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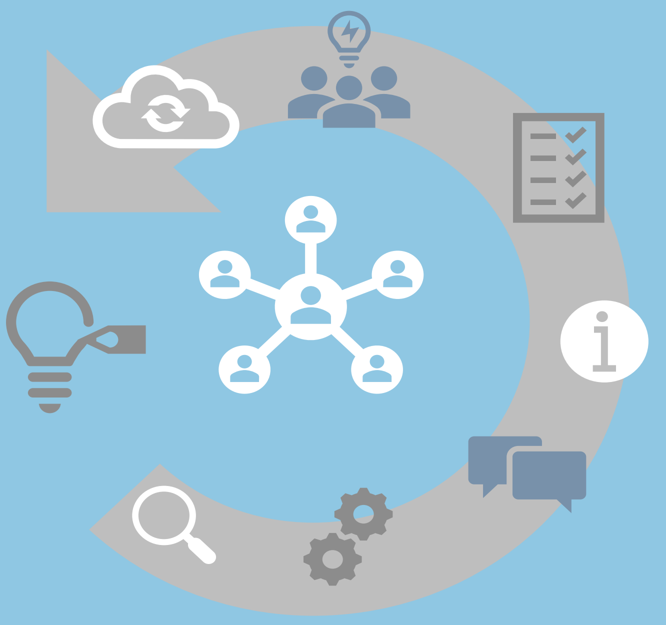
Improving Design for Remanufacturing Through Feedback from Remanufacturing to Design

Louise Lindkvist Haziri



LINKÖPING UNIVERSITY

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IMPROVING DESIGN FOR REMANUFACTURING THROUGH FEEDBACK FROM REMANUFACTURING TO DESIGN

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ABSTRACT

The high demand for products in our society makes manufacturing, and the treatment of products throughout the product life cycle, crucial as it adds to the total environmental impact of a product. Initiatives such as the circular economy promote economic growth while not increasing environmental impacts. The circular economy can also be viewed as a system where the use, maintenance, reuse, remanufacturing, and recycling of materials are optimised to capture the embedded value of products. This doctoral thesis focuses on remanufacturing in particular as an environmentally preferred way to treat products that have reached their end of use. Remanufacturing is an industrial process whereby a used product is restored to its next full life cycle, and thus energy and materials can be saved compared to new production.

A product that is intended for remanufacturing ought to have certain qualities such as ease of cleaning, ease of separation, and ease of reassembly in order to achieve efficient product remanufacturing. By applying design for remanufacturing (DfRem), costs can be saved as the remanufacturing operation time is reduced. Further, integrating DfRem in the design process is essential in order to achieve a more efficient and effective remanufacturing process. However, the current status in industry is that DfRem is not widely applied, and thus, products are not designed to facilitate remanufacturing. Since DfRem requires knowledge about remanufacturing, feedback from remanufacturing to design is needed for making the correct design considerations. The aim of this doctoral thesis is to expand current knowledge on feedback from remanufacturing to design and how it can be used to improve DfRem.

Hence, in order to meet the aim of this thesis, both literature studies and multiple case studies were conducted. The case studies include three companies that design, manufacture, and remanufacture their products. The data collection within the case studies was predominantly conducted through semi-structured interviews. The results from the case studies have been further explored in a cross-case analysis.

The literature studies show the potential feedback from remanufacturing to design can be divided into three main categories: from the remanufacturing personnel, related to the process of remanufacturing, or related to the core to be remanufactured. Further, potential feedback at the case companies was found. However, currently, the potential feedback remains unsought for at the case companies. Indeed, there are barriers for feedback from remanufacturing to design,

such as lack of knowledge, lack of incentives, and organisational barriers. However, there are also enablers, such as business opportunities to be gained, increased customer willingness, and laws, regulations, and standards encouraging more sustainable products.

In this doctoral thesis, a framework for improving implementation of DfRem is presented, as the use of DfRem and feedback from remanufacturing to design was found to be scarce in the case companies. The developed Remanufacturing Information Feedback Framework (RIFF) focuses on breaching the barriers for feedback from remanufacturing to design. Further, the application of the RIFF promotes the implementation of DfRem methods and tools, which, when applied, could make remanufacturing more efficient and effective. Consequently, the increased application of DfRem will contribute to the overall growth of the remanufacturing market, which will also reduce the negative environmental impact and promote, in turn a more circular economy.

SAMMANFATTNING

Den höga efterfrågan på produkter i vårt samhälle innebär att tillverkning av produkter och hur de behandlas under hela deras livscykel är betydande för miljöpåverkan. Detta eftersom allt ifrån tillverkning till hur en produkt tas om hand när den är förbrukad, bidrar till produktens totala miljöpåverkan. Initiativ såsom införandet av cirkulär ekonomi är tänkt att främja ekonomisk tillväxt utan att påverka miljön negativt. Cirkulär ekonomi kan också ses som ett system där användning, underhåll, återanvändning, återtillverkning och återvinning av produkter och material optimeras för att tillvarata och göra det mesta av den energi och det material som använts för att tillverka produkten. Denna doktorsavhandling fokuserar på återtillverkning, såsom ett hållbart sätt att behandla produkter som inte längre används. Återtillverkning är en industriell process där en begagnad produkt återställs till nyskick och på så sätt sparas energi och material, jämfört med nytillverkning.

En produkt som är avsedd för återtillverkning bör ha vissa egenskaper såsom att vara enkel att rengöra, enkel att demontera och enkel att montera. Genom att tillämpa konstruktion för återtillverkning (eng. design for remanufacturing (DfRem)) kan kostnader inom återtillverkning sparas eftersom tidsåtgången reduceras. Integrering av DfRem i produktutvecklingsprocessen är därför viktigt för att uppnå en effektivare återtillverkningsprocess. I nuläget används dock inte DfRem i någon större utsträckning inom industrin. DfRem kräver kunskap om återtillverkning, både i allmänhet, och om den specifika återtillverkningsprocessen för den aktuella produkten i synnerhet. Därför behövs feedback från återtillverkning till produktutveckling för att konstruktörer ska kunna göra korrekta konstruktionsöverväganden. Syftet med denna doktorsavhandling är att utöka aktuell kunskap om feedback från återtillverkning till produktutveckling och hur den kan användas för att förbättra DfRem.

För att uppnå syftet genomfördes både litteraturstudier och flera fallstudier. Fallstudierna inkluderar tre företag som konstruerar, tillverkar och återtillverkar sina produkter. Datainsamlingen genomfördes främst genom semistrukturerade intervjuer. Resultaten från de tre fallstudierna har även undersökts i en syntes från de olika fallstudierna.

Litteraturstudierna visade att den potentiella feedbacken från återtillverkning till produktutveckling kan delas in i tre huvudkategorier; från

återtillverkningspersonalen, relaterad till processen för återtillverkning eller relaterad till komponenten som ska återtillverkas. Vidare hittades potentiell feedback hos fallföretagen. För närvarande förblir emellertid den potentiella feedbacken outnyttjad vid de fallföretag som presenteras i denna avhandling. Fallstudierna visade att det finns hinder för feedback från återtillverkning till produktutveckling; såsom brist på kunskap, brist på incitament och organisatoriska hinder. Det finns emellertid också möjliggörare såsom; potentiella affärsmöjligheter, ökad kundvilja, och lagar, regler och standarder som uppmuntrar till mer hållbara produkter.

I denna doktorsavhandling presenteras ett ramverk för att förbättra implementering av DfRem, eftersom användningen av DfRem och feedback från återtillverkning till produktutveckling är bristfällig i de fall som studerats. Ramverket (eng. the Remanufacturing Information Feedback Framework (RIFF)) fokuserar på att överbrygga hinder för feedback från återtillverkning till produktutveckling. Vidare främjar tillämpningen av RIFF implementeringen av DfRem-metoder och -verktyg, som, när de tillämpas, skulle kunna göra återtillverkning mer effektiv. Följaktligen kan ökad tillämpning av DfRem att bidra till den totala tillväxten av återtillverkningsmarknaden, vilket skulle innebära minskad negativ miljöpåverkan och även gynna en mer cirkulär ekonomi.

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Louise Lindkvist Haziri

Linköping, February 2020

APPENDED PAPERS

The following papers laid the foundation for this doctoral thesis:

PAPER I Lindkvist L. and Sundin E. (2012) Life-Cycle Information Feedback to Product Design. *Proceedings of the 5th Swedish Production Symposium (SPS), pp. 99-105*, Linköping, Sweden, November 6-8.

PAPER II Kurilova-Palisaitiene J., Lindkvist L., and Sundin E. (2015) Towards facilitating circular product lifecycle information flow via remanufacturing. *Procedia CIRP, Vol. 29, pp. 780-785.* Elsevier Science B.V., Amsterdam, The Netherlands.

PAPER III Lindkvist L. and Sundin E. (2015) Assessing barriers for available life-cycle information feedback transfer to product design. *Proceedings of the 2nd International Conference of Remanufacturing (ICoR),* Amsterdam, The Netherlands, June 14-16.

PAPER IV Lindkvist L. and Sundin E. (2016) The Role of Product-Service Systems Regarding Information Feedback Transfer in the Product Life-Cycle Including Remanufacturing. *Procedia CIRP, Vol. 47, pp. 311–316*, Elsevier Science B.V., Amsterdam, The Netherlands.

PAPER V Lindkvist Haziri L., Sundin, E., and Sakao, T. (2019) Feedback from Remanufacturing: Its Unexploited Potential to Improve Future Product Design. *Sustainability, Vol. 11(15), pp. 1-23.*

PAPER VI Lindkvist Haziri L. and Sundin E. (2019) Supporting design for remanufacturing - A framework for implementing information feedback from remanufacturing to product design. *Journal of Remanufacturing. https://doi.org/10.1007/s13243-019-00074-7* Springer, The Netherlands.

AUTHOR'S CONTRIBUTION TO THE APPENDED PAPERS

PAPER I Louise Lindkvist Haziri performed the literature study and wrote most of the paper. Erik Sundin supported and guided the writing process. He also wrote one paragraph of the paper.

PAPER II Jelena Kurilova-Palisaitiene and Louise Lindkvist Haziri performed the empirical studies and divided the writing of the paper equally between them. Erik Sundin guided and provided input throughout the writing process.

PAPER III Louise Lindkvist Haziri performed the empirical studies and wrote the paper. Erik Sundin guided and provided input throughout the writing process.

PAPER IV Louise Lindkvist Haziri performed the empirical studies and wrote the paper. Erik Sundin guided and provided input throughout the writing process.

PAPER V Louise Lindkvist Haziri carried out the empirical studies and wrote the original draft paper. Erik Sundin contributed with review and editing throughout the writing process. Tomohiko Sakao contributed with review, input and improvements. Erik Sundin and Tomohiko Sakao also contributed much to the discussion section.

PAPER VI Louise Lindkvist Haziri performed the empirical studies and wrote the paper. Erik Sundin contributed with review and editing throughout the writing process.

OTHER PUBLICATIONS

Lindkvist L. and Sundin E. (2013) The Use of Product Life-Cycle Information in a Value Chain including Remanufacturing. *Proceedings of the 20th CIRP Conference on Life Cycle Engineering (LCE), pp. 621-626*, Singapore, April 17-19.

Lindkvist L., Sundin E., and Sakao T. (2013) Exploring the Use of Product Life-Cycle Information in Two Value Chains Including Remanufacturing. *Proceedings of the 8th International Symposium on Environmentally Conscious Design and Inverse Engineering, (EcoDesign),* Jeju Island, South Korea, December 4-6.

Lindkvist L., Alonso Movilla N., Sundin E., and Zwolinski P. (2015) Investigating types of information from WEEE take-back systems in order to promote Design for Recovery. *E-book proceedings of 9th International Symposium of Environmentally Conscious Design and Inverse Manufacturing (EcoDesign).* Tokyo, Japan, December 2-4.

Lindkvist L. and Sundin E. (2016) Analysing the service information transfer in the service development process at two automotive companies. *Procedia CIRP, Vol. 48, pp. 51-56,* Elsevier B.V., Amsterdam, The Netherlands.

Lindkvist L. and Sundin E. (2016) A Stepwise Method towards Products Adapted for Remanufacturing. *Proceedings of the 14th International Design Conference* (*DESIGN) pp. 321–330*, Dubrovnik, Croatia, May 16-19.

Licentiate thesis:

Lindkvist L. (2014) Exploring product life-cycle information flows with a focus on remanufacturing. Linköping studies in Science and Technology, Thesis No. 1669, Division of Manufacturing Engineering, Department of Management and Engineering, Linköping University, 581 83 Linköping, Sweden.

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ABBREVIATIONS

BOM — BILL OF MATERIAL
A comprehensive list of parts required to create a product.

CE — CIRCULAR ECONOMY
A regenerative system in which resource input and waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017).

CR — CONTRACTED REMANUFACTURER
A company contracted to perform remanufacturing on behalf of another company (Lund, 1984).

DFA — DESIGN FOR ASSEMBLY
Practices for product design in which the ease of assembly is an explicit design objective that determines the product configuration (Benhabib, 2003).

DFD — DESIGN FOR DISASSEMBLY
Practices for product design in which the ease of disassembly is an explicit design objective that determines the product configuration (Vanegas et al., 2014).

DFM — DESIGN FOR MANUFACTURING
Practices for product design in which the ease of manufacturing is an explicit design objective that determines the product configuration (Benhabib, 2003).

DFREM — DESIGN FOR REMANUFACTURING
Practices for product design in which the ease of remanufacturing and all its process steps are explicit design objectives that determine the product configuration (Shu and Flowers, 1999).

DFS — DESIGN FOR SERVICE
Practices for product design in which ease of service, including disassembly and reassembly operations, is an explicit design objective

that determine the product configuration (Dewhurst and Abbatiello, 1996).

DFX DESIGN FOR X
Practices for product design relative to X, where X can be, i.e., Cost, Manufacturing, Assembly, or Reliability (Ullman 2009).

DRM DESIGN RESEARCH METHODOLOGY
The DRM is a framework developed by Blessing and Chakrabarti (2009), specifically adapted for research considering product design issues.

EEE ELECTRONIC AND ELECTRICAL EQUIPMENT

EOL END OF LIFE
A state where the product is disposed of or incinerated as it no longer satisfies the expectations or needs of the user (Ortegon et al., 2014).

EOU END OF USE
A decoupling point whereby the product no longer satisfies the expectations or needs of the user. If the remaining functional or material value cannot be recovered, by e.g. reuse, remanufacturing or recycling, the product has reached its end-of-life (EoL) (Ortegon et al., 2014).

IR INDEPENDENT REMANUFACTURER
A company that remanufactures a product without any connection to the original equipment manufacturer (Lund, 1984).

HDOR HEAVY-DUTY AND OFF-ROAD EQUIPMENT

LPD LEAN PRODUCT DEVELOPMENT
A term created by American researchers to describe the efficient strategy for product development applied by Toyota in the mid-90s (Holmdahl, 2010).

OEM ORIGINAL EQUIPMENT MANUFACTURER
A company with control over product design and the production of its products (Lund, 1984).

OER	ORIGINAL EQUIPMENT REMANUFACTURER A company with control over product design and the production of its products, also responsible for the remanufacturing of its used products (Lund, 1984).
PSS	PRODUCT-SERVICE SYSTEMS Product-service systems comprise combinations of products and services to fulfil customer needs (Goedkoop et al., 1999).

TERMINOLOGY

ACTOR
A participant in an action or process (Oxford University Press, 2019).

CASE STUDY
An empirical inquiry that investigates a contemporary phenomenon within a real-life context, especially when the boundaries between phenomenon and contexts are not clearly evident (Yin, 1994).

CONDITION MONITORING
Technical diagnostics of the machine where selected parameters are continuously sensed, measured, and recorded for the purpose of reducing, analysing, comparing, and displaying the data and information to support decisions related to the operation and maintenance of the machine (9ISO/TC/108/SC5).

CORE
A used product or component intended for remanufacturing (Lund, 1984).

DESIGN PROCESS
The organisation and management of people and the information they develop in the evolution of a product (Ullman, 2009).

FEEDBACK
Information about reactions to a product, a person's performance of a task, etc. which is used as a basis for improvement (Oxford University Press, 2019).

INFORMATION
Information can be described as a message, usually in the form of a document, or audible or visible communication from a sender to a receiver (Davenport and Prusak, 1998).

KNOWLEDGE
Knowledge is a fluid makes of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In organizations it often becomes embedded not only in documents or repositories

but also in organisational routines, processes, practices, and norms." (Davenport and Prusak (1998)

LEAN
A term created by American researchers to describe the efficient strategy for creating values by, for example, minimising waste and optimising workflows in the manufacturing process, applied by Toyota in the mid-80s (Womack et al., 1990).

PRODUCT
The physical part of an offer a company designs, manufactures and sells (Ullman, 2010).

PRODUCT DESIGN
A set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product (Ulrich and Eppinger, 2008).

PRODUCT LIFE CYCLE
The product life cycle contains the phases; design, manufacturing, use, service, end-of-use, and end-of-life (Östlin et al. 2009).

RECYCLING
A process whereby the material value of used products is preserved by recovering the materials while not preserving the functional value (Ortegon et al., 2014).

REFURBISHMENT
A process whereby products are returned to a functional condition, but its condition and performance do not necessarily equal to the original product specifications (Ortegon et al., 2014).

REMANUFACTURING
An industrial process whereby products are returned to a state of "as good as new" or better and sold with a warranty to match (Ijomah et al., 2004).

REQUIREMENT SPECIFICATION
A formal registration of the conditions that are imposed on a new or altered product design, both preceding as well as during the corresponding product development cycle in a design process (Lutters, 2014).

REUSE
A process where both material and functional value of used products are preserved by transferring the products to new users. The products could be used for their original purpose or used for other purposes (Ortegon et al., 2014).

STAKEHOLDER
A person who has a concern for the product (Ullman, 2009).

VALUE CHAIN
A linked set of discrete activities within a firm which are the sources of competitive advantage. These activities stem from designing, producing, marketing, delivering and supporting a firm's product (Porter, 2004).

1 INTRODUCTION

In this chapter, the research subject is introduced, key concepts are explained, and the research gap addressed in this thesis is presented. Further, the aim of this research and the research questions are presented, as well as the delimitations of this research. Finally, the chapter ends with an overview of this thesis's content.

