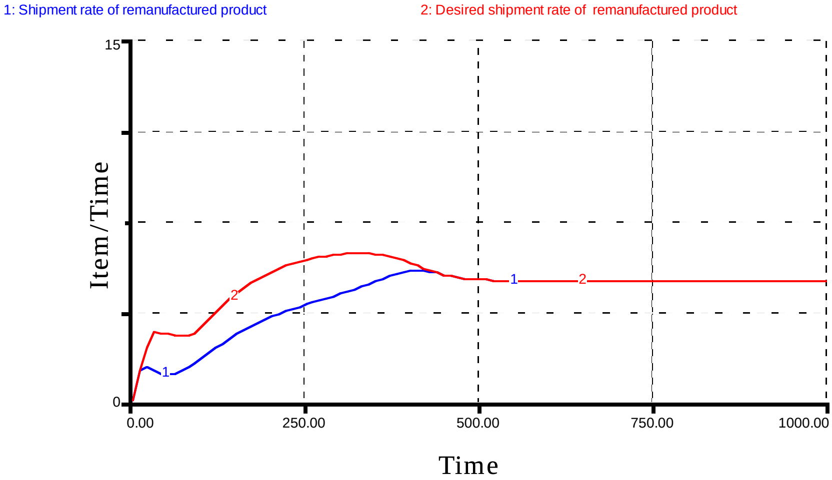

Figure 39: Behaviour of the actual and desired shipment rate of remanufacturing products in the ResCoM closed-loop supply chain (adapted from [1] [45]).

As displayed in the graphs above, in the case of the conventional closed-loop supply chain (Figure 38) the (actual) shipment rate of remanufactured products is having difficulty in reaching the desired shipment rate. However, in the case of the ResCoM proposed closed-loop supply chain, the actual shipment rate (Figure 39) of remanufactured products is reaching the desired level after an initial fluctuation. This is one way of demonstrating that the performance of ResCoM closed-loop chain is enhanced as compared to the conventional closed-loop supply chain.

Besides measuring and comparing the KPIs, the models can also help in planning and control of the closed-loop supply chain which, however, has not been the main focus of this modelling work.

To conclude, the above discussions highlight that, it is possible to achieve a better performing closed-loop supply chain, which is less sensitive to uncertainty in quality, quantity and timing of returning products if the ResCoM-framework is adopted. However, this does not discuss whether the adoption the ResCoM closed-loop supply chain will be economically and environmentally viable or not. To be more specific, whether adopting the proposed demand fulfilling mechanism as shown in Figure 37 (and discussed in section 3.2), will be more profitable or environmentally more sustainable than running a conventional business model or not. The analysis method and tool presented in paper D answers this question which is summarised in the following section.

4.4 Answer to the research question 4

How can the economic and environmental performance of circular manufacturing systems as proposed in ResCoM be measured?

Economic and environmental benefits of resource conservation through circular manufacturing systems seem obvious in many cases ([6] [57] [58]). However, as discussed earlier, adopting the ResCoM-framework would require an organisation to bring changes in several aspects of the business model, product design, supply chain and ICT. Furthermore, as these areas are interdependent, bringing changes in one area will also require changes in other areas, thus creating a complex situation where the outcomes may not be straight forward to envisage. In such situation, organisations will be reluctant to take this risk without knowing the anticipated economic and environmental consequences associated with these changes. Since the implementation of circular manufacturing systems should be economically viable and environmentally feasible, it requires analysis and decision support tool to assess the economic and environmental performance of the systems.

With this in mind, a multi-method approach is developed that combines an Agent-based (AB), a System dynamics (SD) and a Product Design Index (PDI) method. Combination of these methods enabled capturing critical business model, product design and supply chain aspects that are relevant for implementing circular manufacturing systems in a single analysis method and tool. The multi-method approach also enhanced understanding of the interdependencies among critical factors and helped in incorporating all the critical factors to measure the performance of these systems. Paper D and section 3.2 discusses the analysis method and the tool in details which is summarised below.

Although AB, SD and PDI are used in order to develop the analysis and decision support tool, paper D mainly discusses the SD part of the model. To do so, as shown in Figure 40, the SD model takes input from the AB model in the form of demand that emerges from a market. The SD model also takes input from the PDI in the form of ratio of the components/mass of a product to be reused, remanufactured and recycled at EoU/EoL. These inputs are combined in the supply chain model that measures the economic and environmental performance of the system. This performance is then fed back to the AB model to update the features of the AB model. Apart from this flow of input-output and connections between modelling methods, there are higher level connections (as also discussed in section 4.1) among business model, product design and supply chain aspects which are shown with broken lines in Figure 40. These connections show the systemic dependencies among these three areas, that is, how each area influences others and determine the configurations of the final model. For example, let us assume that a new business model that includes leasing with remanufacturing activities is to be introduced in parallel to the conventional sales. In this case, when the leasing period is over, products will be brought back and remanufacturing will be performed. After remanufacturing, products will be leased again to new customers. This new business model consideration requires that the supply chain model is created with two product delivery channels, one for the leasing and one for the conventional sales. Furthermore, additional supply chain stages such as product return, recovery and remanufacturing, etc. need to be included. Similarly, for this particular business model, an OEM may also consider redesigning their products, which may also create new design indices. This means, with the change of business model, product design or supply chain and vice versa, the model configurations need to be adjusted. This is due to the systemic dependencies that exist among business model, product design and supply chain aspects shown with the broken lines (in Figure 40). Once a model configuration is set, connections between input-output and modelling methods also become relevant, which are shown with solid lines (in Figure 40).

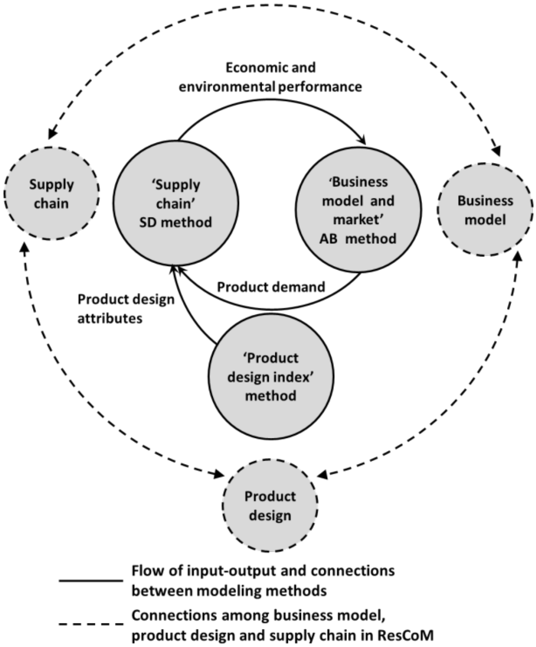

Figure 40: An overview of the flow of input-output and connections between modelling methods and higher level connections among business model, product design and supply chain aspects that determine the model configurations (adapted from [59]).

Considering these higher level connections the analysis method and tool is developed, in which the AB business and the market model covers decision making processes of potential customers who may choose to buy or lease a product. The choice to buy or lease a product is made based on comparing attributes of these two offers, which may consist of price, environmental impact and convenience, etc. Convenience, in this case, covers service-related elements such as free maintenance, spare parts, possibility to upgrade the products, etc. For example, if a customer finds the price, environmental impact and convenience of leasing offer matching to his/her preferences, then this customer will prefer to acquire a product through leasing. As a combined effect of available offers, their attributes and customers' preferences, the AB model generates demands for leasing and buying as the output. These demands are continuously fed to trigger the SD based supply chain model which then supplies products accordingly to meet the demand of customers who want to buy or lease the products.

