On Remanufacturing Systems

Analysing and Managing
Material Flows and Remanufacturing Processes

Johan Östlin
There is nothing so practical as a good theory
Kurt Lewin (1890-1947)
The aim of remanufacturing is to retrieve a product’s inherent value when the product no longer fulfills the user’s desired needs. By taking advantage of this inherent value through different product recovery alternatives, there is a potential for both economically and environmentally advantageous recovery of products.

Remanufacturing is a complex business due to the high degree of uncertainty in the production process, mainly caused by two factors: the quantity and the quality of returned products. These factors have implications both on the external processes, e.g. coordinating input of returned products with the demand for remanufactured products, as well as the internal processes that coordinates the operations within the factory walls. This additional complexity needs to be considered when organising the remanufacturing system.

The objective of this dissertation is to explore how remanufacturing companies can become more competitive through analysing and managing material flows and remanufacturing processes.

The first issue discussed in this dissertation is the drivers that make companies interested in remanufacturing products in the first place. The conclusion is that the general drivers are profit, company policy and the environmental drivers. In a general sense, the profit motivation is the most prevalent business driver, but still there are situations where this motivation is secondary to policy and environmental drivers. Secondly, the need to balance the supply of returned products with the demand for remanufactured products shows that the possible remanufacturing volumes for a product are dependent on the shape of the supply and demand distributions. By using a product life cycle perspective, the supply and demand situations can be foreseen and support is given on possible strategies in these different supply and demand situations. Thirdly, how used products are gathered from customers is categorised by seven different customer relationship types. These types all have different effects on the remanufacturing system, and the characteristics of these relationships are discussed in detail.

When considering the remanufacturing process within the factory walls, a generic remanufacturing process was developed that divides the remanufacturing process into five different phases: pre-disassembly, disassembly, reprocessing, reassembly and the post-assembly phase. These different phases are separated by three different key decision points in the process that also have a major impact on the material planning of the process. For the remanufacturing material planning and production planning, the possibility to apply lean principles can be difficult. One foundation for implementing lean principles in new production is the existence of standardised processes that are stable and predictable. In the remanufacturing system, the possibilities to realise a predictable process is limited by the “normal” variations in quantity and the quality of the returned cores. Even though lean principles can be problematic to implement in the remanufacturing environment, this dissertation proposes a number of solutions that can be used to make the remanufacturing process leaner.
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## Terminology

The following table describes the basic terminology and abbreviations used in this dissertation.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tr>
<td><strong>ABC analysis</strong></td>
<td>One tool to classify different objects is the Pareto analysis – or as it is commonly referred to, “the 80-20 rule” (not to be confused with Activity Based Costing)</td>
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<tr>
<td><strong>Aftermarket</strong></td>
<td>The market for components and accessories to maintain or enhance a previous purchase</td>
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<td><strong>BOM</strong></td>
<td>Bill of Materials</td>
</tr>
<tr>
<td><strong>Core</strong></td>
<td>The worn-out or discarded product that is used to remanufacture a product</td>
</tr>
<tr>
<td><strong>End-of-life</strong></td>
<td>The end-of-life returns refer to those returns where the products are at the end of their economic or physical life</td>
</tr>
<tr>
<td><strong>End-of-use</strong></td>
<td>End-of-use returns refer to those situations where the user has a return opportunity at a certain life stage of the product</td>
</tr>
<tr>
<td><strong>EOQ</strong></td>
<td>Economic Order Quantity</td>
</tr>
<tr>
<td><strong>FAS</strong></td>
<td>Final Assembly Schedule</td>
</tr>
<tr>
<td><strong>Functional Sales</strong></td>
<td>To offer from a life-cycle-perspective a functional solution that fulfils a defined customer need. The functional solution can consist of combinations of systems, physical products and services</td>
</tr>
<tr>
<td><strong>Installed Base</strong></td>
<td>The total number of placed units of a particular product in the entire primary market or product segment</td>
</tr>
<tr>
<td><strong>IPSE</strong></td>
<td>Integrated Product and Service Engineering</td>
</tr>
<tr>
<td><strong>Life Cycle [1]</strong></td>
<td>The evolution of a product, measured by its sales over time. The phases that a product goes through during it life cycle are the introduction, growth, maturity and decline stages</td>
</tr>
<tr>
<td><strong>Life Cycle [2]</strong></td>
<td>The progress of a product from raw material, through production and use, to its final disposal</td>
</tr>
<tr>
<td><strong>MRP</strong></td>
<td>Material Requirement Planning</td>
</tr>
<tr>
<td><strong>MRR</strong></td>
<td>Material Recovery Rate – The uncertainty of the quality of a core and how many of its components that can be recovered, is measured using the metric Material Recovery Rate</td>
</tr>
<tr>
<td><strong>Obsolescence</strong></td>
<td>When the demand of a component decreases and finally is no longer desired or becomes out-of-date, it is considered as obsolete</td>
</tr>
<tr>
<td><strong>OEM</strong></td>
<td>Original Equipment Manufacturer</td>
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Product Recovery
The recovery of used and discarded products, components and materials