1.1 BACKGROUND

As climate change caused by human activities on Earth is established by many researchers around the world (IPCC, 2017), governments, societies, industries, and individuals need to take action in order to create a more sustainable future. The manufacturing industry provides society and companies with the necessary products to improve our lives. With increased populations and affluence, the strain on the environment increases (Rosen and Kishawy, 2012). The high demand for products makes manufacturing and the treatment of products throughout the product life cycle (Figure 1) crucial, as it all adds to the environmental impact of the product. Resource depletion, increasing human population, climate change, reduced biodiversity, toxins, emissions to air and water, and waste are just some of the environmental concerns regarding the making, use, and disposal of products (Kutz, 2007). Thus, manufacturing and the end-of-use (EoU) treatment of products need to be performed in a way that reduces negative environmental impacts.

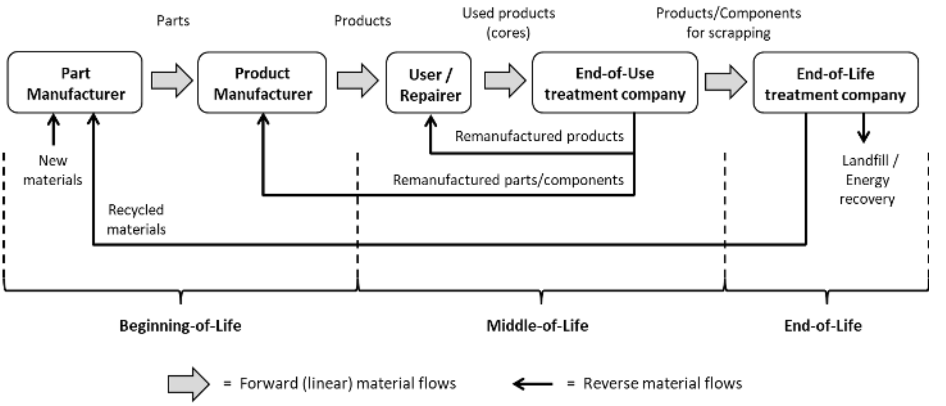

Figure 1. The product life cycle displaying the actors involved and the forward and reverse flows of materials (adapted from Sakao and Sundin, 2019).

1.1.1 Environmental aspects and the circular economy

The application of the circular economy (CE) concept can be one success factor for achieving a more sustainable future. Ideally, the CE promotes economic growth while not increasing environmental impacts (COM, 2014). The CE can also be viewed as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing flows, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017). Further, Geissdoerfer et al. (2017) state that the CE can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. Crucial to the CE is to prevent linear product flows where products are consumed and disposed of. Instead, the CE promotes sensible options for maintaining as much value of the products as possible after EoU.

According to Stahel (2016), CE business models can be divided into two major categories: the first, which enables the extended use and service of products such as reuse, remanufacturing, and refurbishment, and the second, which allows reuse of resources, such as recycling. Indeed, remanufacturing can be seen as a key enabler of CE by enabling multiple life cycles for products and components (Hilton and Thurston, 2019).

1.1.2 Remanufacturing

Remanufacturing is one highly effective way of managing a product's EoU (e.g., Steinhilper, 1998; Sundin, 2004). Instead of discarding products after EoU, the product can be salvaged. Remanufacturing is an industrial process whereby used products are returned to a state of like-new (Ijomah et al., 2007a). A remanufacturing process contains several characteristic steps, namely inspection, disassembly, part refurbishment/replacement, cleaning, reassembly, and testing (Sundin, 2004).

As remanufacturing allows a product to have a second use or more, environmental benefits can be gained. Further, the components are typically reprocessed to a high degree, and consequently, the energy invested in producing the original component can be salvaged to a large extent. Thus, remanufacturing is more environmentally friendly than new production, as it consumes less energy and materials compared to new production (Graedel and Allenby, 2009; Sundin and Lee, 2011).

Remanufacturing is not a new phenomenon; it has been an industrial activity since the Second World War (Lund, 1984). The remanufacturing industry is most prominent in the Western countries. In Europe, the remanufacturing industry is estimated at around €30 billion in sales, but with the potential to increase to €90 billion by 2030 (Parker et al., 2015). In the US, the remanufacturing industry reported $43 billion in sales in 2012 (USITC, 2012).

Drivers for companies to engage in remanufacturing are mainly ecological, economic, and policy-oriented (Östlin et al., 2008a). Remanufacturing is often seen as a good approach for companies that want to adopt more sustainable business plans (Goodall et al., 2014). Nevertheless, without revenue opportunities, there is no real incentive to remanufacture (Ijomah et al., 2007a). Remanufactured products can often be sold with a higher profit margin than newly manufactured products (Allwood et al., 2010). Albeit more profitable, remanufactured products are often sold for a lower price and on markets other than the original product (Östlin, 2008).

Factors such as market demand, product design, EoU condition, and information uncertainty could affect the success of remanufacturing (Goodall et al., 2014). Products most suitable for remanufacturing are typically durable enough to withstand multiple life cycles and also contain high-value parts (Hatcher et al., 2013).

1.1.3 DESIGN FOR REMANUFACTURING

The efficiency and effectiveness of the remanufacturing process depend to a high degree on how the product is designed (e.g., Sundin and Bras, 2005; Ijomah et al., 2007a). Thus, many challenges for remanufacturing can be traced back to the product's design (Ijomah et al., 2007a; Hatcher et al., 2011). By integrating design for remanufacturing (DfRem) in the design process, companies can gain benefits such as the reduction of energy and materials and increased efficiency (Nasr and

Thurston, 2006). One company that has integrated DfRem in its design process is Xerox, which acknowledges it as a way to gain competitive advantage (Nasr and Thurston, 2006). Furthermore, Caterpillar and Xerox amongst others have made DfRem one of the critical elements in the foundation for creating value for their customers (Hilton and Thurston, 2019). However, DfRem is typically motivated by profitability and not necessarily environmental impact (Ijomah et al., 2007a). Nevertheless, DfRem is shown to be environmentally beneficial as well as an opportunity for the company to increase its revenue (Kerr and Ryan, 2001; Chiodo et al., 2011).

There are some characteristic product properties related to remanufacturing, namely ease of identification, ease of verification, ease of access, ease of handling, ease of separation, ease of securing, ease of alignment, ease of stacking, and wear resistance (Sundin, 2004). Product design strategies beneficial for remanufacturing include standardised products (Östlin, 2008), use of modules (Krikke et al., 2004) increased size and thickness of components (Mabee et al., 1999), and upgradability (Östlin, 2008). Assembly methods are also critical for remanufacturing success, as the product is disassembled and reassembled multiple times. Hence, joining techniques such as rivets, glue, and fragile snap fits are unsuitable if the product is to be remanufactured (Sundin and Lindahl, 2008).

Although few products have been reported to be designed for remanufacturing (e.g., Sundin and Bras, 2005; Hatcher et al., 2011), there are still many products being remanufactured. This causes inefficiency in the remanufacturing process, and further research and industrial efforts are needed to facilitate more widespread use of DfRem. According to, for example, Ramani et al. (2010), early decisions in the product development process have the highest impact on a product's sustainability. This includes DfRem, which needs to be included early in the design process in order to be efficient (Hatcher et al., 2011).

In fact, the direction of the product design is determined on when the design process starts and is stated in a product requirement specification. A requirement specification is a document that contains detailed and agreed upon requirements specified so that they serve as the foundation for development activities, such as product design (Pohl, 2010). While developing requirements for a product's design, it is important to consider requirements from all stages of the product life cycle (Figure 1) and feed back those results to the requirement specification design process (Wiesner et al., 2015). The final product requirements specifications describe precisely how a product should perform (Ulrich and Eppinger, 2008).

Thus, by implementing remanufacturing requirements in the product design process, remanufacturability can be improved (Xiaoyan, 2012).

1.1.4 Feedback

A way of improving remanufacturing and cutting costs in the remanufacturing process is by capturing the value of information (Doyle et al., 2011). Information can be described as a message, usually in the form of a document or audible or visible communication from a sender to a receiver (Davenport and Prusak, 1998). Xu et al. (2009) advocate for including information from all life cycle stages, such as the actors shown in Figure 1, that is, manufacturers, users, repairers, remanufacturers, and recyclers.

The information flows should be designed in order to be efficient, and communication needs to be established throughout the product life cycle (Tukker and Jansen, 2006). Information can be communicated forward in the product life cycle, but it can also be fed back from the later steps in the cycle. In the research presented in this thesis, the feedback from *remanufacturing* to *design* is in focus.

Feedback from remanufacturers and service companies to product designers has a positive impact on the product development process (e.g., Doyle et al., 2011; Hatcher et al., 2011; Jagtap and Johnson, 2011). This is demonstrated in the case of single-use cameras by Kodak (Lowe and Bogue, 2007) and Fujifilm (Sundin and Lindahl, 2008), where design changes led to an efficient and effective remanufacturing process. Indeed, information from remanufacturing operators could sometimes be necessary in order to ensure efficient remanufacturing (Badiey et al., 1997). In addition, Zhang et al. (2012) stated that feedback from remanufacturing should be retained and available for designers in order to help them improve the design of future products.

There are many methods, tools, and design guidelines to adhere to in the design process, and sometimes they might contradict each other. For instance, Ferrer and Whybark (2000) state that there is often conflict between design for assembly (DfA) and design for disassembly (DfD). An efficient joining method, such as pop rivets, can cause delays in the remanufacturing process where the components need to be separated. Another example is to use snap-fit designs that allow for several assembly and disassembly sequences (Sundin et al., 2012). Thus, feedback from remanufacturers to the designers, including product requirements from remanufacturing, is needed for making the correct design considerations. Indeed, understanding the remanufacturing process will lead to a gradual understanding of DfRem (Hatcher et al., 2014). This is something that Electrolux understood in its remanufacturing of household appliances, where its product designers visited the remanufacturing facility in order to understand how its products were being worn (Sundin, 2004). Although there are some manufacturers that use feedback from remanufacturing to design, there is a lack of structural methods for achieving better feedback. However, in order to implement feedback from remanufacturing to design there is a need to know what feedback to implement and understand the conditions for feedback from remanufacturing to design in industry.

1.2 AIM

The aim of this research is to expand current knowledge on feedback from remanufacturing to design and how it can be used to improve design for remanufacturing.

1.3 RESEARCH QUESTIONS

The aim is broken down into the following three research questions:

RQ1. What potential feedback is available from *remanufacturing* to *design*?

This research question explores potential feedback at remanufacturers, both what is found in literature and in empirical studies. In this thesis the phenomena *design* and *remanufacturing* are highlighted in italics whereas when the departments are indicated the word department will be spelled out.

RQ2. What are the barriers and enablers for feedback from *remanufacturing* to *design*?

This research question aims at addressing factors involved when the feedback from remanufacturing to design is insufficient and when the conditions are more favourable.

RQ3. How could feedback from *remanufacturing* to *design* be implemented in a structural manner?

This research question aims at providing a solution for integrating feedback from remanufacturing to design in a structural manner.

1.4 DELIMITATIONS

The empirical data in this thesis primarily comes from three case companies based in Sweden, all of which are large international OEMs (original equipment manufacturers). The common denominator for these companies is that they

manufacture and remanufacture products. In the manufacturing companies, the products are developed in Sweden, as is the service. More information about the companies studied can be found in Section 3.5.1.
How remanufacturing is affected by feedback from other actors such as service is not studied in this research of this thesis.

The product design may consist of physical products in combination with software and services. This research focuses on the physical products and pays less attention to the software and services connected to the physical products.

1.5 THESIS OUTLINE

The topic of the research is introduced in Chapter 1, followed by the objective and research questions. Chapter 2 presents the theoretical foundation. Thereafter, Chapter 3 describes the research methodology, including the research design and data collection methods used. In Chapter 4, the empirical data from the cases is presented. Thereafter the findings from the case studies are analysed and presented in Chapter 5 and Chapter 6. Next, Chapter 7 presents a structural framework for implementing feedback from remanufacturing to design based on the findings presented in Chapter 6. Thereafter, Chapter 8 provides condensed answers to the research questions and places the findings presented in this thesis in a larger context. Finally, Chapter 9 presents the answer to the aim and concludes the thesis.

2 THEORETICAL FOUNDATION

In this chapter, previous knowledge of areas relevant to this thesis is presented. The chapter begins with a mapping of the theoretical areas to guide the reader through the theoretical foundation of this thesis. Thereafter, the theoretical areas covered in this thesis are presented.

2.1 MAPPING OF THE THEORETICAL AREAS

An illustration of the theoretical areas that support the research presented in this thesis can be found in Figure 2.

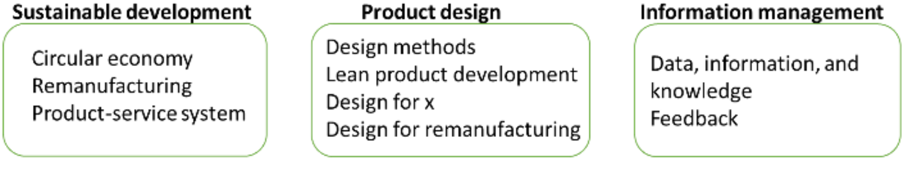

Figure 2. Overview of the theoretical areas covered in this doctoral thesis.

Sustainable development is needed to tackle the negative impact that human activities have on the environment. In this thesis, the *circular economy* and particularly *remanufacturing* are in focus as contributors to sustainable development. Further, the *product-service system (PSS)* could be used as another sustainable strategy, which can be combined with remanufacturing. Moreover, product design plays a vital role in the sustainability of a product. Thus, *design methods* in general, and specifically, *lean product development (LPD), design for X (DfX),* and *design for remanufacturing,* are described in this chapter. In addition, feedback from remanufacturing to design is especially highlighted. Therefore, a general introduction to *data, information,* and *knowledge* is provided as well as theory on *feedback* specifically related to product design.

2.2 SUSTAINABILITY AND THE CIRCULAR ECONOMY

The current way of living, including a high demand for products, makes the way that products are produced an important environmental factor. People's actions throughout the product's life cycle (Figure 1) influence the environmental impact, and resource depletion, climate change, reduced biodiversity, human toxicity, emissions to air and water, and waste are some of the environmental concerns that need to be addressed (Kutz, 2007). Human population growth increases the demand for material assets, which in part has increased material usage and production levels (Graedel et al., 1995). According to Rockström et al. (2009), humanity has already crossed the planetary boundaries with respect to climate change, loss of biodiversity, and disturbance of the nitrogen cycle. Therefore, substantial changes are required, and the transition to sustainable development is the way forward (Rockström et al., 2009). Geissdoerfer et al. (2017) define sustainability as "the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of the current and future generations".

Sustainability has impacts on a global scale (including the 3P's of people, planet, and profit). However, the vastness of the definition makes it more of a guiding principle and less applicable. There are, however, more solution-oriented concepts such as the circular economy. The circular economy is defined by Geissdoerfer et al. (2017) as "a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". In the definition by Geissdoerfer et al. (2017) as well as in the illustration by the Ellen MacArthur Foundation (Figure 3), ways to reduce negative environmental impact are highlighted. Notably, this thesis focuses on the right-hand circular flows (in blue) of the picture.

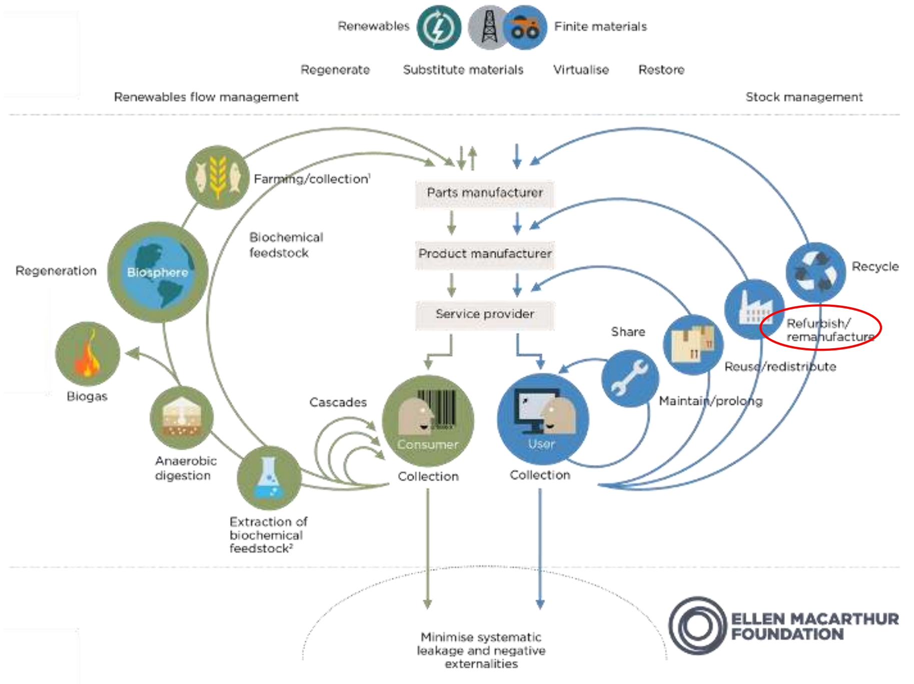

Figure 3. Illustration of the circular economy, where remanufacturing can be found on the right-hand side of the picture (adapted from the Ellen MacArthur Foundation (2017)).

The transition to a CE requires major changes and innovations in organisations, society, and finance methods (EU, 2014). In order to achieve a CE, three main aspects need to be considered simultaneously: the environment, resources, and economic benefits (Lieder and Rashid, 2016). Ideally, a CE promotes economic growth while not increasing environmental impacts. Further, a CE implies the joint efforts of all stakeholders in order to implement a CE on a large scale (Lieder and Rashid, 2016).

A CE can be viewed as a system where the use, maintenance, reuse, remanufacturing, and recycling of materials are optimised to capture the embedded value of the products (Circle Economy, 2020). A product after use can be disposed of and destructed, which means that all the material and energy put into the product as it was manufactured goes to waste. This linear way of treating products is unsustainable and can be replaced by a number of more sustainable strategies (The Ellen MacArthur Foundation, 2017). The goal is to reduce the environmental impact of a product, from the extraction of the raw materials, through the production phase, during the use phase, to a sustainable EoU treatment (ref). Further, there are a number of legislative drivers for sustainable products, including (based on Kutz (2007)):

- The Waste Electrical and Electronic (WEEE) Directive
- The Restriction of Hazardous Substances (RoHS) Directive
- The End-of-Life Vehicles (ELVs) Directive
- The EcoDesign Directive

When many products reach EoU whilst they still have a lot of potential life, the situation for implementing reuse, remanufacturing, and recycling is ideal (Kutz 2007). For example, a gear-box in a scrapped car could be remanufactured and replace a worn-out gearbox in another car. Since remanufacturing enables multiple use cycles for products and components, remanufacturing is an important component of a CE (Hilton and Thurston, 2019).