In this model, the supply chain is modelled for two lifecycles with production, use, return, and recovery stages. In each stage of the supply chain, there are control mechanisms that determine how many products can move from one stage of the supply chain to another. Here, the main control mechanisms are the design attributes including remanufacturability, reusability, recyclability and quality compliance indices coming from the PDI method. As the outputs, the supply chain model provides the sum of products being manufactured, leased, sold, returned, reused/remanufactured/recycled and redistributed over time. This count is then combined with relevant cost and CO_2 parameters, such as cost and CO_2 for production, transportation, recovery, reuse, remanufacture and recycle, etc. to measure the economic and the environmental performance. The economic and environmental performance at a given time is fed back to the AB model which updates the offer attributes and communicates this to customers. For example, for an OEM if the environmental performance improves due to leasing (assuming that leasing has less environmental impact than sales) the OEM can inform customers that their leasing offer has better environmental performance. This information may then be used by the customers when comparing attributes of the buying and the leasing offers. The main underlying assumptions of the model are already mentioned in section 3.2.

For the given boundary of the model, the assumptions and the initial data used (listed in paper D), the tool estimates the economic and environmental performance of the circular manufacturing system with respect to the business as usual (baseline) scenario. Here, the business as usual scenario is conventional sales model with no value recovery activities. For the purpose of comparison, two scenarios are created by varying the values of few variables in the model as mentioned in Table 3. The economic and the environmental performance graphs of the system in scenario-1 and scenario-2 with respect to the business as usual scenario are shown in Figure 41 and Figure 42.

Table 3: Values of the variables used to create scenario-1 and scenario-2

	Business as usual	**Scenario-1**	**Scenario- 2**
Business model	Conventional sales only	Conventional sales & leasing	Conventional sales & leasing
ReturnRatioLeased1stLife/ ReturnRatioLeased2ndLife	0	0.9	1
QualityComplianceIndex2ndLife	0	0.6	0.9

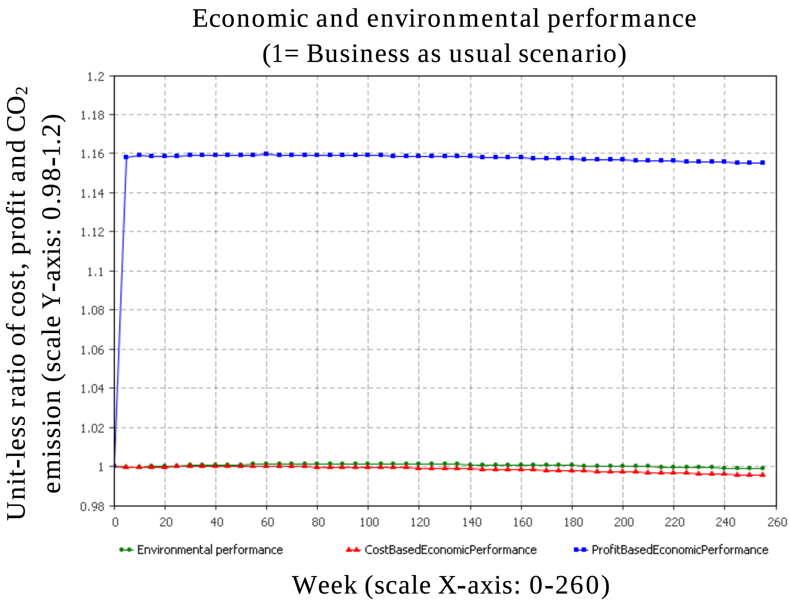

Figure 41: Graph showing the economic (the red and the blue line is showing the cost and the profit based economic performance respectively) and the environmental performance (green line) in scenario-1. In the graph, numerical value '1' corresponds to the performance of the business as usual scenario (adapted from [59]).

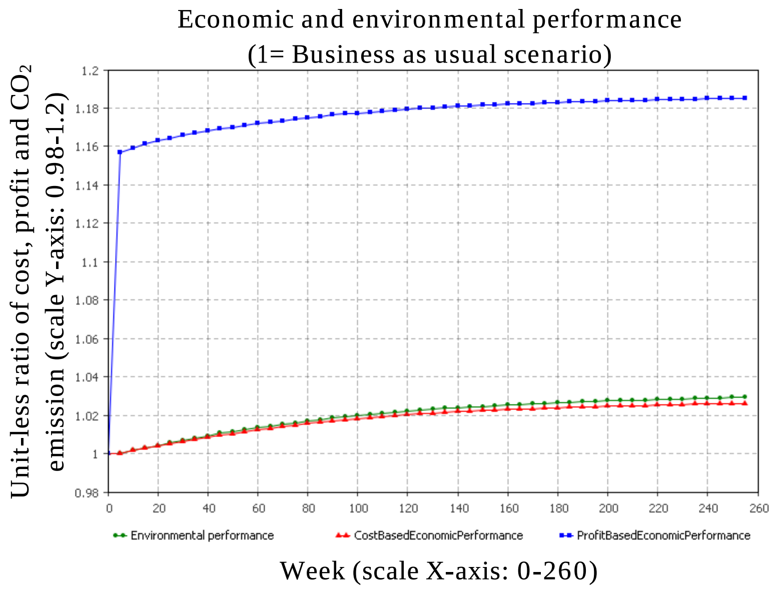

Figure 42: Graph showing the economic (the red and the blue line is showing the cost and the profit based economic performance respectively) and the environmental performance (green line) in scenario-2. In the graph, numerical value '1' corresponds to the performance of the business as usual scenario (adapted from [59]).

In the case of scenario-1, the graph (in Figure 41) shows that the profit based economic performance reaches to a maximum value 1.16 and drops slightly at the end of the simulation time in week 260. On the other hand, the environmental and cost based economic performance gradually drops during the entire simulation time and ends with a value slightly lower than '1'. Here it is important to remember that performance is a ratio between cost, profit and CO_2 emission that is anticipated in a new business approach and the cost, profit and CO_2 emission in the business as usual approach. This means that a value lower or greater than 1 indicates that the performance of the given circular manufacturing system is respectively worse and better than the business as usual scenario.

In the case of scenario-2, as shown in Figure 42, both the economic and the environmental performance of the circular manufacturing system are improved compared to the business as usual scenario and scenario-1. The economic and the environmental performance also has the trend of continuous improvement during the entire simulation time. Main reason for the improved performance in scenario-2 is that the number of products returning with the right quality is higher. As a result, more products are being reused during the 2nd lifecycle and fewer products are being discarded at the end of the 1st lifecycle which eventually improves the economic and the environmental performance.

Apart from measuring the performance, the tool can also support in visualising the behaviour of different variables over time and aid decision making for improving the performance. In addition, users can run optimisations to identify best-suited solutions applicable in a certain case to implement the circular manufacturing systems and plan production and inventory control best suited for the optimised solution.

To conclude, paper D presents an analysis method and tool which is capable of assessing the economic and environmental performance of circular manufacturing systems. This tool is unique and important in facilitating the transition from linear to circular manufacturing systems. In the absence of such tool most OEMs might be reluctant to take the risk of changing their way of working. Thus, the utility of the tool not only rests in the possibility to measure the performance but also in helping OEMs in their decision making process and setting policies for successful implementation of the circular manufacturing systems.

5. IMPLEMENTING THE GENERIC TOOL IN THE ResCoM CASES

This chapter describes some generic aspects of the case company specific decision support tools that are used to analyse the circular manufacturing systems envisaged by the ResCoM case companies.

Chapter 4 summarises the research contributions through answering the research questions. These contributions are published in the form of scientific articles during the course of this research. Besides these contributions, a substantial amount of research work has been carried out, which is of confidential nature and thereby, cannot be published. For example, by adapting the generic decision support tool four case company specific decision support tools are developed. This development is a result of joint efforts over the period of two years. These development activities include several discussions, iterations of model development, coding, model testing, interface development, data collection, result analysis and reporting. Although these efforts do not fit in the discussions of the contributions highlighted in the publications, but it deserves to be mentioned and elaborated. Maintaining the confidentiality, following sections summarise some of the additional research contributions made by me.