Remanufacturing process
An industrial process whereby used products, referred to as cores, are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and testing to ensure it meets the desired product standards.

Remanufacturing system
The system for collecting used/discard products, remanufacturing of the product, and the delivery of the remanufactured product to the customer.

Reversed Logistics
The coordination and control, physical pickup and delivery of the material, parts, and products from the field to processing and recycling or disposition, and subsequent returns back to the field where appropriate.

ROP
Reorder point
APPENDED PAPERS


Information on the authors’ efforts in relation to the papers is presented in Appendix B

OTHER PUBLICATIONS


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This part of the dissertation introduces the remanufacturing industry, describing the need for research in the area and highlighting the gaps in the existing body of literature. Part also motivates the aim of the dissertation and the formulation of its specific research questions.
Product recovery encompasses the recovery of used and discarded products, components and materials. The product recovery consists of several activities, such as collecting the product; determining the potential for the product’s reuse; disassembling the product and segregating valuable components; remanufacturing of the product; recycling materials; and disposing of waste (Toffel, 2004).

Product recovery has proved to be an economically and environmentally beneficial alternative to ordering new products. Product recovery is an umbrella concept involving concepts like reuse, remanufacturing and recycling. The aim of product recovery is to retrieve a product’s inherent value when the product no longer fulfils the user’s desired needs. By taking advantage of this inherent value through different product recovery alternatives, there is potential for both economically and environmentally advantageous recovery of products (Bras et al., 1999). During the last century, the industrialized world has put limited focus on product recovery. Instead, the focus has been on the production of products from virgin materials (i.e. non-recycled). For several different reasons, the focus has now shifted to an increase in product recovery. For example, society’s awareness of environmental problems with the present use of material and products has grown (Ryding, 1995). These social pressures have resulted in increased environmental legislative pressure from the European Union (EU), such as the launching of the WEEE and ELV directives – creating an environment where product recovery potentially can become profitable, if not already, and without take-back laws.

In this dissertation, the remanufacturing option of product recovery will be the focus. Remanufacturing is an industrial process where worn-out/broken/used products are collected from customers and restored to useful life. Here, the worn-out or discarded products used to remanufacture a product are referred to as cores (Amezquita et al., 1996). During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and

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1 WEEE stands for Waste of Electric and Electronic Equipment.  
2 ELV stands for End of Life Vehicle.
testing to ensure it meets the desired product standards (Sundin, 2004). This could sometimes mean that the cores need to be upgraded and modernized according to the customer requirements (see e.g. Seaver (1994), Lund (1996) and Sundin (2004)). The differences and definition of remanufacturing concerning different product recovery options such as reuse, recycling and repair are given in the forthcoming theoretical framework. A simplified illustration of how remanufacturing is related to other product recovery options is seen in Figure 1.