2.3 PRODUCT-SERVICE SYSTEMS

The product-service system is one of the efficient strategies to move toward a CE (Tukker, 2015). PSSs are defined as "combinations of products and services to fulfil customer needs" (Goedkoop et al., 1999). By optimizing the resources such as material and energy during the PSS lifecycle environmental benefits can be gained (Barquet et al., 2016). A PSS enables increased use of the products if sharing or renting is provided, while material and product life can be extended through the provision of services during the use phase (Barquet et al., 2016). Thus, the PSS can be regarded as environmentally friendly as the number of products could be reduced as fewer consumers own the products, while producers could increase profit through service provision (Maxwell and van der Vorst, 2003). Further, in a PSS context, the producer is incentivised to reconsider the product design, manufacturing, service, and EoU strategy (Kutz, 2007). Thus, by applying EoU strategies such as remanufacturing, the PSS can be more sustainable (Barquet et al., 2016).

The PSS can also enable long-term relationships between the customer and PSS provider. These close relationships are also beneficial when a PSS and remanufacturing are combined since it is easier to retrieve cores for remanufacturing (Sundin and Bras, 2005; Östlin et al., 2008b). Further, a PSS and remanufacturing in combination can create benefits for remanufacturing, since a PSS implies greater motivation for the OEM to learn about its products (Sakao and Sundin, 2019). Such knowledge could be implemented in the design phase (Goh and McMahon, 2009). Moreover, for the remanufacturer, knowledge about PSSs can provide a more holistic perspective and aid in improving its activities (Sakao and Mizuyama, 2014).

2.4 REMANUFACTURING

Remanufacturing restores a product to its next life cycle (Steinhilper, 1998). Ijomah et al. (2004) define remanufacturing as “a process of bringing used products to a ‘like-new’ functional state with a warranty to match”. Thus, the product can generate more profit as it is sold anew (Hatcher et al., 2013). Studies report that remanufacturing saves from 30 to 90% of energy and materials compared to manufacturing (Allwood et al., 2010). Thus, it is one of the key strategies for sustainable development (Ijomah et al., 2004).

Remanufacturing, although sharing similarities with refurbishment, is different in terms of the quality of output (Pozo Arcos et al., 2018). Refurbishment is a process whereby products are returned to a functional condition; however, the condition does not have to be up to the original product specifications (Ortegon et al., 2014). Remanufacturing includes the testing of all cores before they are returned to the market and sold with a warranty (Ijomah et al., 2007a). Therefore, the quality of remanufactured products can be higher than that of newly produced products. Further, remanufactured products may be updated as part of the remanufacturing process, and consequently, the remanufactured product is as good as new, or better (Steinhilper 1998, Ijomah et al., 2007a).

A core is a discarded or worn-out product intended for remanufacturing (Lund, 1984). The price of the core prior to remanufacturing is typically about 0-20% of a new product, and the remanufactured product often sold at a price of 40-60% of a new (Allwood et al., 2010). The remanufacturing process, thus, starts with an incoming core, which then passes through the characteristic steps of the remanufacturing process. Those steps are inspection, cleaning, disassembly, reprocessing, storage, reassembly, and testing (Sundin, 2004). Since remanufacturing requires used products from the market, it is significantly different from manufacturing (Sakao and Sundin, 2019). The return of cores requires reverse logistics, and generally, it is hard to predict the incoming volumes since there are uncertainties such as timing and the variation in the quality of the incoming cores (Lundmark et al., 2009). Further, the batches are typically small, and the remanufacturing process often less automated and requiring more manual labour (Steinhilper,1998).

Remanufacturing can be performed by the original equipment manufacturer, which then also becomes an original equipment remanufacturer (OER) (Lund, 1984).

Another alternative for remanufacturing is that the OEM engages a contracted remanufacturer (CR). The CR is then performing the remanufacturing for the OEM, while the OEM remains in control of the remanufactured product (Lund, 1984). The third type of remanufacturer is the independent remanufacturer (IR), which is not connected to the OEM, but remanufacturers products others have produced (Östlin, 2008). The independent remanufacturers do not have the advantage of, for example, the product design and service history, nor easy access to spare parts as the OEM. The independent remanufacturer, thus, has to buy the required spare parts which cannot be retrieved from the cores, whilst the contracted remanufacturer can rely on more assistance from the OEM, to include spare parts and design specifications (Lund, 1984). Thus, the conditions for the independent remanufacturers are quite in the hands of the OEMs, as the design and information created during the design and manufacturing of the product belongs to the OEM. In fact, in some markets, the OEMs have been known to try to hinder independent remanufacturing by altering the design of, for example, toner cartridges (Sundin and Östlin, 2005).

A product and part that are suitable for reuse and remanufacturing should have a stable technology, be resistant to damage, and have aesthetics largely irrelevant to fashion (Kutz, 2007). Products that are commonly remanufactured include automotive parts, IT equipment, office equipment, and investment-heavy machines (Jansson et al., 2017). Within the European Remanufacturing Network, a market study was performed in 2015 by Parker et al. In their findings, they categorised European remanufacturing companies into the following categories: *aerospace, automotive, heavy-duty and off-road (HDOR) equipment, electronic and electrical equipment (EEE), machinery,* and *medical equipment.* They also categorized smaller sectors, such as *furniture, rail* and *marine* (Table 1).

Table 1. A summary of the industrial sectors of the European remanufacturing industry. The sectors are sorted in order of turnover. Based on Parker et al. (2015).

Sector	Turnover (€bn)	Companies	Employment (´000)	Cores (´000)
Aerospace	12.4	1 000	71	5 160
Automotive	7.4	2 363	43	27 286
HDOR	4.1	581	31	7 390
EEE	3.1	2 502	28	87 925
Machinery	1.0	513	6	1 010
Medical equipment	1.0	60	7	1 005
Furniture	0.3	147	4	2 173
Rail	0.3	30	3	374
Marine	0.1	7	1	83
Total	**29.8**	**7 204**	**192**	**132 405**

If manufacturers invested in ways to promote efficient material use and reuse through, for example, remanufacturing, there can be economic gains for the company (Brezet and van Hemel, 1997). However, consumer attitudes towards remanufactured products are a major challenge to be overcome in order to increase the demand for remanufactured products, since consumers often have a poor opinion of such products (Hazen et al., 2017).

Nevertheless, remanufacturing has a vital role in the CE. By enabling circular material flows remanufacturing is an opportunity for organizations that want to explore sustainable production (Hilton and Thurston, 2019). Indeed, Sundin (2019) state that remanufacturing is the heart and lungs of the CE.

2.5 PRODUCT DESIGN

There are many definitions of product design. According to Holmdahl (2010), product design is “creating the prerequisites for producing and the selling products”. As stated by Ullman (2009), product design is “the result of a process that combines people and their knowledge, tools, and skills to develop a new creation”. Further, Ulrich and Eppinger (2008) define a product development process as “the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product”.

A generic product design process consists of six phases: planning, concept development, system-level design, detailed design, testing and refinement, and production ramp-up (Figure 4). However, the design process tends to vary with the organizations and even the project at hand. (Ulrich and Eppinger, 2008)

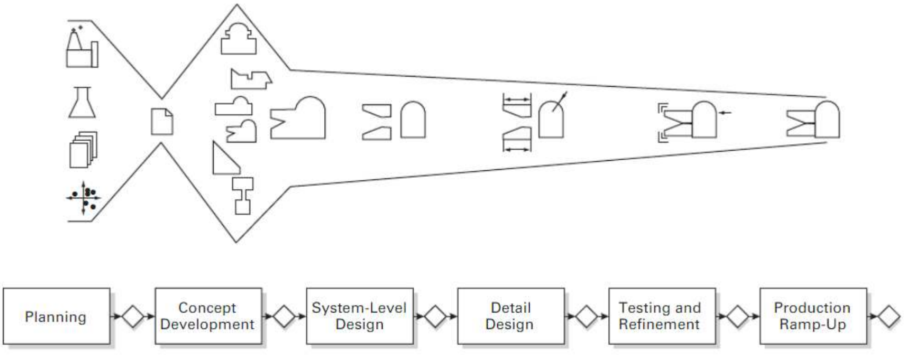

Figure 4. The product design process as illustrated by Ulrich and Eppinger (2008).

Typically, about 75% of the manufacturing cost is determined by the end of the conceptual design phase (Ullman, 2009). Further, the decisions made early in the design process will greatly influence its outcome, and the cost of modifying the design increases rapidly with time (Lindahl, 2005). Thus, the initial steps of the design process are crucial.

The design process may be considered as an information processing system at the beginning of the process, with inputs such as corporate objectives and capabilities, and which continues with the various activities where the information is processed and developed products are formulated into concepts formulated, and the design details are specified. At the end of the process, all information required to support production and sales is completed and communicated (Ulrich and Eppinger, 2008).

According to Clark and Fujimoto (1991), an important factor for the company's competitiveness is the organization and management of information in the product design process. Previously, product design and product manufacturing suffered from not being integrated, a phenomenon illustrated by a wall between the designers and the manufacturers over which the designers threw the blueprints (Clark and Fujimoto, 1991). However, strategies such as face-to-face discussion, direct observation, direct interaction with physical prototypes, and computer-based representations are suggested to increase the information transfer between design and manufacturing (Clark and Fujimoto, 1991). Further, by using teams that include all stakeholders, many over-the-wall issues can be avoided (Ullman, 2009).

2.6 LEAN PRODUCT DEVELOPMENT

Lean product development is an etiquette that American researchers placed on the product development executed at Toyota after initially studying the Toyota Production System (Holmdahl, 2010). The lean approach is directed at creating value by, for example, minimising waste and optimising workflows (Womack et al., 1990). In order to do so in the product design context, capturing knowledge is a key component.

Indeed, a lean organisation is a learning organisation where knowledge is captured and utilised to add value in the daily operations (Ward, 2007). If lessons learned and experiences from previous projects were disregarded in coming projects, time and resources would be wasted. Therefore, lean product development aims at capturing knowledge and creating new knowledge (Ward, 2007). One way of creating new knowledge is to "go see" and thus, with your own eyes, experience and communicate with other functions (Ward, 2007).

2.7 DESIGN FOR X

Design for X (DfX) can include evaluation practices for product design relative to X, where X can be, for example, cost, manufacturing, assembly, or reliability (Ullman, 2009).

Ullman (2009) defines design for manufacturing (DfM) as "establishing the shape of components to allow for efficient, high-quality manufacture". DfM focuses on designing the component for the most suitable manufacturing process so that the components can be manufactured with consistent components and little waste (Ullman, 2009). Manufacturing of the components includes not only machining and processing but also fixture and transport between processes, and thus DfM should be performed in cooperation with manufacturing experts, and the design of the component and tool and fixture should be performed concurrently (Ullman, 2009).

Whilst DfM focuses on the component level, design for assembly (DfA) focuses on the assembly of the components (Ullman, 2009). The major incentive for DfA is to reduce the time for assembling a product and thus reduce cost. DfA requires a refined design of a product before it can be utilised. The assembly operation of a product can be divided into three general steps: retrieving components, handling and orienting them, and mating them. This implies that the time it takes to assemble a product is dependent on the number of components and the ease of carrying out the assembly operation steps (Ullman, 2009).

DfA worksheets can be used to evaluate the assembly efficiency of a product by a scoring system. A high score indicates efficient assembly, and the score is utilised to compare design solutions or similar products. However, as DfA encourages few components, component complexity will increase and might cause an increased cost of manufacturing, for example, tooling costs. Therefore, DfA is more suitable for mass production. Further, DfA is most appropriate for products where the assembly cost is a substantial part of the total manufacturing cost (Ullman, 2009).

Another DfX approach is Design for Service (DfS). According to Dewhurst and Abbatiello (1996), DfS should consider part locations and securing methods during the design process, so that service of a product in use can be facilitated. DfS benefits from DfA as it aims at reducing the number of components and separate fasteners. Fewer assembly operations will most likely also benefit service operations. Another goal of DfS is to reduce the time for the service operation and thus the cost of service. However, DfS, DfA and DfM guidelines may be conflicting, and thus how to balance them needs to be considered during the design process. (Dewhurst and Abbatiello, 1996)

2.8 PRODUCT DESIGN FROM A LIFE-CYCLE PERSPECTIVE

There is a discrepancy between the technical life cycle and the economic life cycle of a product (Östlin et al., 2008b). The economic life cycle relates to the product generation endurance on the market, which typically ends when better and more cost-effective products have taken over the market (Johannesson et al., 2004). In this thesis, the technical life cycle is regarded, as described in Figure 1, and not the economic.

The designer has a vital role and can affect all the phases of a product's life cycle (Johannesson et al., 2004). Ultimately, the product can be reused or refurbished and then used again. Material recycling breaks down components instead of having them reused or reprocessed; however, the material value of the used products is preserved (Ortegon et al., 2014). The remanufacturing process captures the value of the components and restores them to useful life (Steinhilper, 1998). Indeed, remanufacturing may well be comprised of a mixture of end-of-life (EoL) treatments in combination, as some components can be reused, and others need to be recycled. Further, components might be salvaged from other products from different products before one product is remanufactured and returned to the market. One example is truck engines (Smith and Keoleian, 2004).

When efficiency throughout the product life cycle is considered, extended responsibilities for the producer follow. This responsibility is, in turn, related to the exploration of new, potentially economically successful business areas (Westkämper et al., 2000). All companies should adopt methodologies for implementing design for life cycle (DfLC) to their organisation (Maxwell and van der Vorst, 2003).

The ambition for DfLC is to anticipate environmental impact and lessen it through product design (Kutz, 2007). Generally, a company's endeavours for a more sustainable product start with a finished design (Maxwell and van der Vorst, 2003). This approach is not the most advantageous in terms of implementing DfLC (Kutz, 2007). Instead, a true concurrent design process is required where the entire product design is re-evaluated and the end-of-life scenario well-thought-out (Kutz, 2007).

2.9 Design for Remanufacturing

Design for remanufacturing (DfRem) can be defined as "product design that facilitates any of the steps involved in remanufacturing" (Shu and Flowers, 1999). DfRem is necessary in order to achieve efficient and effective remanufacturing (e.g., Sundin and Bras, 2005 and Kutz, 2007). In fact, Hilton and Thurston (2019) suggest that DfRem is critical for remanufacturing. According to Niu et al. (2019), DfRem is generally regarded not only to relate to remanufacturing cost but also manufacturing cost, recovery rate, and competitiveness on the market. Further, DfRem can save costs by reducing the remanufacturing operation time (Prendeville and Bocken, 2017). Indeed, if remanufacturing is planned for in the design process, storage costs can also be reduced (Schöggl et al., 2017).

DfRem is what the design engineer will undertake and adapts according to the specific product (Kutz, 2007). For some products, only a few design changes are required in order to achieve a more remanufacturable product, while other products will benefit from a more extensive DfRem approach. Based on this line of reasoning, DfRem is necessarily case dependent. Hence, design engineers will benefit from checklists with DfRem characteristics to guide the design process (Kutz, 2007). Those checklists will preferably be combined with know-how sheets, where designers illustrate the best-case scenario for specific products and components in the industry concerned. However, according to Allwood et al. (2010), there were not many design guidelines available for DfRem. Hatcher et al.

(2011) presented a compilation of DfRem methods and tools, however, as can be seen in Table 2, they were not applied in industry.

However, research interests in DfRem has increased, and recently Hilton and Thurston (2019) present detailed checklist for three DfRem design principles (Figure 5).

Table 2. Approaches to DfRem found in literature. Adopted from Hatcher et al. (2011).

Approach	**Author(s)**	**Key Purpose**	**Advantages**	**Disadvantages**	**Use in Industry**
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)	Assess remanufacturability	Process oriented Familiar concept (DfMA)	Complex Retrospective No guidance	No
Fastening and joining selection	Shu and Flowers (1999)	Selection of most economical joining method	Lifecycle thinking	Complex Not holistic	No
RemPro matrix	Sundin (2004)	Guidance, prioritisation of issues	Simple Offers guidance	Subjective No guidance	No
REPRO2	Zwolinski et al. (2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)	Decision making, providing past examples	Early in design process Does not require extensive knowledge Offers guidance	Subjective	No
DfRem guidelines	Ijomah (2009); Ijomah et al. (2007b);	Guidance	Simple Offers guidance	Subjective Lack lifecycle thinking	Unknown
DfRem metrics	Willems et al. (2008)	Assess remanufacturability, suggest improvements	Lifecycle thinking Offers guidance	Complex Retrospective	No
Hierarchical decision model	Lee et al. (2010)	Design of product architecture for most profitable disassembly	Lifecycle thinking	Not holistic	No
Energy comparison tool	Sutherland et al. (2008)	Compare manufacture and remanufacture energy usage	Lifecycle thinking	Not holistic No guidance	No
Component reliability	Zhang et al. (2010)	Remanufacturing strategy decision making	Customer focused Process oriented	Not holistic No guidance	No

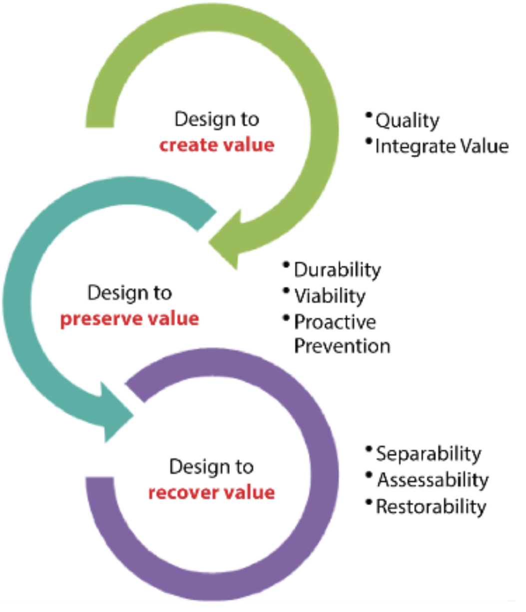

Figure 5. DfRem design principles by (Hilton and Thurston, 2019).