5.1 Case company specific circular manufacturing systems

As mentioned earlier, as part of this research four decision support tools are developed for the case companies which are the adaptation of the generic tool described in 3.2 and paper D. Therefore, detailed explanation of the conceptual models, logics and mathematical relations is not repeated. Instead, this section provides an overview of the circular manufacturing systems that are envisaged by the case companies. This section also includes a tool overview and an implementation example to demonstrate the capability of the tools. To maintain confidentiality, details of the case companies are not disclosed and case companies are named as company A, B, C and D.

Circular manufacturing system of company A

Company A has decided to lease products to customers in addition to their conventional sales model with the purpose of using the same product throughout multiple lifecycles. In this model, customers can lease products for the duration of 6 to 36 months. During the leasing period, customers can change their products with a different model whenever they want. In between leasing, refurbishment will be performed where products will be collected in a location in Western Europe to perform the refurbishment processes. In ideal cases new products will be leased for 3 years and after the 1st leasing period the products will be brought back and refurbished. After refurbishment, the products will be leased again for another 3 years. After the 2nd leasing, the products will be brought back again to refurbish and the refurbished products will be sold on the 2nd hand market. The leasing offer will be introduced in two markets (locations) in Western Europe which the company has identified as the most favourable markets for leasing. To facilitate this, company A has to improve the product design in order to make refurbishing efficient and redesign the supply chain networks to make the reverse operations agile. Moreover, this will allow company A to mix both new and refurbished products to fulfil the demand for leasing. This will also influence the forward and reverse supply chain in terms of return, refurbishment and supply activities. This new business approach will initiate new activities which will require additional investments, new pricing and will have a different environmental impact at different stages.

Circular manufacturing system of company B

Company B is interested in expanding its remanufacturing business. The remanufacturing business is currently controlled by its customers who otherwise buy new products from company B and use in their end products. These OEMs decide how many products company B should remanufacture in a given time and the used products are supplied by the OEMs from three locations in Europe. Although the current remanufacturing activities in company B are planned according to the current demand of the OEMs, company B has excess capacity to expand the business. In this respect, company B is considering two alternatives for expanding. Firstly, buy used products of their own brand and secondly, buy used products of other brands from the free market and remanufacture; a third option is to combine the both alternatives. For this, company B is looking into the possibility of improving the design of products to make remanufacturing efficient and improve the packaging of returning products to reduce damage during reverse transportations. Company B wants to perform remanufacturing in a location in Central Europe where used products will be collected from several locations in Central and Northern Europe. Furthermore, remanufactured products will be sold on the free market in Central and Northern Europe. Since the current legislation does not allow using remanufactured components in new products, it also raises the question if remanufacturing business is expanded and the product design is improved to remanufacture products multiple times, will there be enough market shares to get the return on investment. Furthermore, remanufacturing both own and other brands will also influence the forward and reverse supply chain in terms of return, remanufacturing and supply activities. This new business approach will initiate new activities which will require additional investments, new pricing and will have a different environmental impact at different stages.

Circular manufacturing system of company C

Company C has decided to pursue the strategy of extending product life. To fulfil this aim, they want to introduce better platform design to facilitate product upgrading. In this, the product becomes the ‘platform’ for providing the user experience, while maintenance and upgrading of this experience become the new product offering. Company C wants to explore the potential of the product life extension strategy through periodic product upgrade with more service/function-oriented business model. This involves aspects of product design, forward supply chain as well as the consideration of new revenue streams as part of the new service/function-oriented offer.

It is known that a large portion of current customers of company C considers changing their products after 4 years. In this scenario, it is assumed that if a major upgrading is done in year four (or upgrading steps are spread over year 3 to year 5), the customers will keep on using their products for additional 4 years. For the extended life product, it is also important for company C to make sure that the upgraded products are technologically compatible with the newer models of products that may be launched at the time of upgrading. Therefore, company C wants to develop the products using a modular architecture which will make it efficient for upgrading the products, especially at customers’ sites.

This will be done at one location in Central Europe close to the manufacturing facility. The reason for choosing this location is because company C has a strong service base in this location. This new business approach will initiate new activities which will require additional investments, new pricing and will have a different environmental impact at different stages.

Circular manufacturing system of company D

Company D has the ambition to introduce service/function-oriented offers where customers will pay-per-use. At the same time, the company is considering to remanufacture products in parallel to the conventional manufacturing business. Company D has the plan to offer this pay-per-use possibility to customers both in B2C and B2B markets. Company D also foresees the possibility that each product can go in three service contracts serving up to three customers where the length of each contract is 5 years. In between each service contract products are remanufactured, meaning that products are remanufactured twice in total. To realise this, Company D plans to categorise the offers in three segments. The idea is that for these three segments the offer will include brand new, one time and two times remanufactured products respectively. This will allow Company D to cover all segments from high-income to low-income.

This will be done in some locations in Northern Europe, where remanufacturing will be performed in Eastern Europe. To facilitate this, company D will improve the product design in the form of modules in order to make it efficient for remanufacturing: At the same time company D will redesign the supply chain networks to make the remanufacturing processes efficient. Moreover, the company will mix new products; one time and two times remanufactured products to fulfil the demands of the three segments in both B2B and B2C markets. This will also influence the forward and reverse supply chain in terms of return, remanufacturing and supply activities. This new business approach will initiate new activities which will require additional investments, new pricing and will have a different environmental impact at different stages.

The discussions above highlights the assumptions and the boundaries based on which four company specific tools are developed. Although the core of each tool reflects the generic tool described in section 3.2, the generic tool had to be adapted for company specific use. As a result of this adaptation, some company specific tools became large and complex and others became small and less complex than the generic tool. To give an overview, following table highlights differences in the assumptions, the boundaries and the computer simulations.

Table 4: Summary of the difference in the case company specific decision support tools.

	Company A	Company B	Company C	Company D
Purpose of the decision support tool	Measuring the economic and environmental performance of the circular manufacturing system			
Business model	• Conventional sales of new products • Leasing of new and refurbished products • Sales of refurbished products	• Conventional sales of new products • Sales of remanufactured products	• Conventional sales of new products • Sales of extended services • Sales of product upgrades	• Conventional sales of new products • Sales of service contracts (pay-per-use)
Target segment	• Current segment	• Current segment • Remanufactured spare parts segment	• Current segment	• Current B2C (high-income) segment • B2C medium and low-income segment • B2B high, medium and low-income segment
Product design	• Design for refurbishment	• Design for remanufacturing • Design for better packaging	• Platform design • Modular architecture • Design for upgrade	• Modular design • Design for remanufacturing
Strategy for multiple lifecycles	• Two times refurbishment	• One time remanufacturing	• Product life extension with upgrade	• Two times remanufacturing
Sources of used products	• Own products returning from the leasing	• Own and other brands bought back from the free market	• Own products	• Own products returning from the service contracts
Supply chain	• Leasing in two locations in Western Europe • Refurbishment in one location in Western Europe	• Sales of remanufactured products in Central and Northern Europe • Remanufacturing in one location in Central Europe	• Sales in Central Europe • Upgrade service at customer's sites in Central Europe	• Service contracts in Northern Europe • Remanufacturing in Eastern Europe
Elements of the tool	• 23 stocks • 16 flows • 68 input and auxiliary variables	• 23 stocks • 13 flows • 42 input and auxiliary variables	• 14 stocks • 9 flows • 39 input and auxiliary variables	• 29 stocks • 19 flows • 59 input and auxiliary variables

5.2 Tool overview and implementation example

The tools developed for the case companies include a lot of details and all those details are accessible and editable by the users. However, in order to make the tools user-friendly, the need for interaction with the actual simulation model by users is minimised by introducing several interfaces. Through the interfaces, the users are able to navigate, run simulations and visualise the results without any need to interact with the actual simulation model. There are two input interfaces fed with the default values of the input variables; one allows the users to change the values of the input variables before starting the simulations and the other one allows the users to change the values of the input variables during the simulation runs. In these interfaces, the input variables are categorised as the business model, product design and supply chain variables. As shown in Figure 43, the users can define how many business models to include and to be compared with what sort of business models (both internal and external offers). For each of the business models, the users have the possibility to define the offer attributes, which include price, environmental impact and service level. This part of the interface is connected to the AB model which is not within the scope of this dissertation. The methods and the mechanisms that are used in order to develop the AB model are described in Lieder *et al.* (2017) [60].

Through the interface shown in Figure 44, the users have the possibility to input the values of the variables concerning product design (shown in the upper part of the figure). The input values of the product design variables are usually the output from the PDI method. In addition to this; the users have the possibility to input the values of the supply chain variables related to cost and CO_2 emission. The values of all these input variables can also be changed during the simulation runs using the 2nd input interface as mentioned earlier.

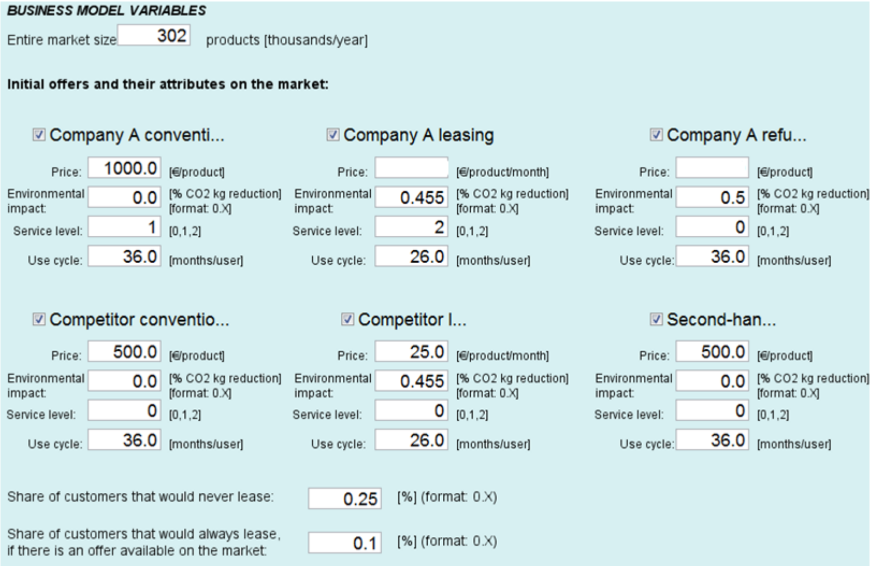

Figure 43: Partial view of the input interface allowing users to change the value of the business model variables before starting the simulation.

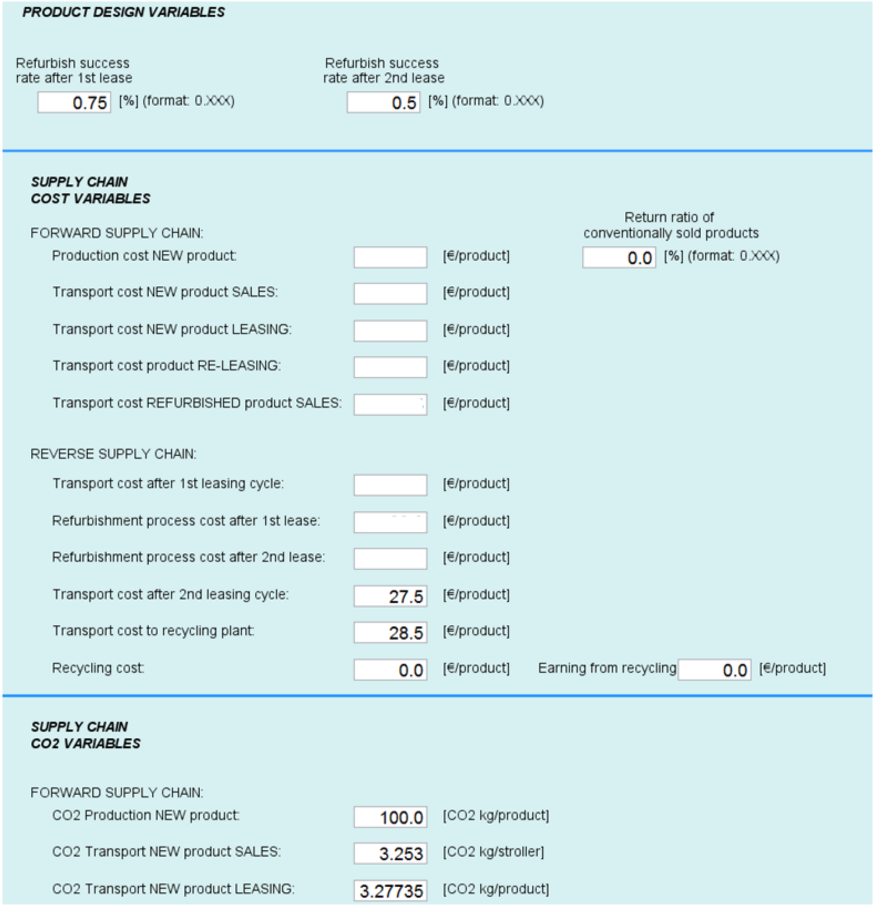

Figure 44: Partial view of the input interface allowing users to change the value of the product design and supply chain variables before starting the simulation.

As discussed earlier, by selecting certain business models and changing the values of the input variables the users can create several scenarios and compare the outcomes of those scenarios. For the purpose of the visualisation and analysis, a 3rd interface is created which includes graphs of several key output variables as shown in Figure 45. This interface includes among other things, graphs of economic and environmental performance and key business model outputs. The following section provides two example scenarios and discusses the outcomes of those scenarios in terms of the economic and environmental performance of the circular manufacturing systems for Company A.

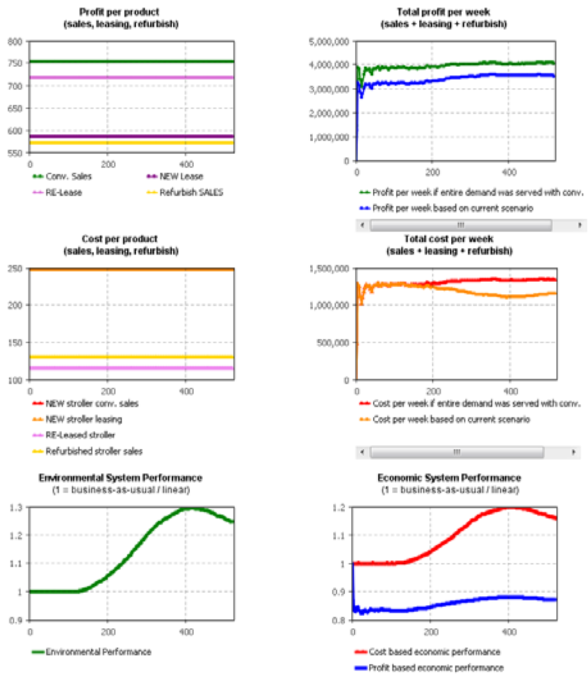

Figure 45: Partial view of the visualisation interface allowing users to observe the outcomes. This is an illustration of the capability of the tool in visualising the results of the simulation.

5.3 Creating scenarios and analysing the results

As mentioned earlier, by selecting certain business models and changing the default values of the input variables the users can create several scenarios of their interest to analyse. To illustrate this further, for company A following two scenarios are created by changing the default values of the input variables:

Scenario-1: Leasing of products is introduced in location X. This location is identified as the most favourable location for introducing leasing (which is a different location than where company A is current located). In this scenario, the products are leased twice. In between leasing the products are refurbished once. After the 2^{nd} leasing period is over, the products are brought back and sent for material recovery through recycling. For scenario-1 following additional assumptions are made:

- The market size in location X is assumed to be the same as the market size of Company A in the current location.
- Cost and CO_2 variables of the transportation activities are set according to the supply chain in location X.
- Company A has leasing monopoly in location X.
- No refurbishment after the 2^{nd} leasing, i.e. all products after the 2^{nd} leasing are sent for material recovery through recycling.