One product example that is often remanufactured today is the diesel particle filter (Sundin and Dunbäck, 2013). This filter is important to keep the pollution levels of diesel cars at acceptable levels. The filter and its casing are never seen while handling a car; therefore, even if the casing looks used, it does not affect the buyer's willingness to purchase it. Thus, in such cases where functionality is the only attribute that the customer will consider, exterior flaws need not necessarily be treated. However, if a surface has an aesthetic function, cleaning it without damaging it is necessary (Hilton and Thurston, 2019).

There are, however, design features that most products benefit from, such as the use of standardised parts and modularisation (Niu et al., 2019). Since remanufacturing will be carried out months or years after the product is produced, the inflow of used products will be mixed not only in terms of wear and tear but also as far as age and product edition. Therefore, the remanufacturing process would benefit from standardised components such as screws and fasteners, as well as common platforms (Kutz, 2007). Furthermore, other aspects of the product's design, such as ease of cleaning, will also be relevant for most products since cleaning is not only required by the customer but may also be necessary in order to assess the state of the used product when it arrives at the remanufacturer's site (Hilton and Thurston, 2019). Moreover, upgrading used products in the remanufacturing process will, in most cases, probably not be needed for purely mechanical products, whereas electromechanical and small products are most certainly in need of upgrades in order to be compatible with the standard requirements of the customer for the remanufactured product (Hilton and Thurston, 2019). Nevertheless, the upgrading of non-electronic products such as office furniture will be necessary in order to satisfy the customer (Krystofik et al., 2018).

Finally, assembly methods that allow for non-destructive disassembly are implicit when applying DfRem (Sundin et al., 2012). On a general level, assembly methods such as welding, glue, and pop rivets are not suitable for remanufacturing (Kutz, 2007). However, as mentioned above, the diesel particle filters need not be disassembled, and therefore, the assembly methods such as welding are not a hindrance. Nevertheless, disassembly is typically an integral part of the remanufacturing process (Sundin, 2004). In particular, high-value components ought to be disassembled without damage done to them (Hilton and Thurston, 2019). DfD criteria can support both serviceability and EoL material recovery (Boothroyd and Alting, 1992). However, while recycling can allow for destructive disassembly and separation processes, this is not generally applicable for remanufacturing (Hilton and Thurston, 2019). Below, DfD guidelines applicable for remanufacturing as described by Hilton and Thurston (2019) can be found:

- Minimize the part count and part variety and standardize parts with common functions.
- Do not integrate parts/functions when they have fundamental differences in durability due to, for example, wear or fatigue.
- Avoid non-rigid parts.
- Design reusable parts to be stackable.
- Minimize the number of joints and connections and make joints visible and accessible.
- Position the joints to minimize the need for realignment during dismantling, and minimize the number of handling operations that require heavy lifting.
- Protect joining elements from corrosion and wear.
- Avoid fastening methods that are not easily separable or cause damage in disassembly between modules or components that will be replaced, remanufactured, or recycled.
- Minimize the need for specialized disassembly processes or tools.
- Minimize tight tolerances or narrow clearances on components that require disassembly or separation.
- Provide sufficient space between fasteners, away from obstructions, and with easy access for the tools needed for disassembly.

- Standardize the fastener head technology used in the assembly and reduce the number of and variety of fasteners used.
- Isolate components or modules that may have material or handling hazards.
- Where possible, components in modules should have similar technology and physical (wear-out) obsolescence cycles.
- Minimize the number of connections between modules, as well as multi-modular connections.
- Minimize the number of disassembly operations required to separate components with different dispositions (recycling versus remanufacturing)
- Use self-explanatory product structures, e.g., structures for which disassembly order and tools required are obvious and/or clearly marked/identifiable/visible.
- Structure the product to make the highest value components the most accessible and do not bury important components.

When designing a product, the EoL options should also be designed down to the component level (Bufardi et al., 2004). In fact, not all components may be suited for remanufacturing; some may be recycled or even scrapped, while others might be reused. Nevertheless, according to Hilton and Thurston (2019), companies that remanufacture, or are planning to, have strong incentives to consider DfRem.

2.10 DATA, INFORMATION AND KNOWLEDGE

The terms data, information, and knowledge are not interchangeable. Data is a set of discrete, objective facts about events. Within an organisational context, data is preferably described as structured records of transactions. Information can be described as a message, usually in the form of a document, or audible or visible communication from a sender to a receiver (Davenport and Prusak, 1998).

Information is one of the most powerful resources a company has (Kehoe et al., 1992) and can be regarded as assets that enable a company to improve its effectiveness and efficiency (Barney, 1991). A company that has the ability to provide the right information to the right receiver at the right time can have a competitive edge towards competitors (Peteraf, 1993). Further, information is often company-specific and embedded in the organisation, and thus hard to imitate or substitute (Slack and Lewis, 2002).

The management of information plays a vital role in the success or failure of a new product (Ottum and Moore, 1997). This is no simple matter; in fact, getting the right information at the right time is often a problem, and too much information is not effective (Edmunds and Morris, 2000). Indeed, searching for the right information can take up to 34% of the engineer's workday (MacGregor et al., 2001).

Knowledge is hard to define. Davenport and Prusak (1998) define it as follows: "Knowledge is fluid and made up of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In organizations it often becomes embedded not only in documents or repositories but also in organisational routines, processes, practices, and norms."

According to Hansen et al. (1999), knowledge can be divided into codification and personalisation: codification is knowledge transferred in databases, while personalisation is knowledge communicated person to person. In this research, both types of knowledge are considered. Indeed, product design is a knowledge-intensive process where knowledge is shared and applied (Ullman, 2009; Ward 2007).

2.11 FEEDBACK TO PRODUCT DESIGN

For the purpose of this research, the focus is on feedback from remanufacturing to design. Feedback is defined here as "information about reactions to a product, a person's performance of a task, etc. which is used as a basis for improvement" (Oxford University Press, 2019). Although feedback is information per se, the feedback can be based on data, information, and knowledge.

By gaining knowledge about remanufacturing and products after use, the design process can be more effective. Communication between design and remanufacturing has the potential to lead to products that are more remanufacturable as well as a more efficient design process (Hatcher, 2013). Additionally, Yang et al. (2015) propose cross-functional communication as one recommendation for better integration of DfRem into the design process. Thus, via communication between, for example, the *design* department and *remanufacturing,* designers can have a better understanding of the remanufacturing requirements.

According to Magniez et al. (2009), feedback about a product's performance has issues in terms of quality and the manner the information is processed at the companies. Examples of feedback are data from built-in smart functions in the product that will communicate numbers regarding a part's performance, information regarding what service operations have been carried out, and knowledge based on experiences on the best disassembly sequence. Further, Badiey et al. (1997) wrote a report on design for remanufacturability and analysed the product design, and found issues with ease of part identification. Many similar parts, and parts that are hard to disassemble, will complicate the remanufacturing process. According to Badiey et al. (1997), information from remanufacturing operators could sometimes be necessary to ensure efficient remanufacturing.

There are many methods, tools, and design guidelines to adhere to in the design process, and sometimes they might contradict each other. For instance, according to Ferrer and Whybark (2000), there is often conflict between DfA and DfD. Thus, the transfer of feedback from remanufacturers to designers, to include information on the remanufacturing process and the products, would be needed for making the correct design considerations.

Data is a set of discrete, objective facts about events (Davenport and Prusak, 1998). The product's actual performance, which is measurable, as well as its perceived performance, which is non-measurable, are both factors that can affect perceived customer value. Conditioning monitoring is one way to achieve objective data, which has the potential to enhance the profitability of the company (Rao,1996). However, preferably, both subjective and objective information should be collected throughout the product's life and transferred as data in a digital tool (Beck and Schornack, 2005; Haider, 2009; Zhang et al., 2012). This data can be used in the design process to enhance the product design of future products. Furthermore, Ramani et al. (2010) stated that data from the latter parts of the product life cycle, such as remanufacturing, should be integrated into design tools. However, restructuring the design process is not enough if the information for making informed decisions about each stage of the product life cycle is lacking (Kutz, 2007). Moreover, such information needs to be easily accessible to the designers (Kutz, 2007). DfLC affects the whole supply chain. According to Graedel and Allenby (2003), legislation should encourage product information sharing along the supply chain.

3 RESEARCH METHODOLOGY

In this chapter, the research methodology of the research in this thesis and how the methodology was applied are described. In addition, the logic between the research questions and the data collection methods are explained.

3.1 RESEARCH DESIGN

The research presented in this thesis is qualitative. The design research methodology (DRM) by Blessing and Chakrabarti (2009) has been used to outline, plan, and support the research presented in this thesis. In order to assess previous research, literature studies have been applied. Regarding the empirical research, the case study methodology was applied, while the data collection was predominantly conducted through semi-structured interviews. The results have been analysed in a cross-case analysis.

3.1.1 THE DESIGN RESEARCH METHODOLOGY

Design research, in general, aims at making design more efficient and effective and improving design practices. Design is a complex and dynamic phenomenon that involves people, processes, knowledge, and methods and tools within an organisation (Blessing and Chakrabarti, 2009). The DRM is a framework developed by Blessing and Chakrabarti (2009), specifically adapted for research considering product design issues. The DRM outlines a systematic research approach but also implies many iterations between the different stages of the research (Blessing and Chakrabarti, 2009).

The DRM consists of four stages, namely Research Clarification, Descriptive Study 1, Prescriptive Study, and Descriptive Study 2. The Research Clarification stage mainly includes literature studies that will end up in an initial description of the current situation and a description of the desired situation. Further, in this stage and research questions are formulated, and an overall research plan for answering those is created. (Blessing and Chakrabarti, 2009)

In Descriptive Study 1, a literature study alone, or a literature study and empirical research in combination, may be carried out, depending on the research plan. In this stage, the goal is to create a better understanding of the current situation. If the goal is to proceed to the Prescriptive Study stage, the Descriptive Study should also propose factors relevant to address and provide a basis for the prescriptive studies. During the Prescriptive Study stage, a support aiming at improved design practices is created based on the findings in the previous Descriptive Study. The support could be in the form of, for example, methods, tools, or guidelines. The main outcomes of the Prescriptive Study stage are a description of the support and a plan for how to introduce it. Finally, Descriptive Study 2 focuses on empirical studies to evaluate the support developed in the Prescriptive Study stage (Blessing and Chakrabarti, 2009).

The research presented in this thesis is based on research carried out within the DRM framework (Figure 6). This framework has been used to support and guide the research process of this thesis. Figure 6 shows an overall description of the four stages of the DRM framework and how the research questions of this thesis fit into it.

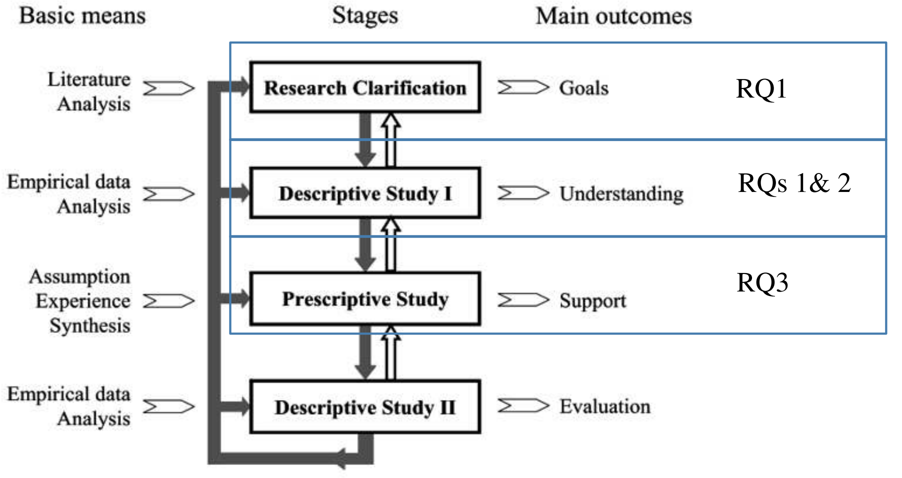

Figure 6. The DRM framework, based on Blessing and Chakrabarti (2009), and the relation to the research questions of this thesis. The Research Clarification Stage contributes with answers to RQ1, the Descriptive Study 1 Stage contributes with answers to RQs 1 and 2, and the Prescriptive Study Stage contributes to answering RQ3.

Initially, the research clarification stage started with a literature study on r*emanufacturing*, *design for remanufacturing (DfRem)*, and the *product-service system*. Once the initial literature study was carried out, the next step was to narrow down the research area and identify a research gap. This led to a more focused literature study on information transfer in the product life cycle and DfRem (Paper I). During the second phase of the DRM, a descriptive study was performed by applying a case study methodology for the collection of empirical data. The descriptive study was launched by a pilot study. This study was then improved and expanded to include more cases in multiple case studies (Papers II to IV). Paper II focuses on feed forward as well as feedback in the product life cycle and includes two more cases other than the three cases on which this thesis focuses. The wider perspective was utilised to create a better understanding of the information flows in the product life cycle; these results were compared and contrasted vis-á-vi remanufacturing and the other actors in the product life cycle.

As the research progressed, the research focus was increasingly centred around feedback from remanufacturing to design. The final part of the descriptive stage was a cross-case analysis of the empirical data, and those results were compared to literature findings (Paper III). The initial cross-case analysis was expanded on and refined (Paper V). The descriptive studies were the most prominent in this research, which is often the case in design research (Blessing and Chakrabarti 2009). Finally, a prescriptive study was carried out, resulting in a supporting framework to implement feedback from remanufacturing to design (Paper VI). The framework was initialised at one case company. What is left for future research is to continue the research by applying the fourth and final step in the DRM framework.

The results from answering these research questions are mostly described in the appended papers as indicated in Table 3 but more clearly described in Chapters 5, 6 and 7 of this doctoral thesis.

Table 3. The relationship between the appended papers and the three research questions in this thesis. A small x indicates relevance, while a large X indicates strong relevance.

RQ \ Paper	I	II	III	IV	V	VI
1	X	x	X	X	x	
2		X	X	X	X	
3						X

3.2 RESEARCH METHODS

The empirical data was collected by applying case study research. This research was performed by applying multiple case studies at three case companies. The results from the individual case studies were then analysed in a cross-case analysis.

3.2.1 CASE STUDIES

The empirical studies of this research were carried out through case studies. A case study is defined by Yin (1994) as “an empirical inquiry that investigates a contemporary phenomenon within a real-life context, especially when the boundaries between phenomenon and contexts are not clearly evident”.

Case studies are mostly applied to qualitative studies (Williamson, 2002). They are, in general, appropriate for research questions on the *how* and *why* nature of contemporary contexts, where the researcher has little or no control (Yin, 1994). Research questions starting with *how* and *why* tend to be explanatory (Yin, 1994). Moreover, research questions of *what* nature may be exploratory or about prevalence. If the *what* question is exploratory, several research strategies could be applied, including case studies. If the *what* question is about prevalence, such as *how many* or *how much*, surveys or archival analysis are probably more suitable strategies (Yin, 1994). However, Yin (1994) points out that for some research questions, a choice of research strategies could be appropriate.

Further, case studies are suitable for considering multiple stakeholders and analysing processes (Larsson, 1993). Therefore, case studies are suitable for studying *how* and *why* processes or phenomena occurring in, for instance, organisations or companies. By studying current processes and phenomena, strengths and weaknesses can be identified. Furthermore, case studies can also provide a more in-depth analysis of complex organisational phenomena better than questionnaires (Larsson, 1993).

Although case studies are not as scientifically rigorous as formal experiments, they can provide sufficient information on, for instance, if a technology is suitable for a specific organisation (Kitchenham et al., 1995). While experiments often study phenomena on a small scale and questionnaires on a large scale, case studies often aim at studying a typical scenario (Kitchenham et al., 1995). Thus, it follows that case studies can show what happens in a typical scenario, but the outcome is not generalisable to every situation (Kitchenham et al., 1995). Further, research in applied research disciplines generally aims at improving practice (Williamson, 2009).

3.2.2 MULTIPLE CASE STUDIES

Multiple case studies can strengthen the findings of the research, similar to the way that multiple experiments do (Benbasat et al., 1987). If there is more than one case and the conclusions in the cases are the same, despite the different circumstances of the cases, the results' generalisability is considerably better than results from a single case study (Yin, 1994). Such an approach strengthens the external validity. Multiple case studies reduce the potential question that the single case study contains something unique or artificial such as a special bond to a certain informant. (Yin, 1994)

However, every case in a multiple case study must have a specific purpose within the case study design. Also, multiple case studies should follow a replication logic similar to multiple experiments. In the case of multiple case studies, this means that each case must be carefully selected based on either the prediction of a similar result or the prediction of different results for predictable reasons (Yin, 1994). Further, multiple case studies can be used for theoretical or analytical generalisation, where the results from the case studies are used to develop theory or to test previously developed theory (Cavaye, 1996).

3.2.3 CROSS-CASE ANALYSIS

Cross-case analysis is used for analysing data from multiple cases (Miles et al., 2014). As case studies do not allow for statistical analysis or patterns, cross-case analysis can be used to overcome those weaknesses (Larsson, 1993). Thus, cross-case analysis can support the summary and comparison of findings within or across the cases (Miles et al., 2014). Cross-case analysis enhances the generalisability or transferability of the results from the case studies to other contexts (Miles et al., 2014).

Through cross-case analysis, the relevance or applicability of the research findings can be discerned (Miles et al., 2014). However, more importantly, cross-case analysis can deepen the understanding and explanation as similarities and differences across cases are examined (Miles et al., 2014) and the theoretical and analytical generalisations of the results from the case studies are used to develop theory or to test previously developed theory (Williamson, 2002). According to Walsham (1995), there are four types of generalisations from an interpretive case study research perspective: development of concepts, generalisation of theory, drawing on specific implications, and contribution of rich insights.

Cross-case analysis can be done in several ways, and the approach applied in this research is a replication strategy, as described by Yin (1994). This strategy aims at analysing one case in-depth and then seeing whether patterns found can be matched in other cases. It is also beneficial to explore cases where the pattern is expected to be weaker or absent (Yin, 1994).