Scenario-2: Leasing of products is introduced in location X, same as the scenario-1. Furthermore, in this scenario, the products are leased twice and refurbished twice. However, after the 2^{nd} refurbishment, the products are sold on the 2^{nd} hand market instead of sending for material recovery through recycling. For scenario-2 following additional assumptions are made:

- The market size in location X is assumed to be the same as the market size of Company A in the current location (same assumption as scenario-1).

- Cost and CO_2 variables of the transportation are set according to the supply chain in location X. (same assumption as scenario-1)
- Company X does not have leasing monopoly in location X anymore. In location X, the main competitor of company A starts leasing. In addition, the refurbished products those are to be sold on the 2nd hand market face competition with the 2nd hand products of other brands.

The combination of scenario-1 with the assumptions mentioned above creates the economic and environmental performance graphs shown in Figure 46 and Figure 47.

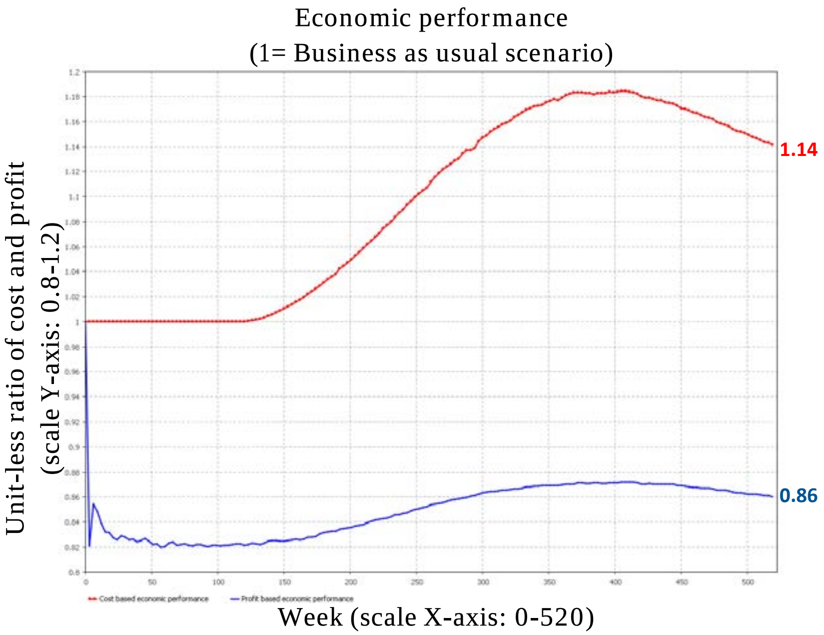

Figure 46: Graph showing the cost based (red line) and the profit based (blue line) economic performance in scenario-1. In the graph, numerical value '1' corresponds to the performance of the business as usual scenario.

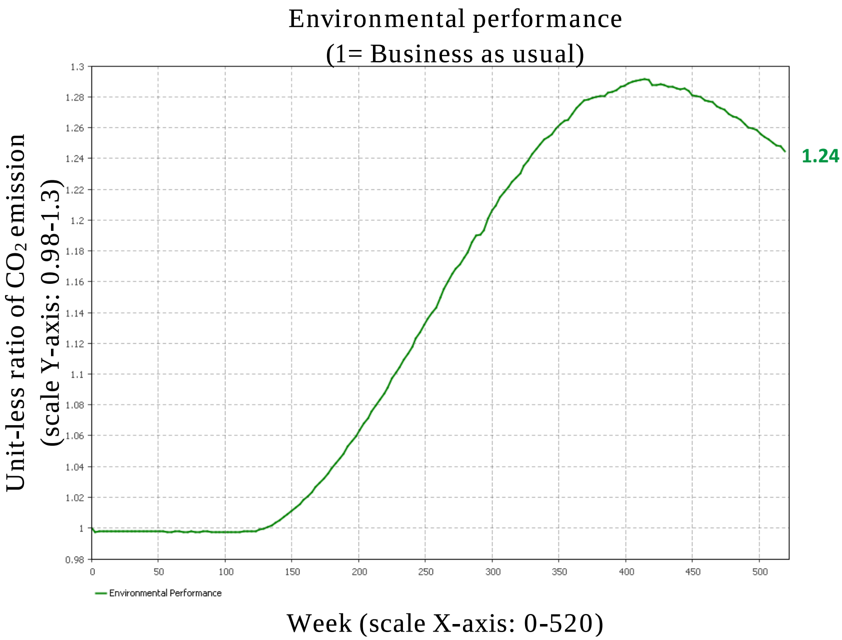

Figure 47: Graph showing the environmental performance in scenario-1. In the graph, numerical value ‘1’ corresponds to the performance of the business as usual scenario.

Figure 46 and Figure 47 displays the economic and the environmental performance graphs of scenario-1. For the given model boundaries, the assumptions and the input values of the variables, the cost performance remains steady at ‘1’ until the time when leasing demand is entirely fulfilled by serving new products. As the refurbishment of the products starts and continues, fulfilling demand becomes cheaper due to re-leasing of refurbished products and as a result cost performance continues to improve. This improvement continues until the time when re-leased products start to return and products are sent for material recovery through recycling.

In contrast, the profit performance declines right after the start of the simulation and remains below '1' during the entire simulation run time. The main reason for this lower profit performance is due to the lower profit margin for Company A in the circular manufacturing system (when considering all cost factors in leasing) as compared to the business as usual scenario. As shown in Figure 48, different business models can have different cost structure and pricing that may result in different profit margins. For example, in the case of both senario-1 and senario-2, company A has decided to have a lower price for the leasing offers and sales of the refurbished products as compared to the sales price of the new products. Note here that the price in leasing is calculated by multiplying the leasing duration in months with the monthly leasing fees. Similarly, the cost incurred during sales and leasing of the new products is higher than re-leasing and sales of the refurbished products. Due to the combination of different pricing and the cost structures and their accumulation over a long period can lead to an overall profit which is lower or higher than the profit in the business as usual scenario. In the cases of both senario-1 and senario-2, the overall profit in the circular manufacturing system for company A is lower than the profit in the business as usual scenario and therefore, the profit based economy performance remains below '1'.

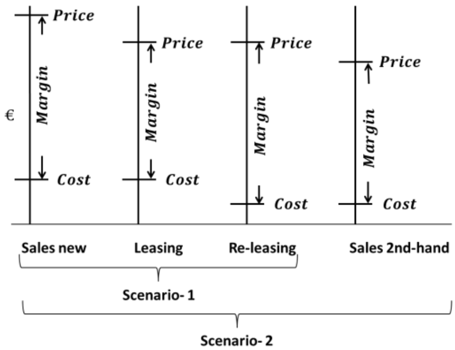

Figure 48: An illustration of different profit margin that may exist in different business models.

In scenario-1, the environmental performance remains steady to a value slightly lower than '1' until the time when the products start to return after the 1st leasing period. The slightly lower value at the beginning of the simulation run is due to the fact that the supply chain in location X has a higher CO_2 footprint (in comparison to the supply chain of company A in the current location) due to longer travelling distance for the products. As the refurbishment activities continue, more and more products are re-leased after the 1st refurbishment. As a consequence, the environmental performance continues to improve until it hits the peak when re-leased products start to return and products are sent for material recovery through recycling.

Scenario-2 with the assumptions mentioned above creates the economic and the environmental performance graphs that are shown in Figure 49 and Figure 50.