3.3 Data collection methods

The research method for answering the research questions was, as mentioned in Section 3.2, case studies; however, the data collection methods for the individual research questions can be found in Table 4. RQ1 was first answered from a theoretical standpoint, where literature studies were applied in order to find potential feedback from remanufacturing to design. Thereafter, empirical data was gathered during the multiple case studies. A cross-case analysis approach was used to answer RQ2, and the results were compared with other research found in the literature. Finally, RQ3 was answered based on the findings in the multiple case studies and examples of feedback implementation strategies found in the literature.

Table 4. The research questions addressed, and the main data collection methods applied.

Research Question	Data collection methods
RQ1. What potential feedback is available from ***remanufacturing*** to ***design?***	Literature study Semi-structured interviews
RQ2. What are the barriers and enablers for feedback from ***remanufacturing*** to ***design***?	Literature study Semi-structured interviews
RQ3. How could feedback from ***remanufacturing*** to ***design*** be implemented in a structural manner?	Literature study Semi-structured interviews

3.3.1 Literature study

A literature study is important in several ways in the research (Williamson, 2002). Firstly, a literature study can serve to build a logical framework for the research and also position it in a tradition of inquiry and the context of related studies (Rossman and Marshall, 1995). According to Gorman and Clayton (1997), the chosen research topic should aim at filling the gap or adding a new complexion to existing research. Further, through literature studies, the researcher can identify the gaps in previous research and therefore justify their research topic (Williamson, 2002). Secondly, the literature study is important for the generation of theory but also in the formulation and refinement of research questions (Williamson, 2002).

Indeed, Yin (1994) states that researchers should review previous research to formulate better and more insightful research questions about the research topic.

Once the research topic and the research questions are initially defined, the research methods have to be chosen. Here, a literature study also plays a part as the research presented in the literature will be presented alongside a research method. This might enable the researcher to choose methods that are well accepted by other researchers within the field (Williamson, 2002). For the case studies, the literature study is used for designing the research project and also to determine the appropriate number of cases for the unit of analysis (Williamson, 2002). Finally, the results of the literature study can be used for comparison with the new findings, studies, and thus place them in a context (Williamson, 2002).

3.3.2 Semi-structured Interviews

The primary data collection method applied in this thesis has been semi-structured interviews. Interviews are a form of discourse between the researcher and the interviewee (Mishler, 1986). Since interviews are carried out in person, the response rate is naturally higher than with questionnaires (Williamson, 2002). Further, the interview includes not only what is said, but also facial expressions, which show the verbal and nonverbal communication between the parties (Mishler, 1986).

Unstructured interviews allow for articulating specific needs and issues, while structured interviews are useful for detailed and specific information about current operations and future requirements (Williamson, 2002). The structured research interview is built on carefully formulated questions in a certain order of occurrence (Jacobsen, 1993). All interviewees get the same questions asked with the same attitude from the interviewer's part. Structured interviews may perhaps not cover issues or problems important to the interviewee (Corbin and Strauss, 2008). Such an approach is opposite to the nature of all grounded theory, which is based on the concerns and problems of the participants (Corbin and Strauss, 2008).

A semi-structured interview, on the other hand, is built on an interview guide where a number of themes or subjects are covered (Jacobson, 1993). This guide is used for multiple interviews with different interviewees, and thus all interviewees will be asked relevant and similar questions. During the semi-structured interview, however, there is no need to follow a special order of the prepared questions (Jacobson, 1993). Thus, semi-structured interviews are a good way for the researcher to create some consistency between the interviews with notes being locked in by specific pre-constructed questions (Corbin and Strauss, 2008). Whilst semi-structured interviews allow the participants to add other relevant input after the initial planned question has been asked, they also allow the interviewer to add additional questions in order to clarify or develop topics further (Corbin and Strauss, 2008).

At the beginning of the research project, explanatory questions can be very useful for the researcher to get a good understanding of the types of content and participants involved. Usually, in-depth interviews are recorded, granted the permission of the interviewee (Jacobsen, 1993). According to Slater (1989), if the interview can be recorded in full, the analysis and conclusion will benefit from it, since the interviewer can return to the recording and listen to the answers again. Further, interviews performed within case studies should only be used to obtain information that cannot be reached otherwise. Thus, factual information that can be read in reports or written answers should be gathered before the interview (Williamson, 2002).

3.4 VALIDITY AND RELIABILITY

According to Yin (1994), using the same case study procedure for all case studies during the data collection enhances reliability. Moreover, the researcher should prepare before the data collection starts by, for instance, sending a letter of introduction to the participants in the case study. Regarding the case study questions, interview questions also need to be prepared in order to keep the interviewer on track about what information needs to be collected (Yin, 1994).

The validity of the interview answers can be checked during the interview as the interviewer observes the interviewees' nonverbal cues, and misunderstandings can be reduced by explanations and clarifications during the interview (Williamson, 2002). The interviewer can, at any time, summarise what has been said and repeat to the interviewee, and thus verify that the responses have been correctly interpreted (Jacobson, 1990).

Triangulation is an approach where evidence is gathered from multiple sources. One example is conversions of multiple sources of evidence from the same case study, for example, structured interviews and surveys, open-ended interviews, focused interviews, observations, documents, and archival records. Applying triangulation will strengthen the quality of the research (Yin, 1994).

3.5 DATA COLLECTION FOR THE THESIS

For the research presented in this thesis, the literature study was used in two ways: firstly, for mapping the research area, and secondly, for analysing the empirical data. Search words used for the initial literature studies (Papers I to III) included *remanufacturing, information*, *feedback*, *product life cycle*, *end-of-life*, *design for remanufacturing, design for service*, and *product take-back*. Those papers were obtained in the Scopus and Science Direct databases. As the research process progressed, literature was also sought in Google Scholar (Papers IV to VI), and search words and combinations of them included *remanufacturing requirements*, *product design, product development*, and *lean product development*.

In Science Direct, there is a function that will recommend similar papers to the ones that were read. This function was also used. Furthermore, by reading papers and finding references in them, other promising publications were found. In this way, papers, theses, and books were found using the so-called snowballing approach.

The semi-structured interviews were chosen for the research presented in this thesis as a means of describing the current situation regarding feedback from *remanufacturing* to *design* at the case companies. However, in order to put feedback from *remanufacturing* to *design* in perspective, feedback from *manufacturing* and *service* to *design* was also subject to inquiry.

Prior to the interview, the interviewees were provided with an interview guide (Appendix A). The persons selected for the interviews were foremost managers of the design, manufacturing, service, and remanufacturing departments (Table 5).

Table 5. The functions of the interviewees at the different case companies. The number in the brackets indicates the number of interviewees of the specific function.

Interviewees in Case A	Interviewees in Case B	Interviewees in Case C
Design managers (2)	Design managers (2)	Design manager (1)
Manufacturing manager (1)	Designers (2)	Manufacturing manager (1)
Service manager (1)	Manufacturing manager (1)	Service manager (1)
Manager at OEM Remanufacturing (1)	Service manager (1)	Remanufacturing manager (1)
Managers at CR (3)	Environmental manager (1)	
	Remanufacturing managers (2)	

The interview questions that guided the semi-structured interviews can be found in Appendix B. The interviews were about two hours long, and all interviews were recorded in full. During the interviews, notes were taken, and, where suitable, sketches of information flows were made in cooperation with the interviewee and interviewer. At the end of each interview, the interviewer summarised the answers, and the interviewee was able to verify them. After compiling and analysing the interviews, workshops were held where the interviewees could see the result and provide feedback.

3.5.1 CASE COMPANIES

In the multiple case studies presented in this thesis, the companies had similar experiences in remanufacturing (Table 6).

Table 6. The main characteristics of the three case companies included in the case studies.

Variable	**Case A**	**Case B**	**Case C**
Company size	Large	Large	Large
Sector	Machines	Machines	Furniture
Product complexity	High	Medium	Low
Remanufacturing for	>10 years	>10 years	>20 years

All the case companies are large, operating on the international market. However, the parts of the organisation study are all based in Sweden, with the exception of the contracted remanufacturer in Case B. The companies differ in sector: Case Company A produces and remanufactures machines of medium complexity, Case Company B produces large complex machines and has signed contracted remanufacturers, and Case Company C produces and remanufacturers furniture. All the case companies have more than ten years of experience in remanufacturing.

Case A involves a large international company with a long tradition of producing food processing machines. The focus of this study is the company’s headquarters in Sweden, where product design and the service organisation are located. The machines are manufactured by contracted suppliers, and the product is delivered, assembled, and installed by the OEM at the customer’s site. Thus, the supplier can guarantee that the product is installed correctly and will have the best possible prerequisites to meet the set quality standards. The product is complex but robust and comes with an extended warranty.

Case B concerns a large international company with a long tradition of producing material handling machines. The OEM facility located in Sweden is one of its largest and the focus of this study. The company designs and manufactures products, and the sales and service organisation are also located in the area. The remanufacturing facility is situated close to the main factory. From an organisational perspective, the design and manufacturing sections are grouped together in the producing organisation, whereas service and remanufacturing are linked to the sales organisation.

Case C focuses on a large international company with a long tradition of producing office furniture. The focus of this study was on the company's headquarters in Sweden, where product design, manufacturing, and the service organisation are located. All products are designed in-house, and roughly half of the components are manufactured by the company, while the remainder is purchased from suppliers. The final assembly is performed by the case company to ensure high quality.

4 CASE COMPANY DESCRIPTIONS

In this chapter, the case companies are presented in general terms. In addition, feedback from different actors within the product lifecycle is described.

As presented in Chapter 3, case studies were the foremost source of data collection in the empirical part of the research. The case companies that are in focus in the research presented in this thesis were briefly introduced in Section 3.5.1. Here, the results from the three case studies are presented; the presentations can also be found in Paper V. The information found in this section provides a background to the cases that is needed to address the research questions presented in Chapters 5, 6 and 7. The findings are mainly based on the semi-structured interviews but also on information from and observations made on the guided tours of the companies. The chapter presents the Case Companies A, B, and C, including the feedback, from *manufacturing* and *service* to *design.* This section does not include feedback from remanufacturing, which is described in Chapter 5.

4.1 CASE COMPANY A

The robustness and long life of Case Company A's products make them attractive to the second-hand market. Around 15 years ago, the company noticed that other companies had started to remanufacture its used machines; its brand was being sold by other actors. Thus, the company's remanufacturing business was established about ten years ago to retain the quality associated with its brand. A relatively small number of its products are now remanufactured by CRs. The food processing machine is the focus of this study; however, only a few product models are remanufactured.

The company has a PSS concept in which machines can be leased, but this is not yet well established as the concept is relatively new, and accounts for only a small share of the business.

The product development process has shifted over the years to a more integrated product development, with manufacturing and service involved in product development projects. The service side has a strong influence on the development process as the product is designed in modules. Those modules can be exchanged during the product's lifetime, and upgrading is possible. However, the manufacturing side suffers from not being in-house, as its representatives feel less empowered in the development process.

> "Our (manufacturing) demands are often overrun since we only have one representative from manufacturing, and he has to split his time between all (product) development projects"—Supply Chain Manager at Case Company A.

4.1.1 Feedback at Case Company A

The feedback from service engineers in the field is highly valued in Case Company A. Service technicians are expected to write reports after each completed assignment and provide suggestions for jobs and then send them to the service department. These reports are deeply appreciated, as this enables service technicians to interact both with the machines and the customers in the field. This provides data on the current status of the machine, as well as suggestions for design improvements. The incoming feedback from the service technicians is clustered, prioritised, and forwarded to the design department.

Design also receives feedback from the customers via the marketing department. There, customers' opinions are analysed, prioritised, and forwarded to both the design and service departments.

4.2 Case company B

This company's product is fairly complex and available in numerous models and custom-made versions. The product is robust but not specially designed for remanufacturing. Over the years, the company has become a PSS provider, and now the vast majority of its machines are leased. The machines can be leased long term (up to 7 years) and short term (one day up to months). The company's ambition is that most machines are leased and that they are remanufactured multiple times before being sold as used machines or scrapped. The machines are sold worldwide, and the company has service centres around the world as well. Hence, the service sector is very important for this OEM.

The remanufacturing business started because the company experienced a flow of leased machines being returned at the end of their leasing periods. This was almost 15 years ago. The remanufacturing business has increased over the years, even during the recession of 2008, which had a negative impact on the sales of new machines. However, the revenue from remanufacturing is not specifically stated in the annual reports of the company. Thus, remanufacturing is not clearly recognised within the organisation. Its physical distance from the manufacturing facility is not large, but the mental gap is evident.

4.2.1 Feedback at Case Company B

Manufacturing receives information on issues with products on the market via the quality department. There, customers' opinions are analysed, prioritised, and forwarded. Likewise, design receives feedback if the problem is related to the product's design. The quality department also communicates feedback to services about the quality of the service and suggestions for improvements (for example, increased service costs due to poor quality). Occasionally, service provides feedback to manufacturing if malfunctions occur frequently.

Service technicians have frequent contact with customers and users in the field and receive first-hand information about any problems. There are planned yearly service meetings at the customer's sites, where service asks questions relating to customer satisfaction with both service and the machines. The meeting also includes questions about the frequency of machine use as well as following up on the terms of the leasing contract. The feedback collected by services is communicated to design via the marketing department.

Another source of information is the pre-delivery inspections at the customer's site, which are occasionally attended by services. The product is demonstrated in-use, providing an opportunity for services to learn about its customer's business and application of the machines.

Services and manufacturing representatives are part of product development projects and thus have a platform from which they can contribute their point of view. Experts, amongst the service technicians working in the field, can be requested to provide information for product development projects.

4.3 Case company C

The product at this company is high-end and robust but not very complex, and the products come with extended warranties. In addition, this OEM delivers and installs its products to maintain the intended quality. For the past few years, the company in Case C has had a leasing program; however, it is still only a minor part of its overall turnover.

The company has been remanufacturing office furniture for more than 20 years. Remanufacturing was initiated when exhibition products, reclaimed products, and old products were returned to the company, which saw its intrinsic value and the potential in giving it a second life. However, the OEM feared that the remanufactured product with its reduced price would compete with the newly produced products, and the company did not market the remanufactured products. Thus, the remanufactured products were initially only sold to local customers. Nonetheless, knowledge of the remanufactured products has spread by word of mouth, and the turnover has increased steadily over the years.

4.3.1 FEEDBACK AT CASE COMPANY C

The quality department reports daily to design about returns, reclaimed products, and other statistics. Furthermore, design is supplied with information about customer needs, specifications from manufacturing, and unique selling points (USPs), all of which are important for product development projects.

Technicians, buyers, and representatives from manufacturing and quality participate in the design projects. Everyone involved in the project has access to, for example, sales volumes, sales functions, and material specifications, and USPs are identified in the pre-study stage. Representatives from manufacturing are involved in the pre-study stage, where the next design project is determined. Manufacturing writes its own specifications in which things such as materials and quality are specified. Manufacturing then has time to adjust to any new requirements, such as the introduction of new materials into the manufacturing process. Design makes drawings and bills of materials (BOMs) used for manufacturing and service.

As the service is performed by this OEM, it is crucial that the service and installation can be performed as swiftly as possible. Hence, feedback provided by the service technicians is important for product development projects; remanufacturing is currently not involved in such projects.

5 POTENTIAL FEEDBACK FROM REMANUFACTURING TO DESIGN

In this chapter, the answers to RQ 1 can be found. In order to answer the first research question, literature studies and multiple case studies were performed.

In this chapter, the answer to *RQ1. What potential feedback is available from remanufacturing to design?* is given in Sections 5.1 and 5.2. Firstly, the results from a literature study regarding feedback from remanufacturing to design are presented. Secondly, potential feedback from the multiple case studies is offered.

5.1 POTENTIAL FEEDBACK FOUND IN THE LITERATURE

In the literature study, potential feedback sources from remanufacturing to design were gathered by searching the databases *Science Direct* and *Google Scholar* for articles containing the two search words *remanufacturing* and *feedback.* Papers were selected if the feedback was proposed to be communicated to design in order to impact the design of future products. The result of the study can be found in Table 7.

Table 7. Potential feedback contents from the literature study (adapted from Papers I and V).

Remanufacturing Feedback Sources	**Feedback Content**	**Literature Sources**
Remanufacturing process data	Evaluating how well the product was adapted for efficient treatment in each remanufacturing process step	Ferrer and Whybark (2000), Doyle et al. (2011), Hatcher et al. (2011), Zhang et al. (2012)
Remanufacturing personnel data	Suggestions for improvements	Xu et al. (2009), Zhang et al. (2012)
Cores to be remanufactured	Evaluating how well the component was adapted for its estimated life cycle	Grey and Charter (2008), Abramovici et al. (2009), Xu et al. (2009)

Ferrer and Whybark (2000) argued that designers should have access to feedback from remanufacturing such as information on the remanufacturing process and the products. Further, Hatcher et al. (2011) and Doyle et al. (2011) suggest that feedback from remanufacturing to design could have a positive effect on the design process. In addition, Gray and Charter (2008) argue that the OEMs that remanufacture should use the opportunity to retrieve feedback from remanufacturing concerning the design of the products.

Furthermore, Xu et al. (2009) argue for circular information flows by using technology to enable information transfer between the actors in the product life cycle, including remanufacturing. Zhang et al. (2012) suggest a digital tool for managing knowledge from, for example, remanufacturing to design in a PSS context. They propose that tips from the remanufacturing technicians should be communicated in the tool and provide an example where photos document wear on components in the remanufacturing process. Further, Abramovici et al. (2009) also recognize the need to include feedback from downstream actors to design in a PSS context.

5.2 FEEDBACK FOUND IN THE CASE STUDIES

In the cases studied, there was only one instance of feedback from remanufacturing to design. At Case Company A, one CR had, on occasion, called on the design department to give its opinions on certain design features that occurred frequently and were hindering the remanufacturing of certain parts. The feedback was given on the initiative of the remanufacturing manager at the CR. The feedback was, however, not structured, nor routinely provided nor required. Similarly, the CR has been known to provide constructive feedback on how the service manuals are written. However, the present CR at Case Company A does not provide feedback.

Table 8. The observed feedback from remanufacturing to design in the case companies (Adapted from Paper V). The number of + signs represents how frequently the feedback channel is utilized, where no + means no activity and +++ means frequent activity.

Remanufacturing Feedback Sources	**Feedback Content**	**Feedback Frequency Case A**	**Feedback Frequency Case B**	**Feedback Frequency Case C**
Remanufacturing process data	Evaluating how well the product was adapted to efficient treatment in each remanufacturing process step			
Remanufacturing personnel data	Suggestions for improvements	+		
Cores to be remanufactured	Evaluating how well the component was adapted for its estimated life cycle			

To briefly summarise, the feedback at the case companies, described in Chapter 4, share significant similarities (for further details on feedback frequency from other actors in the product life cycle, see Paper V). The main feedback flows to design stem from service in all the case companies. Manufacturing feedback is also sought to a great extent. However, Case Company A differs as it has external suppliers of subassemblies. In Case Company B, the remanufacturer provides feedback to the service department, and the remanufacturers in Case Companies A and C provide some feedback to the manufacturers. The only direct connection between feedback from remanufacturing to design is the reported phone call from one contracted remanufacturer in Case Company A. However, no other feedback from remanufacturing to design was provided in any of the three cases.

As the literature study (Table 7) indicates, there is potential feedback to be sought at the remanufacturers, and it is interesting to see what such potential feedback could be. Although the case studies showed a lack of feedback actually transferred from remanufacturing to design, there might be potential feedback that is not transferred. Initially, when the remanufacturers were asked what feedback they could provide to design, the answer from all the case companies was that they were not considering providing any particular feedback since there is no such request or channel to provide the feedback through. The present CR at Case Company A initially claimed that it had no feedback to provide to design. Indeed, it stated that providing or even knowing what information to provide was outside of its competences.

Despite this fact, as the case studies progressed, all case companies could give examples of feedback they would like design to have. Table 9 shows examples of such feedback. These feedback examples are from case studies presented in Papers II and V. The feedback examples in Table 9 below have been divided into the same three remanufacturing feedback sources as in the literature study (Table 7).

Table 9. Potential feedback at remanufacturers found in the case studies (adapted from Paper V).

Remanufacturing Feedback Sources	Feedback Content	Feedback Examples
Remanufacturing process	Evaluating how well the product was adapted to efficient treatment in each remanufacturing process step	Aspects of: Cleaning, Disassembly, Finish/surface qualities, and Packing
Remanufacturing personnel	Suggestions for improvements	Material selection Standardisation Verification aspects
Cores to be remanufactured	Evaluating how well the component was adapted for its estimated life cycle	Component quality Component quality of purchased components Weak component analysis Wear on component

Here follows a connection between the feedback sources in Table 8 and the feedback examples in Table 9. The feedback source “cores to be remanufactured” can be the feedback of, for instance, component quality, quality, component quality of purchased components, weak component analysis, and wear on the component. For example, in Case Company A, the cleaning of some machine components could be facilitated by using different surface treatments. According to Xu et al. (2009), the most important feedback from EoU, including remanufacturing, is the quality assessment and information about how products can best be processed.

In Case Company B, the remanufacturer personnel report that less durable materials increase the remanufacturing costs as components need to be replaced. This can be related to Zhang et al. (2012), who propose that tips from the remanufacturing technicians should be communicated to design.

In Case Company C, non-destructive disassembly is not possible for one sub-assembly, which prevents the remanufacturing of those components. This causes unnecessary waste. According to Gray and Charter (2008), OEMs that remanufacture should apply design that aids remanufacturing and thus benefits both business and the environment.

The common denominator of these feedback examples is that, if adhered to, they could benefit remanufacturing. In particular, the feedback examples presented in Table 9 are directly related to DfRem aspects; more aspects of DfRem can be found in, for example, Sundin (2004).

6 BARRIERS AND ENABLERS FOR FEEDBACK FROM REMANUFACTURING TO DESIGN

In this chapter, the answers to RQ 2 can be found. In order to answer the second research question, a cross-case analysis was applied. The cross-case analysis can also be found in Paper V.

Here, the answer to RQ2. *What are the barriers and enablers for feedback from remanufacturing to design?* is presented. The results are based on the findings of the case studies presented in Section 6.1. Those findings were analysed in a cross-case analysis (Paper V), and the result is found in Sections 6.2 and 6.3.

6.1 BARRIERS AND ENABLERS AT THE CASE COMPANIES

In this section the barriers and enablers for feedback from remanufacturing to design found in the interviews at the three case companies are presented. As shown from the literature study in Table 8, and in Paper II, there is potential information available at remanufacturers that could be fed back to design. Nonetheless, the potential feedback is not employed in the cases studied (Table 8). Moreover, the information flows at the three case companies share significant similarities. The main feedback flows to design stem from service in all the case companies. Manufacturing feedback is also sought to a great extent. However, Case Company A differs as it has external suppliers of subassemblies. In Case Company B, the remanufacturer provides feedback to the service department, and the remanufacturers in Case Companies A and C provide some feedback to the manufacturers. The only direct connection between feedback from remanufacturing to design is the reported phone call from the contracted remanufacturer in Case Company A. Still, no other feedback from remanufacturing to design was provided in any of the three cases. Therefore, it is interesting to see why there is a lack of feedback from remanufacturing to design.

6.1.1 CASE A—BARRIERS

Case Company A's product development process is integrated, and service and manufacturing members are invited to take part in it. However, manufacturing finds it hard to get its voice heard in the product development process. Thus, manufacturing often feels overlooked in relation to services. Design states that remanufacturing requirements are adhered to when voiced. The same applies to manufacturing requirements. However, manufacturing and remanufacturing do not share that view when asked about their contribution to and role in the product development process. One reason is that the supply chain that manufactures the machine components is not in-house nor is remanufacturing, whereas service is, and thus they suffer from being external units.

One CR has undertaken remanufacturing for the European market in a facility in Italy. It is less prone to provide unrequested feedback than other CRs that have a closer relationship with the OEM over the years, and it reported a few phone calls to design to provide feedback on reoccurring design issues. However, the Italian CR does not provide any feedback to design, as the OEM does not request it.

> "We don't have the competence to suggest improvements (to design). We only have to recondition the machine and satisfy the customer"—remanufacturing manager at Case Company A.

The contracted remanufacturers rely on the manufacturers to provide them with spare parts and, thus, to interact with the supply chain. Problems arise when the required components are no longer manufactured, and the CR must find another supplier. This delays the remanufacturing process.

6.1.2 Case A—Enablers

The OEM in Case A uses condition monitoring, both continuously integrated into the machines and designated to specific components, and instantaneous monitoring when the machines are inspected upon arrival at the remanufacturer. The initial result from instantaneous condition monitoring is later compared to the test result after remanufacturing is completed, enabling the impact of the remanufacturing process to be assessed. Furthermore, the same measurements will be taken at the customer's site after installation to verify that the shipping and installation process has not impacted negatively on the machine's performance. The OEM is considering expanding its condition monitoring and including more smart functions in its machines. However, current data from condition monitoring is sparsely used, and a new data system would be required to manage all the incoming data. A better-managed and improved data collection system could be used to monitor the components' performance, uptime, and maintenance intervals and thus supply remanufacturing and design with valuable information.

6.1.3 Case B—Barriers

Other departments within the organisation have previously suffered from poor collaboration in the case company. Communication between manufacturing and design was quite different seven years ago. Manufacturing received drawings behind schedule because they were not involved in the product development process until a late stage. Now, the product development process is more integrated, and representatives from manufacturing and services are active in the overall product development process.

Within the organisation, there is a lack of knowledge of remanufacturing. The remanufacturing team suffers from being organised and grouped together with services. Consequently, remanufacturing is seen as a more extensive service rather than as a distinct operation with specific demands. Remanufacturing does not, however, benefit much from design for service (DfS). For instance, components that are often exchanged and accessed during service are fewer and may differ from those replaced in the remanufacturing process. Furthermore, when remanufacturing was given access to software designed for service technicians, remanufacturing technicians were unable to benefit from it.

Moreover, the remanufacturing team noticed a trend to include more plastic components in the products, which makes remanufacturing more time-consuming and costly, as these components must be replaced. For example, a footrest previously made of metal and easy to repaint is now made of plastic and must be replaced with a new one in the remanufacturing process, causing more waste in the process. However, the designers are limited by the controlled cost of manufacturing, which does not include service or remanufacturing costs.

> "If it costs more to solve the after-market (service) problems, we don't do it"—designer at Case Company B.

6.1.4 Case B—Enablers

Information exchange is not a one-way activity. Remanufacturing does not realise what information can be shared with design. Actions have to be implemented on both sides to have a functioning feedback system. However, the design team does not see the potential benefits of receiving information from remanufacturing.

> "Occasionally, product designers come to us at the remanufacturing facility to see how the products that they have designed have been worn out and not only look at service breakdown figures"—remanufacturing manager at Case Company B.

However, the PSS offered in Case Company B is very popular and has increased in sales; up to 80% of its products are now leased. The number of products that are returned after the leasing contract ends has similarly risen. Customers are more and more conscious about sustainability aspects but ask mostly for figures on energy savings and recycling rates, which are also presented in the sustainability reports. However, the OEM has recently increased its attention on remanufacturing, and the company released a film on the Internet in 2014, promoting and informing about its remanufacturing. Hence, there is a high potential for a more prominent role for remanufacturing in the entire organisation.

There are smart functions in the machines that help users to monitor the machines' whereabouts, and there is potential to expand the use of smart technologies and information gathering from the entire product life cycle.

6.1.5 Case C—Barriers

The OEM still sees the remanufacturing business as a threat to newly manufactured sales. Therefore, the remanufactured products are not marketed. Nevertheless, the remanufacturing business has steadily increased over the years, as customers have spread the news by word of mouth.

According to design, *more* information is not needed but rather the *right* information. Information is not requested from remanufacturing because remanufacturing is not seen as necessary, and therefore, is not considered in the product development process. In fact, design regards remanufacturing to be similar to material recycling.

6.1.6 Case C—Enablers

The current trend on the market is to demand furniture with more sustainability and increased environmental considerations. In response, Case Company C has developed a stronger interest in cradle-to-cradle design. The company's leadership decided that all its furniture should meet eco-label standards; in other words, all materials should be, for example, separable and recyclable. The objective is that products could be disassembled by a recycler. However, that could also benefit remanufacturing in the future.

In addition, customers require more flexible services and products that are more easily adapted to their future variable needs. For instance, open landscape offices and offices without dedicated workplaces for staff require the workplace to be quickly adapted to the different needs of the workers. Currently, remanufactured products stem mostly from reclaimed and exhibition products. However, as the PSSs offered are increasingly sought after, returned products will start to increase after the leasing contracts end. Remanufacturing thus has the potential to increase in the future, given that it will be regarded as an asset by the organisation.

The robust design allows the furniture to be used for more than 20 years. However, the design may not actually be that robust, or as one interviewee said:

> "The furniture is not worn out; it is "uglied" out"—remanufacturing manager at Case Company C.

Thus, to prolong the lifetime of the furniture, one option is to update the surfaces and fabrics so that the product may be reused many times.

6.2 BARRIERS FOR FEEDBACK—CROSS-CASE ANALYSIS

A cross-case analysis of the barriers found in the cases was performed. The results of the analysis are presented in Figure 7 and in the text below.

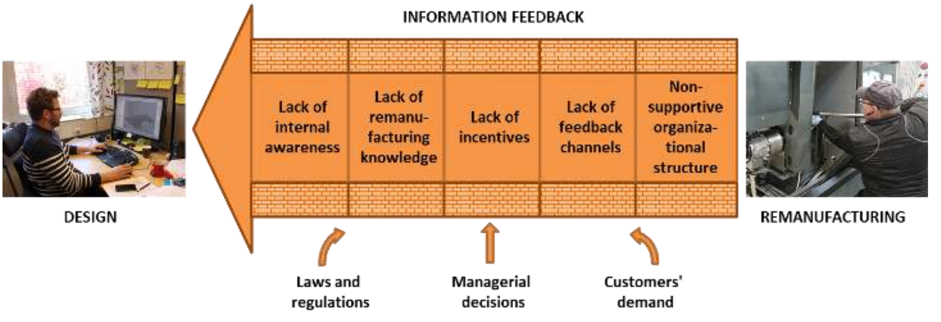

Figure 7. Barriers for feedback from remanufacturing to design and factors influencing the barriers found in the case studies (Paper V).

The barriers, and the factors that influence the barriers, are further described in the following paragraphs (Paper V):

Lack of internal awareness: Surprisingly, the case companies' awareness of remanufacturing is unclear. The turnover from remanufacturing is not specified in the three companies' results and budgets, and, subsequently, remanufacturing is not on the agenda at the three OEMs.

Lack of remanufacturing knowledge: An understanding of the concept of remanufacturing and the requirements for the remanufacturing process among design, manufacturing, and services in these case studies is vague and sometimes incorrect. This was apparent in interviews from all the cases. It is not possible to apply DfRem when designers do not know the needs and requirements from remanufacturing.

Lack of incentives: incentives to learn about and communicate with remanufacturing must be in place in order to establish a feedback flow from remanufacturing to design. The incentives to interact more appear to be hidden, ambiguous, or not stated clearly enough in the three companies. The benefits and challenges of DfRem need to be communicated in order to motivate designers to learn about remanufacturing and apply DfRem.

Lack of feedback channels: As there is feedback available at the remanufacturers (Table 9), the lack of feedback should not be attributed to a lack of information to be fed back, but rather to the lack of feedback channels. For example, in Case B, remanufacturing did not inform design that the change of material in the footrest to a less durable material has a negative impact on the remanufacturing process. At the same time, remanufacturing needs to know what feedback to provide to design. Indeed, the contracted remanufacturer in Case A considers providing feedback to be outside its scope and competence. Regarding Case C, despite the proximity of the remanufacturing facility to the building where design is, there is no feedback.

Non-supportive organisational structures at the case companies can also be a reason for the lack of feedback channels. In Case Company B, the information exchange between the producing organisations, where design is located, and the service organisation, which remanufacturing belongs to, is poor. In Case Company A, the remanufacturer does not belong to the OEM as it is a CR, and hence the OEM does not provide the remanufacturer with full access to its databases. Finally, Case Company C has an organisation that does not acknowledge remanufacturing other than as an isolated side-business, even though the remanufacturing facility is literary wall-to-wall to manufacturing.

Regardless of the crucial role design and remanufacturing play, they do not set the pre-conditions for their potential mutual interactions. Other factors influencing feedback between design and remanufacturing are as follows:

Managerial decisions such as the business case, future product plans and original product specifications and requirements all influence the current situation. If remanufacturing is not acknowledged and its requirements are not documented when the product specifications are set, the designers are not in a position to change those decisions. The cases presented in this study all have design projects with budgets focusing on manufacturing costs. This perspective does not include the cost of remanufacturing and, therefore, DfRem has no obvious benefit. The remanufacturing activities are considered more of an add-on activity; in view of the low volumes of remanufactured products compared to new products in Cases A and C, this is not surprising.

Laws and regulations often push for more sustainable products. An example is the EU WEEE Directive (2003), which regulates the free return of electrical and electronic equipment and thus promotes recycling and reducing waste. However, for Case Company B, there are no laws concerning the recycling of its material handling machines, except for the producer's responsibility for the batteries. Still, it has an ambitious internal goal of 99% recyclability of the machines. Regulations for import and sales of used goods can hinder remanufacturing (Case A).

Last but not least, ***customers' demand*** for remanufactured products expressed clearly could contribute to more DfRem and feedback from remanufacturing to design. However, there is a lack of knowledge of what remanufactured products are and their environmental and economic benefits in general. Thus, informing customers about remanufactured products is essential. When customers are informed about remanufactured products, the customers' demands can be properly accessed and responded to. As previously mentioned in Case B, the sales company described its remanufacturing process on YouTube to inform its customers of what steps its remanufactured products go through in order to ensure a high-quality standard.

Notable is that the above-mentioned barriers are all internal, whereas amongst the influencing factors, customer demand and the laws and regulations are external while managerial decisions are internal. This means that there is much that the companies can do within their organisations to achieve better feedback.

6.3 ENABLERS FOR FEEDBACK—CROSS-CASE ANALYSIS

The cross-case analysis indicates that there are opportunities for remanufacturing to increase its importance within the companies. The opportunities which can be used to enable feedback from remanufacturing to design are presented below. These enablers can be divided into five categories: business opportunities, integrated design processes, customers' willingness, laws, regulations and standards, and new technologies.

Business opportunities include two trends that were evident in all three cases. More and more products are remanufactured, and the remanufacturing business is increasing in the markets. The case companies are, to varying extents, PSS providers. Ownership of products within PSSs is expanded, and the products are returned to the provider at EoU; hence, the incentive to extract the full potential of these product's value increases. The ratio of the turnover generated by the remanufactured products contra new products in the concerned company is also relevant. As remanufacturing currently contributes to a minor part of the turnover, the motivation to elevate remanufacturing remains low.

Integrated design processes. In the cases studied, the design processes were increasingly integrated as knowledge and requirements from manufacturing and services were adhered to in the design processes, and representatives were active in the design projects. If remanufacturing was given a more prominent position within the OEM organisations, or within the value chain in the case of contracted remanufacturers, remanufacturing would more likely be involved in future design projects. Then the needs and requirements from remanufacturing will be more evident. Product design is the key to a product's performance and at the EoU. It is evident in Cases A and C that the robustness of the products is a driver for remanufacturing. In Case B, the product design certainly is robust, although trends such as demanding lower weight push for less durable materials in the product.

Customers' willingness. There is an increased demand for sustainable products (Cases B and C), and product use cycles are shorter than before (Cases B and C). This means that many more potential robust products exist after EoU. Non-utilisation of the full potential lifetime of products is a waste and results in reduced sustainability. Remanufacturing after EoU, which prolongs the life of the products, is one way to maintain the material in the loop.

Laws, regulations, and standards could be used to push and encourage the remanufacturing of products and/or facilitate trading and shipping of used products. Case Company C strives towards fulfilling the Nordic Ecolabel criteria, where factors to be fulfilled include an eco-friendlier design process alongside improved environmental performance. Worldwide, there are more standards being developed within the scope of CE and remanufacturing, and specifically within the energy-related products manufactured or imported to Europe.

New technologies can be an enabler of sustainability, as smart technologies facilitate the capture and use of information. In the cases, two aspects were mentioned. One is condition monitoring, which enables insight into the product's core components without disassembly (Case A). The other is smart technologies, which can monitor the product's whereabouts. The product can, in addition, communicate other information (Cases A and B). Thus, it is possible to include features in the product that would benefit remanufacturing, and data from remanufacturing could be fed back to design.