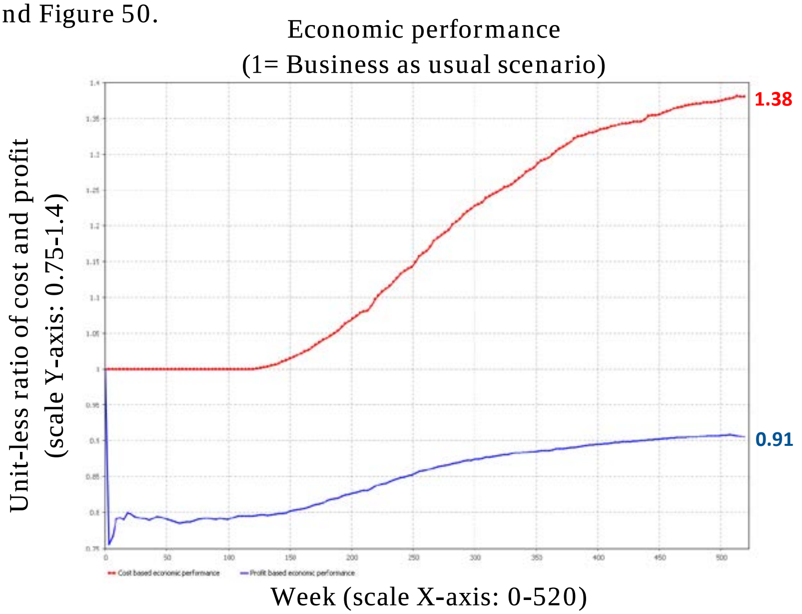

Figure 49: Graph showing the cost based (red line) and the profit based (blue line) economic performance in scenario-2. In the graph, numerical value '1' corresponds to the performance of the business as usual scenario.

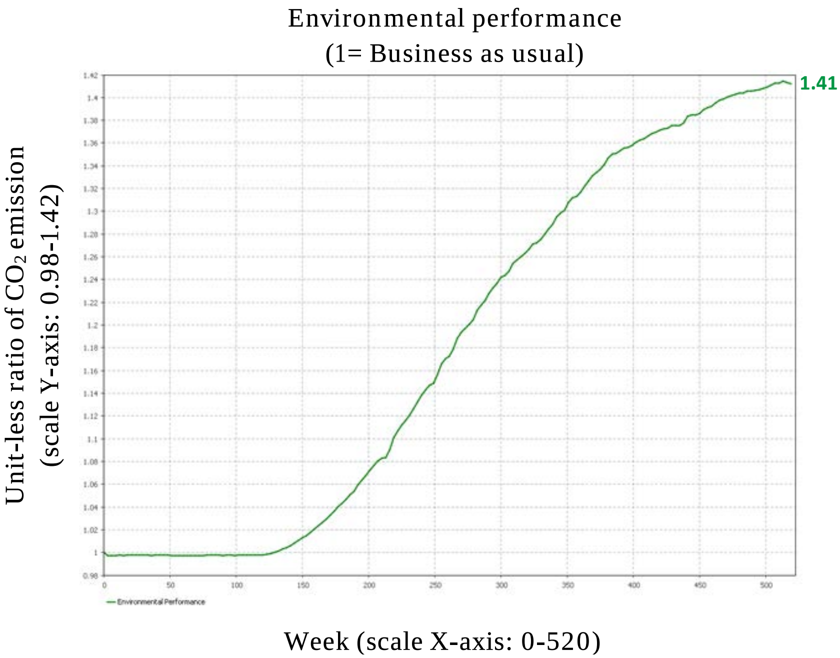

Figure 50: Graph showing the environmental performance in scenario-2. In the graph, numerical value '1' corresponds to the performance of the business as usual scenario.

Figure 49 and Figure 50 displays the economic and the environmental performance graphs of scenario-2. For the given model boundaries, the assumptions and the input values of the variables in scenario-2, the shape of the curves remains similar as scenarios-1. However, in comparison to senario-1, the performance peaks are not reached at the end of the simulation run time. The results of scenario-2 indicate a higher improvement in terms of the performance. The cost performance is improved as more demand is fulfilled using the refurbished products which cost less than producing new products. For the same reason, the profit performance continues to grow as more products are being refurbished. However, the overall performance remains below '1' due to the lower profit margin in the circular manufacturing system as highlighted earlier. Similarly, the environmental performance improves mainly due to the fact that the products in scenario-2 are used for the 3rd lifecycle. Table 5 below summarises the outcomes of the above-mentioned two scenarios.

Table 5: Summary of the difference in the outcomes of both scenarios.

	Scenario-1	**Scenario-2**	**Change**
Cost based economic performance	1.14	1.38	21 %
Profit based economic performance	0.86	0.91	5.8 %
Environmental performance	1.24	1.41	13.7 %

The above discussions highlight the features of the case company specific decision support tools. It also provides an overview of the interfaces and describes how to create scenarios and visualise the outcomes of each scenario. Once several scenarios are identified which are of interest, users can compare and analyse the outcomes of each scenario. If the outcomes of certain scenarios are not indicating the expected results, the users can identify the critical variables that are affecting the results and thereby, can set appropriate actions. These outcomes can be the basis for the decision making and finding alternative solutions.

6. DISCUSSION AND CONCLUSIONS

This chapter presents the final remarks, self-critiques and sets the direction for the future work.

The manufacturing industry is facing a unique challenge; on the one hand, manufacturing activities are essential for economic growth, and on the other hand, the manufacturing industry is also responsible for the overwhelming consumption of natural resources and generation of wastes. In this circumstance, to continue developing in a sustainable manner, the manufacturing industry has to move towards circular systems approach and consequently support the society in transition from the 'take-make-use-dispose' approach. Resource Conservative Manufacturing (ResCoM) is a research initiative and also an EC funded research project promoting circular manufacturing systems. Unlike remanufacturing and closed-loop supply chains in the conventional manufacturing systems, the ResCoM-framework proposes a systemic and systematic approach, considering interdependencies among business model, product design and supply chain aspects to overcome the classic challenges of uncertainty in quality, quantity and timing of returning products.

The research contributions presented in this dissertation cover development of the ResCoM-framework as well as development of the analysis methods and decision support tools to support the implementation of circular manufacturing systems. Nevertheless, all developments come with its pitfalls and among other things self-critique is an appropriate way to identify these pitfalls.

The first and the biggest hurdle has been to maintain consistency in the terms and their definitions used in this work. This was realised already during the start of the ResCoM project when in the very first meeting the partners were using different terms to refer to same ideas and concepts due to having their experiences from different fields and industries. Due to this, in the early stage of the ResCoM project, a common terminology was proposed. However, it was too early to adopt the common terminology since this area is evolving fast and new ideas are emerging frequently with new terminology. Furthermore, as the CE initiative is receiving wider coverage in media, policy making and research, we found it useful to align the terminology in ResCoM with CE as much as possible. After almost three and half years of work in the project, we are now in the stage of converging the terminology to help standardisation and create convenience for future use. For example, circular manufacturing system is a term used both to align ResCoM with the CE initiative and generalise the terms such as closed-loop manufacturing system, closed-loop product system, closed-loop supply chain, circular product system and ResCoM product system to a single term.

The second issue is to prioritise the elements of the ResCoM-framework for the purpose of implementation. The ResCoM-framework has a wide scope which had to be adapted to fit the implementation approach that aims at developing specific solutions for industries. For example, in the context of the ResCoM-framework, the term 'technology' is used to cover a wide range of manufacturing and remanufacturing technologies along with information and communication technology (ICT), which are essential for the successful implementation of circular manufacturing systems. However, in the context of the ResCoM project, the focus is limited to the ICT covering both manufacturing systems and manufactured products. Similarly, in the ResCoM project, the focus is placed only on the 'bottom-up' implementation approach driven by OEMs. At the same time, ResCoM-framework also includes 'top-down' approach combining social innovation, education, financial instruments, policy and legislative aspects.

The third issue is the reality-check of the ResCoM concepts. The ideas presented in the initial ResCoM-framework seem to be quite radical in the context of the reality that manufacturing industries operate in today. Considering the current way of operations in the industries, intermediate steps before a full-scale implementation of these ideas are required. For example, the ResCoM-framework proposed an ideal closed-loop supply chain that is fully integrated. While this should be the ultimate goal, a pragmatic and incremental approach is needed during the transition phase. Although a company may like to establish an ideal closed-loop supply chain, there are practical issues that prevent them from taking this giant step. An intermediate step, in this case, could be a semi-closed-loop supply chain based on the buy-back model. Such an intermediate transition step that is targeting and aiming for a semi-closed-loop supply chain in between the conventional and the ResCoM closed-loop supply chain is not explicitly covered in the ResCoM-framework.