7 THE REMANUFACTURING INFORMATION FEEDBACK FRAMEWORK (RIFF)

In this chapter, the results from the multiple case studies and literature studies have been applied in a framework. This framework is presented in detail in Paper VI. With the help of this framework, this chapter answers RQ3.

Here the answer to RQ3. *How could feedback from remanufacturing to design be implemented in a structural manner?* is presented. The results are based on the findings of the multiple case studies presented in Chapter 4 and 5 and the cross-case analyses presented in Chapter 6. The framework can be found in Paper VI.

7.1 BACKGROUND

As presented in the case studies in Chapter 5, there is a lack of feedback from remanufacturing to design. There is also an absence of DfRem in industry as presented by, for example, Hatcher et al. (2011), although, by employing DfRem, the remanufacturing process is more likely to be effective and efficient (Gray and Charter, 2008). Nevertheless, academia provides methods for executing DfRem (see, e.g., Ijomah et al., 2007a; Yang et al., 2015). Thus, in order to increase the application of DfRem, a structural support for companies to implement DfRem has been developed. Section 7.2 presents the remanufacturing information feedback framework (RIFF). This framework aims at strategically defining and practically implementing feedback from remanufacturing to design in order to support and improve DfRem (Paper VI).

7.2 THE CONTENTS OF THE FRAMEWORK

The RIFF framework is based on backcasting principles and consists of four steps, as presented in Paper VI. The barriers found in the cross-case analysis presented in Section 6.2 provided the foundation for what the framework needs to accomplish. Further, the data collection required in the framework is based on the interview studies presented in Section 3.5. Moreover, a literature study on potential feedback (Section 5.1) provided a structure for improvement approaches. Additionally, state-of-the-art practices were sought in the literature.

The outline of the RIFF framework is illustrated in Figure 8.

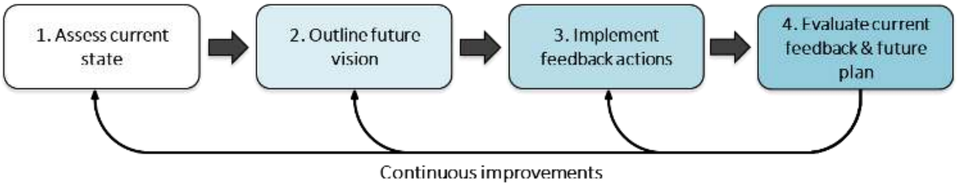

Figure 8. Outline of the remanufacturing information feedback framework, RIFF (Paper VI).

Firstly, the current situation is assessed in Step 1, and thereafter the future vision is outlined in Step 2. Step 3 provides actions for the stepwise implementation of feedback from remanufacturing to design. These actions are prioritized, and a time plan is created. The identified first action is then carried out. The final step is an evaluation of the effects of the implemented actions and the effect that they have regarding DfRem. Further, Step 4 is also a checkpoint evaluating if the plan created in Step 3 needs revising or not. After that, the method steps are repeated until the vision is fulfilled. The following subsections will describe the steps in more detail.

7.2.1 Step 1—Assess current state

Initially, the current situation regarding the feedback flows is assessed. The assessment is conducted via interviews with stakeholders within design and remanufacturing, in this case, relevant staff within the product development department such as managers, design engineers, and project managers. Likewise, within the remanufacturing organisation, managers and remanufacturing technicians may be interviewed. These individuals, representing one of the appointed stakeholders (e.g., project manager), should preferably be interviewed separately in order to obtain answers reflecting reality rather than what is, for example, accepted internally as policy.

The interview setup is based on getting input from *design, manufacturing, service,* and *remanufacturing* regarding the feedback to *design*. The outlook in many companies is that there is a lack of feedback from remanufacturing to design (see Chapter 5). Thus, the questions cannot solely focus on that subject but rather aim at painting a picture of what the information transfer looks like regarding the design process. It is important not only to see and visualise the information transfer process but indeed to verify the conditions for the information transfer. Although systems for information sharing and transfer are in place, the picture of what the information transfer looks like will probably vary a bit, depending on who is asked. Every department will have knowledge about its information flows, but in this step, the collective view is explored. It is important that the interviews are carried out by an unbiased person. The interviewees should feel compelled to freely answer the questions so that the answers reflect the real, and not the ideal, situation. It is also essential that the aim of the interview is clearly defined, and that the respondent has received the information well before the interview so that he or she can prepare by thinking over the questions. An interview guide, including the aim and purpose of the interview as well as contact details of the interviewer, is preferable should there be any questions (Appendix A). Together with the guide, the interview questions (Table 10) should be made available so that the interviewee can prepare his or her answers properly in order to get the best results out of the interview.

Table 10. Interview questions to representatives from design regarding information received from manufacturing, service, remanufacturing, and other stakeholders, respectively.

Subject	**Questions to Stakeholders**
Information from *manufacturing,* *service* and *remanufacturing* and *other stakeholders*, respectively	1. What information does *design* receive from *manufacturing*, *service, remanufacturing,* and *other stakeholders*? 1.1 How is that information transferred (channel/system)? 1.2 How is that information used? 1.2.1 When in the design process is that information used? 1.3 What information is most important? 1.4 Is there information that is not used? 1.4.1 If so, why is that information not used? 1.5 What other information could be useful for *design*?
Decisions and requirements	2. How are the decisions taken in the *design* phase? 2.1 What criteria go into the design process? 2.2 What laws and regulations must be considered when designing the product? 2.3 What requirements does design have to include regarding end-of-use aspects (e.g., remanufacturing)? 2.4 What are the entities of the requirements specification relevant to remanufacturing?

During the interview, follow-up questions and questions that will clarify the responses are required. This semi-structured approach will contain interview questions that will vary from interview to interview and thus are not specified. A preferable approach for performing these interviews is to illustrate the information flows on, for example, a whiteboard while the interview is carried out. Thus, as a stakeholder is brought up in the interview, the name of that stakeholder is also written down on the whiteboard. Likewise, as the information flows are described, lines will be drawn between the stakeholders to illustrate the information exchange.

The intention of this step is to capture the actual situation in a way that is illustrative of the reality. This might bring clarity to the current situation, and not only to the interviewer but also to the interviewee. The illustration can then be used as a communication tool when merged with the answers of the other relevant interviewees. Each profession will have its angle of the complex system that is information sharing within an organisation. It is, however, very important that the interviewee gets an opportunity to verify his or her answers. Hence, at the end of each interview, the interviewer summarises the interview by reading the answers to the interview questions and letting the interviewee verify, add to, or correct the answers.

After all the interviews have been carried out, they need to be analysed. The analysis is conducted by drawing up information flows. More stakeholders than those interviewed will be in the illustration. It could be valuable to interview them as well to get a richer picture; however, the responses from the four stakeholders design, manufacturing, service and remanufacturing are enough to get a sufficient picture of the current situation. Indeed, the feedback between remanufacturing and design might be very different from feedback from manufacturing and design. However, all information transfer found in the interviews should be included in the final illustration. Although remanufacturing may not provide feedback to design, remanufacturing needs to be included as one of the stakeholders in the final illustration. Thus, when setting up the illustration of the information flows, one should start by placing design, manufacturing, service, and remanufacturing.

If carried out correctly, the assessment of the current state should be disseminated throughout the organisation, and areas for improvement clearly pointed out. Often, the situation is not clear until the illustration is complete, and it is easier to compare and contrast remanufacturing's involvement in the feedback than if only remanufacturing and design were interviewed. Preferably, areas for improvement should be discussed, clarified, and summarised in a document.

7.2.2 STEP 2— OUTLINE FUTURE VISION

When the current situation is mapped, analysed and communicated, the next step is to identify a vision of a desirable scenario: in other words, what the ideal scenario looks like concerning how feedback from remanufacturing should reach design and be integrated into the design process. This scenario should be outlined by a team of representatives from design, remanufacturing, and top management. What the desired future vision is will be company dependent; however, it should specify a principle-based scenario for optimal feedback from remanufacturing to design.

When the initial mapping of the current stage and a clear vision has been established, there will be a gap between the current state and the vision. That gap is addressed in this framework by implementing feedback actions such as the following (presented in order of complexity to implement, and ranked from estimated low to high):

- **Genchi Genbutsu** ("go see"), where the product designers visit the remanufacturers to learn about the remanufacturing process and specific issues.
- **Feedback from technicians** in the remanufacturing facility, for example, collected via a software application or a "know-how" database.
- **Wear on components** from visual inspection, measurements, and/or condition monitoring.
- **Workshops/integration events**, where remanufacturing staff and product designers meet to learn from each other and solve problems.
- An **ombudsman** for *remanufacturing*, appointed to speak for the remanufacturer in the product development projects.
- A **fully integrated product development process** with cross-functional teams, including *remanufacturing* represented as one of the stakeholders and value providers in the value chain.

These examples of actions are suggested based on findings in empirical studies and the lean product development literature; see, for example, Hatcher (2013), Kuo et al. (2001), Lee et al. (2006) and Chakravorty (2009). The idea is that once the current stage and vision are clarified, different strategies for integrating feedback into the product design process should be discussed. The actions should be chosen based on the level of appropriateness for the specific case company. It should be pointed out, however, that not all these actions need to be taken; the best combination is to be decided by each company based on its current assessed state and outlined future vision.

In order to reach the desired vision outlined in Step 2, the actions are prioritised and specified in a time plan that will also include evaluations after each implementation action. Thus, when promising actions have been chosen, they should be ranked according to how easy they are to implement, then prioritised. Initially, easily implementable actions should be adopted. It is better to start taking actions in the aimed direction than to do nothing and wait for major changes if the different actions are not heavily interdependent. The actions will then be implemented stepwise, where the actions are implemented and evaluated after a fixed period of time. What is seen as an easy strategy or a difficult one will depend on the specific company.

7.2.3 Step 3—Implement feedback actions

The planned actions are now to be implemented. The stakeholders will participate in the actions, and the goal is that design will not only receive feedback from remanufacturing but also get knowledge about the remanufacturing process and use the information and knowledge in the design process. For instance, if Genchi Genbutsu is applied, the designers will visit the remanufacturers to learn about the remanufacturing process and specific issues. During the visit, they can ask questions and get information about the used products and components first-hand. They can also get a demonstration of how certain parts are disassembled and see with their own eyes how design features affect the remanufacturing process.

In the process of working with implementing the actions, the achieved information and knowledge need to be captured. Such documentation is, for instance, design support such as design checklists (see Section 7.2.4), guidelines, and "know-how" sheets. Other documentation methods such as A3 reports, where all improvement work information is written down and illustrated (Lindlöf et al., 2013), and other intra-organisational documents will support the process of upholding the actions and continuous improvements.

When the actions have been implemented and at a certain time interval (e.g., six months), an evaluation follows. The evaluation will take place before the next implementation phase begins, and so on, until the goal is reached.

7.2.4 Step 4—Evaluate current feedback and future vision

The evaluation phase consists of two parts. The first evaluation and success criteria will indicate whether or not the actions' increase of feedback from remanufacturing to design has led to DfRem. Thereby the current state in Step 1, Section 7.2.1, should be updated. Here, a DfRem checklist could be used to verify the actions that have taken place during the implementation phase (Step 3) in order to achieve DfRem. Examples of design criteria for DfRem are listed below:

- Use of standardised parts
- Robust material selections
- Modular design

- Upgradeability
- Assembly methods that allow for non-destructive disassembly and reassembly
- Minimal number of connectors
- Reusable connectors
- Easy access to wear and tear parts
- Shapes that are suitable for cleaning
- Materials that are easy to clean
- Corrosion-resistant parts
- Timeless design

Hence, the provided checklist should be filled in to verify what components were modified and to meet the requirements from remanufacturing. For instance, the component thickness may have been increased to allow for the reprocessing of goods (e.g., the grinding of engine parts), or a more durable material may have been used on a critical component to prolong its predicted lifetime (e.g., metal instead of plastic). Thus, the outcome of the work with improved feedback strategies can be monitored, and the progress documented after each feedback action implemented. In order to monitor the progress and DfRem design change achievements, spider charts are used. The initial design is assessed, and then the following evaluation of DfRem design achievements is added to the chart. Thus, the results of the evaluation can be illustrated, and the progress more easily observed.

The second part of the evaluation is an assessment of how the implementation of feedback from the remanufacturers proceeded, that is, whether the implementation occurred as planned and what unforeseen factors may have influenced the outcome. The evaluation step requires involvement from top management as it is also relevant to re-evaluate the implementation plan. Since companies operate in a changing environment, it is possible that the vision and/or implementation plan must be revised. Alterations of the market, such as the financial situation, technology developments, or intra-organisational restructures, may impact the plan. Hence, this part of the evaluation step adds a dynamic element to the framework. The main reason for this dynamic part is that the framework need not be discarded even though external or internal factors may interfere with the initial action plans. As the evaluation is complete, the implementation will continue with the next action until the results are aligned with the desired vision. Continuous improvement should then be applied.

The contents of the framework are presented in a condensed form in Table 11 (from Paper VI). The table shows the steps of the framework with associated input to the required activities. Further, the tools provided in the framework are listed, and the expected, resulting output presented. Finally, the primary stakeholders involved in the respective steps are presented.

Table 11. The Remanufacturing Information Feedback Framework (RIFF) supporting the implementation of feedback from remanufacturing to product design (Paper VI).

Steps	Input	Activities	Tools	Output	Stakeholders
1. Assess current state	Information about actual information flows	Interviews Illustrations Compiled information flow chart Analysing Communicate result	Interview guide Information flow chart	Information flow illustration Coherent understanding of current information flows	*Product design management, Project leaders Remanufacturing management, etc.*
2. Outline future vision	Information about feedback implementation actions	Back casting Set goals Choose feedback implementation actions Prioritise Choose product or part/s Make time plan	Feedback implementation action list	Action plan	*Top management, Design, Remanufacturing*
3. Implement feedback actions	Action plan and information flow illustration	Initialise Utilise tools Document process	DfRem checklists and tools Feedback implementation action list	Changes in feedback transfer	*Design, Remanufacturing*
4. Evaluate current feedback and future vision	Product and part/s design features Changes in feedback transfer Action plan	Document DfRem progress Evaluate implementations (Step 3) Evaluate future vision (Step 1) Evaluate time plan (Step 2) Continue implementation (Step 3)	DfRem evaluation sheet	Complete DfRem evaluation sheet Revised action plan	*Design, Remanufacturing, Top management*

8 DISCUSSION

In this chapter a brief answer to the three research questions is given in order to summarise the previous sections of the thesis. The chapter continues with a discussion linking the research results to other research findings and reflections.

In order to summarise the research results presented in Chapters 5, 6 and 7 brief answers to the research questions are provided below. The aim of the research presented in this thesis is to expand current knowledge on how to improve design for remanufacturing through the implementation of feedback from remanufacturing to design by answering three research question.

8.1 ANSWERS TO THE RESEARCH QUESTIONS

This section will deal with each research question, one at a time. The first research question is as follows:

RQ1. What potential feedback is available from *remanufacturing* to *design*?

This research question was initially answered in the literature study presented in Section 5.1. Table 7 shows the potential feedback from remanufacturing divided into three main categories, illustrating that feedback can be either straight from the remanufacturing personnel, related to the process of remanufacturing, or related to the core to be remanufactured. The researchers quoted in the table highlight the benefit of supplying such feedback.

The potential feedback from the case studies presented in Section 5.2 gives a clearer picture of what feedback, as is presented in Table 9, could consist of. These examples of feedback from *remanufacturing* to *design* are presented below:

- Aspects of cleaning
- Aspects of disassembly
- Aspects of finish/surface qualities
- Aspects of packing
- Material selection
- Standardisation

- Verification aspects
- Component quality
- Component quality of purchased components
- Weak component analysis
- Wear on components

The examples of potential feedback in the case studies are still not demanded by the design departments at the case companies. Therefore, this potential feedback remains unexplored in the case companies. Thus, there is a lack of feedback from remanufacturing to design (for further details, see Chapter 5 and Papers I, II, and V).

RQ2. What are the barriers and enablers for feedback from *remanufacturing* to *design*?

The barriers complicating feedback from remanufacturing to design are presented in Section 6.2. The five barriers found in the case studies consist of the following intra-organizational barriers:

- Lack of internal awareness
- Lack of remanufacturing knowledge
- Lack of incentives
- Lack of feedback channels
- Non-supportive organizational structures

Furthermore, there are extra-organizational factors influencing the barriers presented above:

- Managerial decisions
- Laws and regulations
- Customers' demand

The barriers and the extra-organizational factors influencing the barriers are part of the explanation of why there is almost no feedback from *remanufacturing* to *design* at the case companies. However, in the case studies, enablers for future feedback from remanufacturing to design were also found. These enablers, presented in Section 6.3, are as follows:

- Business opportunities
- Integrated design processes
- Customers' willingness

- Laws, regulations, and standards
- New technologies

These enablers influence the conditions for feedback from remanufacturing to design. Thus, the prerequisites for feedback from remanufacturing to design could benefit from exploring the enablers (for further details, see Chapter 6 and Paper V).

RQ3. How could feedback from *remanufacturing* to *design* be implemented in a structural manner?

This research question was answered by developing the Remanufacturing Information Feedback Framework (RIFF), based on the literature studies and case studies performed during this research. In Chapter 7, this framework for implementing feedback from remanufacturing to design in a structural manner is presented. The aim of the RIFF framework is to provide a structured approach to improve or implement feedback from remanufacturing to design. The method has four steps:

Step 1—Assess current state

Step 2—Outline future vision

Step 3—Implement feedback actions

Step 4—Evaluate current feedback and future vision

The framework encourages collaborations between departments and requires managerial commitment. The implementation phase requires changes in the interaction between the remanufacturing and design departments and will increase knowledge about remanufacturing amongst the designers. The framework is based on the evaluation of the current state, as well as re-evaluations of how the progress of implementing feedback from remanufacturing has improved design for remanufacturing (for further details, see Chapter 7 and Paper VI).

8.2 RESULT DISCUSSION

In this section the outcome of the research presented in this thesis is further discussed.