The fourth issue is related to the modelling work presented in this dissertation. Models, in general, represent the views of a modeller and the reflections of his/her knowledge of the systems at the time of modelling. Revisiting the models after a considerable time gap raises a lot of new questions and new ideas for alternative approaches and possible simplifications. Similarly, models generally include a hand full of assumptions that a modeller considers relevant and important but leaves several other assumptions out. This often comes back in the form of criticism when the models are to be used or considered for other purposes by the users different than the modeller. Furthermore, often the main purposes of the system dynamics modelling, that is incorporating the system thinking in decision making and observing the system's behaviour over time are overlooked. Instead, discussions focus on the accuracy of the numerical results of the simulations. Although all system dynamics models generate numerical results, taking a point result and making a decision only based on that particular result may lead to making wrong decisions. In the context of circular manufacturing systems presented in this dissertation, the main purpose of the models is to incorporate system thinking and create analysis methods that consider interdependencies as well as feedback among different critical aspects. In addition, the aim is to analyse system's behaviours over time by creating different scenarios and all these to be carried out using a single decision making tool.

The fifth issue is to pinpointing the value that circular manufacturing systems will bring to all relevant stakeholders, especially for the manufacturers and the customers who will be directly affected by this paradigm shift. Most of the data that is available today to promote circular manufacturing systems are either presented at the macro level or too specific to some examples. Although the main driving factor in implementing circular manufacturing systems and adopting the CE initiative is economic sustainability; a key question still remains, i.e. are there other factors that may accelerate these initiatives? If so, how to make the value understandable and measurable for all the stakeholders? This aspect has not been emphasised sufficiently and as a result, many outcomes of the research remain rather specific to the specific case companies involved.

Nevertheless, none of the above-mentioned pitfalls is unique for a research initiative of this magnitude where each and every theory, method and tool is to be developed from scratch, implemented and verified. This is how research progresses; through questioning, revisiting, and altering until a theory, method or tool becomes useful and complete for a given purpose. Besides these reflections, it is worthwhile to mention that the papers appended in this dissertation are cited 73 times (until May 2017 in Google scholar) in a context, which supports further development. This can be considered as an indication that the research is acknowledged as relevant and there are not yet alternative approaches that have challenged the fundamentals of the ResCoM idea.

Before concluding, it is also important to lay a foundation for the future work which can be categorised as short and long term future work. The short term work could include revisiting the ResCoM-framework with respect to the outcomes of this research and create a revised and improved version of the framework. This revisiting may also lead to developing new methods and decision support tools. It will also be useful to standardise some of the terms (if not all) based on the learning. From the modelling point of view, a short term future work could be to combine key ideas such as the influence of material scarcity on manufacturing, the flow of products in the close-loop supply chain and the demand fulfilling mechanism, etc. discussed in the papers to create a new model. This proposed model will measure the economic and environmental performance of circular manufacturing systems under the influence of the dynamics of the material supply and demand for understanding the consequences of scarcity.

In the long term, more testing of the ResCoM-framework and further implementation of the methods and tools will be useful to widen the scope to fit other industries, beyond the ResCoM cases. Although the ResCoM-framework addresses both 'bottom-up' and 'top-down' approaches, the ResCoM project focused mainly on the 'bottom-up' approach, which is supporting the manufacturing industry in implementing circular manufacturing systems. The 'top-down' approach that requires social innovation, education, awareness and financial instruments as well as the involvement of policy makers need to be investigated further and can be a considered as a long-term endeavour.

Another critical aspect that is worth further investigation is how to make the value of the circular manufacturing systems understandable and measurable for all stakeholders involved. Currently, the value propositions in CE are presented at macro level highlighting mainly the benefits for the society and in limited cases for businesses. First of all, there should be a systemic and systematic way to identify what value is available in a particular case for a particular OEM, their customers and the society. Secondly, this value should be measured and presented at the micro level so that each party is fully aware of the benefits of implementing the circular manufacturing systems.

BIBLIOGRAPHY

[1] F. M. A. Asif, Resource Conservative Manufacturing: a new generation of manufacturing, Stockholm: KTH Royal Institute of Technology, 2011.

[2] Unknown, “www.rescoms.eu,” ResCoM project consortium, 2013. [Online]. Available: http://www.rescoms.eu/. [Accessed 13 December 2016].

[3] A. Rashid, F. M. A. Asif, P. Krajnik and C. M. Nicolescu, “Resource Conservative Manufacturing: An essential change in business and technology paradigm for sustainable manufacturing,” *Journal of Cleaner Production,* vol. 57, p. 166–177, 2013.

[4] N. Nasr and M. Thurston, “Remanufacturing: A key enabler to sustainable product systems,” in *13th CIRP International Conference on Lifecycle Engineering, Proceeding of LCE 2006* , 2006.

[5] V. D. R. Guide Jr and L. N. Van Wassenhove, “OR FORUM—The evolution of closed-loop supply chain research,” *Operations research ,* vol. 57, no. 1, pp. 10-18, 2009.

[6] Ellen Macarthur Foundation, “Towards the Circular Economy Vol. 1, 2 & 3,” Ellen Macarthur Foundation, 2012-2014.

[7] W. Hauser and R. T. Lund, “Remanufacturing – An American Perspective,” in *The International Conference on Responsive Manufacturing*, Ningbo, China, 2011.

[8] P. D. Leedy and J. E. Ormrod, Practical Research: Planning and Design, New Jersey: Pearson Education, Inc, 2005.

[9] C. R. Kothari, Research methodology: Methods and techniques., New Delhi: New Age International, 2004.

[10] J. W. Creswell, Research design: Qualitative, quantitative, and mixed methods approaches., Sage publications, 2013.

[11] J. W. Creswell, Educational research: Planning, conducting, and evaluating quantitative and qualitative research., Upper Saddle River, NJ: Merrill Prentice Hall, 2002.

[12] D. Denyer and D. Tranfield, “Using qualitative research synthesis to build an actionable knowledge base,” *Management Decision,* vol. 44, no. 2, pp. 213 - 227, 2006.

[13] Unknown, “World Population Prospects, The 2015 Revision,” United Nations, Department of Economic and Social Affairs, New York, 2015.

[14] Unknown, “www.cia.gov,” Central Intelligence Agency , 2015. [Online]. Available: https://www.cia.gov/library/publications/resources/the-world-factbook/geos/xx.html. [Accessed 13 December 2016].

[15] D. H. Meadows, D. H. Meadows, J. Randers and W. W. Behrens III, The limits to growth: a report to the club of Rome (1972)., New York: Universe Books, 1972.

[16] M. Donella, J. Randers and D. Meadows, Limits to growth: The 30-year update, Chelsea Green Publishing, 2004.

[17] T. Jackson, Prosperity without Growth: Economics for a Finite Planet, UK: Earthscan, 2009.

[18] A. Wijkman, K. Skånberg and M. Berglund, “The circular economy and benefits for society: jobs and climate clear winners in an economy based on renewable energy and resource efficiency,” Club of Rome, 2015.

[19] Unknown, “www.worldbank.org,” The World Bank, 2014. [Online]. Available: http://data.worldbank.org/indicator/NE.CON.PRVT.PC.KD?end=2014&start=1984. [Accessed 13 December 2016].

[20] W. Hauser and R. T. Lund, “www.bu.edu,” Boston University, 2012. [Online]. Available: http://www.bu.edu/reman/RemanSlides.pdf. [Accessed 13 December 2016].

[21] R. Steinhilper, Remanufacturing The Ultimate Form of Recycling, Stuttgart: Fraunhofer IRB Verlag, 1998.

[22] M. Lieder and A. Rashid, “Towards circular economy implementation: a comprehensive review in context of manufacturing industry,” *Journal of Cleaner Production ,* vol. 115,

pp. 36-51, 2016.

[23] M. P. De Brito, R. Dekker and S. D. P. Flapper, “Reverse logistics: a review of case studies.,” in *Springer* , Berlin Heidelberg, 2005.

[24] Unknown, “http://remanet.org/,” Remanufacturing Networks, 2016. [Online]. Available: http://remanet.org/index.php?option=com_content&view=article&id=12&Itemid=119. [Accessed 14 December 2016].

[25] T. Guidat, M. Uoti, H. Tonteri and T. Määttä, “A classification of remanufacturing networks in Europe and their influence on new entrants,” *Procedia CIRP 26,* vol. 26, pp. 683-688, 2015.

[26] I. A. Williamson, D. R. Pearson, S. L. Aranoff, D. A. Pinkert, D. S. Johanson and M. M. Broadbent, “Remanufactured Goods: An Overview of the U.S. and Global Industries, Markets, and Trade,” United States International Trade Commission, Washington, 2012.

[27] D. Parker, K. Riley, S. Robinson, H. Symington, J. Tewson, K. Jansson, S. Ramkumar and D. Peck, “Remanufacturing Market Study,” European Remanufacturing Network, 2015.

[28] P. Ghisellini, C. Cialani and S. Ulgiati, “A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems,” *Journal of Cleaner Production,* vol. 114, pp. 11-32, 2016.

[29] D. W. Pearce and R. K. Turne, Economics of natural resources and the environment., JHU Press, 1990.

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

[31] R. S. Bhatti, P. Kumar and D. Kumar, “Evolution of system dynamics in supply chain management,” *International Journal of Indian Culture and Business Management,* vol. 5, no. 1, pp. 1-14, 2011.

[32] B. J. Angerhofer and M. C. Angelides, “System dynamics modelling in supply chain management: research review,” *In Simulation Conference, 2000. IEEE Proceedings,* vol. 1, no. Winter, pp. 342-351, 2000.

[33] K. H. Van Dam, I. Nikolic and Z. Lukszo, Agent-based modelling of socio-technical systems, Springer Science & Business Media, 2012.

[34] E. Kiesling, M. Gunther, C. Stummer and L. M. Wakolbinger, “An Agent-based simulation model for the market diffusion of a second generation biofuel,” in *Proceedings of the 2009 Winter Simulation Conference*, 2009.

[35] I. Wolfa, T. Schröder, J. Neumann and G. d. Haan, “Changing minds about electric cars: An empirically grounded agent-based modeling approach,” *Technological Forecasting and Social Change,* vol. 94, pp. 269-285, 2015.

[36] L. M. Sonderegger-Wakolbinger and C. Stummer, “An agent-based simulation of customer multi-channel choice behavior,” *Central European Journal of Operations Research,* vol. 23, no. 2, pp. 459-477, 2015.

[37] C. Stummer, E. Kiesling, M. Günther and R. Vetschera, “ Innovation diffusion of repeat purchase products in a competitive market: An agent-based simulation approach,” *European Journal of Operational Research,* vol. 245, no. 1, pp. 157-167, 2015.

[38] E. Suryani, R. A. Hendrawan, U. Salama and L. P. Dewi, “Agent Based Model to Analyze Consumer Behavior in Consuming the Electricity Energy,” *Jurnal Teknologi,* vol. 72, no. 4, 2015.

[39] T. Zhang and D. Zhang, “Agent-based simulation of consumer purchase decision-making and the decoy effect,” *Journal of Business Research,* vol. 60, no. 8, pp. 912-922, 2000.

[40] Y. Liu and H. Ye, “"The dynamic study on firm’s environmental behavior and influencing factors: an adaptive agent-based modeling approach.,” *Journal of Cleaner Production,* vol. 37, pp. 278-287, 2012.

[41] J. W. Forrester, “Some basic concepts in system dynamics,” Sloan School of Management, Massachusetts Institute of Technology, ., Cambridge, 2009.

[42] T. Cooper, Beyond recycling. The longer life option., London: The New Economics Foundation, 1994.

[43] C. M. Rose, K. Ishii and A. Stevels, “Influencing design to improve product end-of-life stage,” *Research in Engineering Design,* vol. 13, no. 2, pp. 83-93, 2002.

[44] R. Knoth, B. Kopacek and P. Kopacek, “Case study: multi life cycle center for electronic products,” in *Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment*, 2005.

[45] F. M. A. Asif, B. C., A. Rashid and C. M. Nicolescu, “Performance Analysis of the Closed Loop Supply Chain,” *Journal of Remanufacturing,* vol. 2, no. 4, 2012.

[46] V. D. R. Guide Jr and J. L, “ The potential for cannibalization of new products sales by remanufactured products,” *Decision Sciences,* vol. 41, no. 3, pp. 547-572, 2010.

[47] A. Atasu, M. Sarvary and L. N. Van Wassenhove, “Remanufacturing as a marketing strategy,” *Management science ,* vol. 54, no. 10, pp. 1731-1746, 2008.

[48] EU, “Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE),” European Union, Brussels, 2003.

[49] EU, “Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles,” European Union, Brussels, 2000.

[50] EU, “Directive 2005/64/EC on the type-approval of motor vehicles with regard to their re-usability, recyclability and recoverability,” European Union, Brussels, 2005.

[51] H. C. Haynsworth and R. T. Lyons, “Remanufacturing by design, the missing link.,” *Production and Inventory Management,* vol. 28, no. 2, pp. 24-29, 1987.

[52] R. Subramoniam, D. Huisingh and R. B. Chinnam, “ "Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs.,” *Journal of Cleaner Production ,* vol. 17, no. 13, pp. 1163-1174, 2009.

[53] Unknown, “Minerals, Critical Minerals,and the U.S.Economy,” The National Academies Press, Washington D.C., 2008.

[54] Unkown, “ Critical Raw Materials for the EU, Report of the Ad hoc Working Group on defining critical raw materials,” European Commission, Brussels, 2010, 2014.

[55] F. M. A. Asif, A. Rashid, C. Bianchi and C. M. Nicolescu, “System dynamics models for decision making in product multiple lifecycles,” *Resources, Conservation and Recycling,* vol. 101, pp. 20-33, 2015.

[56] EU, “Directive 2011/65/EUof the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment,” European Union, Brussels, 2011.

[57] Unknown, “Scoping study to identify potential circular economy actions, priority sectors,material flows and value chains,” European Union, Luxembourg, 2014.

[58] P. Mitchell and K. James, ““Economic Growth Potential of More Circular Economies,” WRAP, Banbury, 2015.

[59] F. M. A. Asif, M. Lieder and A. Rashid, “ Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems,” *Journal of Cleaner Production,* vol. 139, pp. 1261-1281, 2016.

[60] M. Lieder, F. M. A. Asif and A. Rashid, “Towards Circular Economy implementation: an agent-based simulation approach for business model changes,” *Autonomous Agents and Multi-Agent Systems,* pp. 1-26, 2017 .

Paper A

Resource Conservative Manufacturing: an essential change in business and technology paradigm for sustainable manufacturing

RASHID, AMIR; ASIF, FARAZEE M. A.; KRAJNIK, PETER & NICOLESCU, CORNEL M.

Published in
Journal of Cleaner Production, 57(2013), 166–177.

Paper B

System dynamics models for decision making in product multiple lifecycles

ASIF, FARAZEE M. A.; RASHID, AMIR; BIANCHI, CARMINE & NICOLESCU, CORNEL M.

Published in

Resources, Conservation and Recycling, 101 (2015), 20-33.

Paper C

Performance analysis of the closed loop supply chain

ASIF, FARAZEE M. A.; BIANCHI, CARMINE; RASHID, AMIR & NICOLESCU, CORNEL M.

Published in
Journal of Remanufacturing, 2:4 (2012)

Paper D

Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems

ASIF, FARAZEE M. A.; LIEDER, MICHAEL & RASHID, AMIR

Published in
Journal of Cleaner Production, 139 (2016): 1261-128