8.2.1 CASE CHARACTERISTICS

Although all the case companies are large OEMs that remanufacture, the results are not automatically transferable to all companies with similar preconditions. Indeed, the results from case studies are not generalisable as such but can show what happens in a typical scenario (Kitchenham et al., 1995). Further, as the Case

Company OEMs are only large companies, the results cannot be transferred to small or medium-sized companies (SMEs). Whether or not the results are applicable for SMEs remains to be researched.

The product complexity varies in the cases, from high product complexity (Case A) to low product complexity (Case C). However, whether or not the lack of feedback is disconnected to the complexity of the product itself cannot be verified in this study.

For the purpose of this research, only OEMs that remanufacture or have contracted remanufacturers have been chosen. The incentives for independent remanufacturers to provide feedback to the OEMs are low since the benefits for the OEM to DfRem, if it does not remanufacture itself, are few. However, Hilton and Thurston (2019) point out that many of the DfRem criteria could also facilitate maintainability and repairability, and thereby be beneficial to the OEM.

8.2.2 PRODUCT DESIGN AND FEEDBACK

Regarding DfX, the case companies have experience in DfM and DfS and include manufacturing and service representatives in the design process. However, the lack of inclusion of representatives from remanufacturing and the lack of DfRem coincides in all three case companies. Hilton and Thurston (2019) stress that the lack of DfRem is a considerable barrier to the market potential of remanufactured products and also to the expansion of the remanufacturing industry. Already in 2011, Hatcher et al. (2011) pointed out the need for exploring organizational factors that are linked to the DfRem integration into the design process, considering the OEM and their designers.

Previous studies report on the lack of DfRem, which the studies presented in this thesis add to. For instance, Hatcher et al. (2011) point out that although researchers have developed design tools and methods for DfRem, they are scarcely used in industry. The suggested RIFF (Section 7.2) intends to support the use of DfRem methods and tools in industry. Whether or not feedback implementation will have an impact on the actual design of a product remains uncertain since this framework has not been fully implemented yet. Also, designers have many design criteria in the design process; consequently, trade-offs between design criteria need to be considered (Hilton and Thurston, 2019). Therefore, Hilton and Thurston (2019) call for processes that facilitate design trade-offs that include remanufacturing criteria. Indeed, the RIFF does not include guidelines for trade-offs between different design criteria. This weakness might affect the impact of applying the suggested framework.

Moreover, the aim of the case studies was to describe a typical scenario for feedback from *remanufacturing* to *design*. The three cases show a lack of feedback from *remanufacturing* to *design*. However, given that the actual transfer of feedback was so limited in the cases, the essential part was to verify potential feedback at the remanufacturers. Although the results show the feedback scenarios at the case companies and potential feedback at the time of the case studies, the results are not generalizable for every company.

Furthermore, as pointed out in Paper IV, a PSS allows better control of the products during their use and remanufacturing phases. Moreover, a PSS implies greater motivation for the OEM to learn about its products (Sakao and Sundin, 2019). It seems that applying a PSS could be the solution for the lack of feedback from remanufacturing to design. However, as pointed out by, for example, Matschewsky (2017), some companies that have successfully applied a PSS have not yet explored its full potential. This is also true for the case companies presented in this thesis. Therefore, the RIFF is also applicable for companies that apply both remanufacturing and PSSs.

8.3 METHOD DISCUSSION

In this section, the methods applied for the research presented in this thesis are discussed.

8.3.1 DESIGN RESEARCH METHODOLOGY (DRM)

The DRM framework (Blessing and Chakrabarti, 2009) has guided the research presented in this thesis (see Section 3.1.1). The framework was selected since it is specifically aimed at design research. As this thesis also focuses on a method for improved design, the research is well fitted into the DRM framework. Further, applying the DRM framework provided the foundation for aiming at describing the current situation and additionally trying to improve future circumstances.

The DRM framework provided a structure for the planning of the research, as it guided the researcher through the different stages of the research process. This research includes three out of the four steps in the DRM framework: the Research Clarification Stage, Descriptive Study I, and the Prescriptive Study (Figure 6). The descriptive stage of the research was dominant, as case studies were the predominant research method. This is not uncommon amongst researchers in design, who, according to Blessing and Chakrabarti (2009), often tend to focus on the descriptive phase. However, the application of the DRM framework was strong in the Research Clarification Stage and the initial parts of Descriptive Study I, whereas the framework could have been better applied in the later parts of

Descriptive Study I and in the Prescriptive Study. Furthermore, the suggested RIFF would have a stronger impact if the research had also included the final step of the DRM framework, where the support is evaluated by several users.

This research does not include Descriptive Study II, where the support or method is evaluated. In the prescriptive stage, the suggested support is only evaluated on completeness and internal consistency with or without users involved (Blessing and Chakrabarti, 2009). In the creation of the support (in this case, the RIFF), assumptions are made (Blessing and Chakrabarti, 2009). For the RIFF creation, it was assumed that remanufacturers would like to provide feedback and that they have the competence to provide feedback that can be used to apply DfRem. Further, it is assumed that the designers will use their gained knowledge about remanufacturing and apply DfRem methods and tools in order to improve DfRem. Moreover, it is also assumed that companies that apply the RIFF are OEMs that remanufacture or intend to remanufacture their products and are open to making the changes required to implement the feedback (Section 7.2) best suited for their needs.

8.3.2 CASE STUDIES

Case studies were chosen as the research method since they are appropriate for research of contemporary contexts, where the researcher has little or no control (Yin, 1994). Multiple ways of collecting data are possible within the form of the case study. In these studies, the key data collection method was semi-structured interviews since they provide the opportunity to ask the same in-depth questions to respondents at different case companies but also allows for indents or clarification questions. The interviews were combined with visits at the shop floors, during which questions could be asked and observations made by the researcher. Further, workshops were used in order to verify the results from the interviews and observations. However, while the interviews were the primary source of information, more structured and frequent observations, as well as better structured workshops, could have contributed to a stronger validation of the results.

Additionally, this research also provides additional background information about the cases and the missing link between *design* and *remanufacturing*, as it showcases the lack of feedback. Further, the cross-case analysis provides a picture of what barriers were found in the cases that complicate feedback from remanufacturing to design. However, these results are not applicable in all the case companies with similar characteristics. Rather, case studies can show what happens in a typical scenario (Kitchenham et al., 1995). Nevertheless, these insights could be compared in future studies, and in order to strengthen the results presented in this thesis, future studies should include cases where the barriers are expected to be weaker or even absent (Yin, 1994).

8.3.3 Semi-structured interviews

The selection of functions in the companies that were interviewed was made by the researcher. The number of suitable interviewees was limited, since, for the purpose of this thesis, managers of design, manufacturing, service, and remanufacturing were expected to have the best prerequisites to describe the feedback flows from their perspectives.

The interviews were all carried out at the case company sites but on separate occasions. Participating in the interview was the interviewee and interviewer, as well as a second researcher who was taking notes and making sketches of the information flows. Notes were also taken by the interviewer, and the interviews were recorded. One weakness of the interview is that the interviewee might feel compelled to paint a more productive picture of the actual situation at the company. In order to prevent that, the interviewees were asked to verify the results after the interview was complete. Also, later on, the interview results were compiled and presented at a workshop with those from other functions in the company, who could give their opinions and views about the results. Notably, the respondents were anonymous to the rest of the workshop group. However, a weakness of using workshops is that some participants tend to dominate the discussions.

Academia and industry tend to use terms and abbreviations frequently. However, sometimes terms are used in different ways. One example is refurbishment and renovation, which are sometimes used to describe remanufacturing (Sundin, 2004). Therefore, during the tours of the shop floors and in the interviews, follow-up questions were asked in order to avoid misunderstandings and clarify the meaning of terms and abbreviations.

8.3.4 Validity and reliability

In preparation for the data collection for the research presented in this thesis, an introductory email was sent to the participants of the case studies, including an interview guide (Appendix A). The interview questions were first prepared by identifying the topics of the questions. Following that, each question was further prepared so that the same questions could guide each interview. However, different questions were directed at representatives from different departments within the companies. According to Yin (2009), such preparations are essential for the reliability of the data collection.

As the interviews were done face-to-face, the interviewer could ask the interviewee to clarify when uncertainties occurred during the interview. This, according to Williamson (2002), improves the validity of the interviews. However, there is a risk that the respondent will feel loyalty to their employer and not disclose all relevant information. Further, at the end of each interview, the interviewer summarized the answers, and the interviewee was able to comment and make additions and corrections before the session was over. According to Jacobsen (1993), such practice also improves validity. During the data collection phase of this research, the same approach was applied in all the case companies (Section 3.4). However, the number of respondents in the case companies varied, and thus the results can be affected.

In order to verify the findings in the semi-structured interviews, the results of the interviews and the observations made during the tours of the companies were presented at the workshops at the case companies. There, the participants could provide feedback on the results. Thus, triangulation was applied by using multiple sources to verify findings. However, the workshops include representatives from many departments, and the organizational structures will impact the atmosphere of the workshops, and therefore the results might be influenced

9 CONCLUSIONS

This chapter concludes the thesis. Firstly, how the research presented in this thesis meets the aim of the thesis is presented. Secondly, the contribution to academia and industry is offered. Finally, suggestions for future research are given.

In this chapter, the findings presented in this thesis are highlighted and the implications of the findings are presented.

9.1 MEETING THE AIM OF THE THESIS

The aim of this research is to *expand current knowledge on feedback from remanufacturing to design and how it can be used to improve design for remanufacturing*. The aim is met through several sequential steps. Firstly, this research has expanded the current knowledge of feedback from remanufacturing to design by providing case studies illustrating a lack of feedback from remanufacturing. Secondly, based on a literature study and empirical studies at the case companies, the results in this thesis show that there is potential feedback from remanufacturing to design. Thirdly, barriers for feedback from remanufacturing to design have been presented, thus providing an explanation of why there is a lack of feedback from remanufacturing to design at the case companies. Fourthly, enablers that could improve the prerequisites for feedback from remanufacturing to design have been presented. Finally, a framework for implementing feedback from remanufacturing to design is described, thus showing how it can be used to improve design for remanufacturing activities.

9.2 CONTRIBUTION TO ACADEMIA

This research has contributed to previous research by compiling literature on feedback from remanufacturing to design. When the literature study was performed, no comprehensive review of the subject was available. Although the review is seemingly short, it offers an overview of the literature, including remanufacturing amongst the actors in the product life cycle from which to retain feedback. Other authors argue for feedback from actors in the downstream product life cycle but do not include remanufacturing as one of those actors. Furthermore, the compilation of barriers that hinder feedback from remanufacturing to design adds to the understanding of the current situation.

The advancement of the comprehensiveness is highly useful to, and often wanted by, practice because an academic method for optimizing specific decision making on particular circumstances is not always called for by industry (Sakao and Sundin, 2019). Therefore, this research is expected to contribute to academic research aiming to improve industrial practice.

Matsumoto et al. (2016) state that OEMs' lack of awareness of DfRem, sometimes also in combination with their lack of motives for remanufacturing, prevents DfRem methods and tools from being a part of the industrial practice. The suggested RIFF framework in Section 7.2 aims at overcoming such barriers. Furthermore, RIFF complements the DfRem tools and methods developed by academia with support to implement them in industry, something that is called for by, for example, Hatcher et al. (2011) and Matsumoto et al. (2016).

9.3 Contribution to Industry

The empirical studies add to the understanding of the lack of feedback from remanufacturing to design in industry but also insights into how to improve feedback.

The case companies have gained insight into the feedback flows as well as an understanding of the uneven distribution of feedback from the actors in the product lifecycle. Furthermore, the case companies could benefit from the RIFF presented in this thesis in Section 7.2 in order to change the lack of feedback from remanufacturing to design. On a general level, the results presented in the workshops at the case companies have provided the case companies with increased insight and awareness of remanufacturing.

Further, the application of the RIFF promotes the implementation of DfRem methods and tools, which, when applied, could make remanufacturing more efficient and effective. If DfRem was more often applied, remanufacturing OEMs could benefit from reduced costs in the remanufacturing process (Matsumoto et al., 2016; Hilton and Thurston, 2019).

Furthermore, the designers' knowledge about remanufacturing could be improved by applying feedback action practices, as presented in Section 7.2. The results from the interview show that the awareness and knowledge about remanufacturing at the case companies are low. By applying the RIFF, the designers, managers, and remanufacturers are challenged to apply a more holistic thinking and life cycle perspective on the product design. From a wider perspective, designers at companies that remanufacture their products could contribute to increasing the potential for the remanufactured products on the market by applying DfRem. Consequently, the increased application of DfRem will contribute to the overall growth of the remanufacturing market, which will also reduce the negative environmental impact (Hilton and Thurston, 2019).

9.4 FUTURE STUDIES

Future studies, including more cases that are expected to provide similar results as well as cases that are expected to be dissimilar, would provide better insight into the state of the industry. Such case studies would also contribute to the current knowledge of feedback from *remanufacturing* to *design*. Furthermore, the research presented in this thesis concerns large companies, and thus the situations of SMEs are not considered. Therefore, future research focusing on differences and similarities with feedback from *remanufacturing* to *design* in SME contexts where the organisational structures may differ would also contribute to richer insights into the remanufacturing industry.

Moreover, the future implementation of RIFF to verify its potential for implementing feedback from remanufacturing to design in its entirety will be essential for the evaluation of the support. Implementing RIFF at case companies would contribute to the validation and improvement of the current framework.

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Papers

The papers associated with this thesis have been removed for copyright reasons. For more details about these see:

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APPENDIX A

Appendix A contains the interview guides used for the case study interviews.

Introduction to interviews

This study is part of a cooperation/project between Linköping University and [redacted] during the KEAP (Design for Remanufacture through Efficient Use of Product Life-cycle data) project.

The aim of this study is to find out how remanufacturing companies use and handle product life-cycle information. Thus different departments at remanufacturing companies will be interviewed; product design, manufacturing, service and remanufacturing departments. Answers from different remanufacturing companies will be compared in order to describe and analyze the present state.

In this context, a generic product life-cycle is defined as the material flow through the phases of raw material extraction, design, service, manufacturing, use and end-of-life (Figure 1).

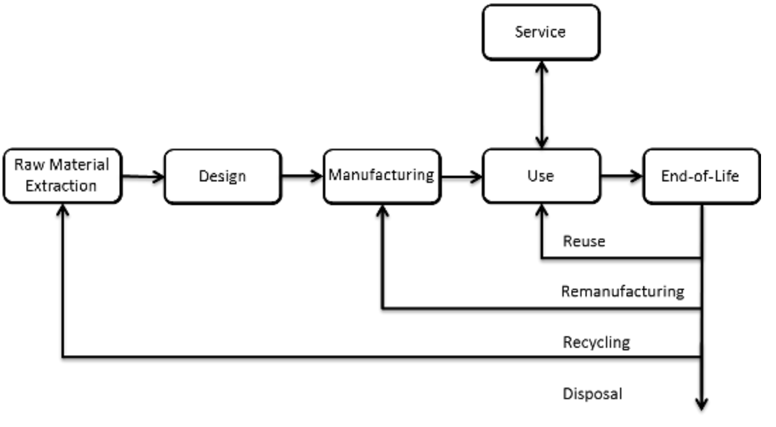

Figure 1. The material flow of a generic product life-cycle

The questions interview includes topics such as:

- Information retrieval
- Information provided
- Information management

The interview will last for between 30 minutes to one hour depending on the answers. The anonymity of the respondent is guaranteed. The respondent's answers will be recorded in order to be transcribed later on. A report will be written and sent to the respondent.

Interviewer: Louise Lindkvist, PhD student, Division of Manufacturing Engineering, Linköping University louise.lindkvist@liu.se tel. 013-28 27 96

For further questions, please do not hesitate to ask me or my supervisor Erik Sundin erik.sundin@liu.se tel. 013-28 66 01

APPENDIX B

Appendix B contains the interview questions used for the case study interviews.

Priority Level	**Type of Question**	**Questions**
low	*Basic information*	Company size Company/affiliation location Position at company
high	*Remanufacturing department*	What information does the manufacturing/service/remanufacturing department receive from product *design*? How is that information transferred (channel/system)? How is that information used? When in the manufacturing/service/remanufacturing process is that information used What information is the most important? When in the manufacturing/service/remanufacturing process is that information used Is there information that is not used? If so, why? What other information could be useful for the manufacturing/service/remanufacturing department?
high	*Remanufacturing staff*	What information does the manufacturing/service/remanufacturing staff receive from product design? How is that information transferred (channel/system)? How is that information used? When in the manufacturing/service/remanufacturing process is that information used What information is the most important? Is there information that is not used?

		If so, why? What other information could be useful for the manufacturing/service/remanufacturing staff?
high	*Use of information*	How is the retrieved information used? In what stage in the manufacturing/service/remanufacturing development process is the information used? During what type of manufacturing/service/remanufacturing operations is that information used?
	Efficiency	What information about the products life is required for the service/remanufacturing process? What information would be required in order to make the manufacturing/service/remanufacturing process more efficient? What information is desired in order to make the manufacturing/service/remanufacturing process more efficient?
	Feedback	What information feedback does the manufacturing/service/remanufacturing department provide product design with today? How does manufacturing/service/remanufacturing provide product design with feedback (channel/system)? What further information feedback could be of use for product design?
high	*PSS*	If the business model PSS and functional sales was applied, how do you think that would influence the information exchange between remanufacturing and product design?
	Virtual tools	Do manufacturing/service/remanufacturing currently use any virtual tools, e.g., 3D-models of products and disassembly instructions?

		How could the use of virtual tools, e.g., 3D-models of products and disassembly instructions that simulates the manufacturing/service/remanufacturing process, influence the work? What requirements would there be on such tools? What features would be desired in such tools?
high	*Information provided*	What information is provided from the manufacturing/service/remanufacturing department to other life cycle phases? What information is provided to each stage? Why is that information provided?
high	*Storing information*	How is the information stored? In what format? For how long?
high	*Accessing information*	Who has access to the information? Why?
high	*Information management*	How are the information flows managed? Why? Are there other alternative ways that would be better?
high	*Priorities*	How are priorities made between all the incoming information? What information usually has the highest priorities?
low	*Filtering information*	How can the information be filtered?
med	*Models*	How would incoming information from product design be handled (model/method)?
low	*Influence*	How do you think the remanufacturing business type, i.e., in-house, contracted or independent remanufacturer influences the information flows?

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