Figure 1: Product recovery in the closed-loop supply chain (Thierry et al., 1995)

Material flows are an important factor for the overall remanufacturing system (Guide, 2000). Regarding the flow of products linked to remanufacturing, there is a specific term called “the closed-loop supply chain”. A traditional view of the closed-loop supply chain is that it encompasses two distinct supply chains, the forward and the reverse, as illustrated in Figure 1. Generally, the forward chain concerns the flow of physical products from producer to customer, while the reverse chain describes the flow of physical products from customer to producer. These flows are then “closed” by, for example, the remanufacturing operation (Krikke et al. 2004).

Figure 1 illustrates the closed-loop supply chain, where new products are created in the forward flow of material through fabrication and assembly out to the end user. When the product reaches the end of its usage period at the customer, it is subject to one of the eight different product recovery options shown.

### 1.1 The Remanufacturing Industry

The remanufacturing industry got a boost during the Second World War when many manufacturing facilities changed from ordinary production to military production;
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hence, the resources (labour, material, etc.) for civilian production became scarce. As a result, the products in use by civilians were mainly remanufactured in order to keep society running. The concept of remanufacturing has spread during the latest decades to sectors such as electrical apparatus, toner cartridges, home appliances, machinery, cellular phones and many others, as discussed by e.g. Sundin (2004).

The remanufacturing industry, as an industry sector, is often referred to as a “hidden giant” as described by Lund (1996). The reason for describing it as hidden is that the majority of the remanufacturing performed in industry is done at companies that are not focused on pure remanufacturing operations, and provide it mainly as an aftermarket service. Therefore, it is difficult to estimate the turnover of the remanufacturing industry, since the data is hidden in aggregated numbers. To give some examples of the importance of the remanufacturing industry, the size of the industry in the United States was estimated to have a turnover of $40.5 billion in 2003 (Reman, 2007). In the United Kingdom, the size of the remanufacturing industry was been estimated to be £5 billion in 2004, which places it on par with the recycling industry in the U.K. (OHL, 2004). However, remanufacturing proposes a great business opportunity, and the European market has an enormous growth potential. In the USA, it is a major business, and the automotive industry sells approximately 60 million remanufactured automotive products, compared to 15 million products in Europe for an equivalent stock of vehicles (Seitz et al., 2004).

1.2 The Remanufacturing Process

The process with which the used product is remanufactured is called the remanufacturing process (Sundin, 2004). In the remanufacturing process, the product goes through a number of specific phases. Within these phases, the used product undergoes a set of remanufacturing operations such as cleaning, identification, machining, etc. The order and the purpose of the different operations are not standardised, but rather are dependent on the individual remanufacturing cases and the needs for recovery of individual components.

The remanufacturing definition used throughout this dissertation is as follows:

Remanufacturing is an industrial process whereby used products, referred to as cores, are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and testing to ensure it meets the desired product standards.

Adapted from Sundin (2004)

Here, a core is defined as the worn-out or discarded product that is used to remanufacture a product (Amezquita et al., 1996).
The remanufacturing process can be organised in many different ways. The type and complexity of the product to be remanufactured has a high degree of impact on the organisation of the process (Sundin, 2004). Another issue that influences the organisation of the process is the type of decisions that have to be made during the process. For example, if a component has been found to be faulty, there must be a reprocessing operation or a replacement with a new component. If the decision is taken to reprocess the component, then there is a need for a reprocessing operation. Therefore, the organisation of the remanufacturing process is highly affected by this decision (Paper IV).

1.3 The Remanufacturing System

In respect to the remanufacturing process, the remanufacturing system is a broader context that also addresses the external processes of supplying remanufactured products to customers, as well as collecting cores from the previous customers (thus becoming suppliers of cores). The external processes in the remanufacturing system set limitations on the input and output from the actual remanufacturing processes which transform cores into remanufactured products through e.g. reprocessing operations and new replacement components. The remanufacturing system and the link to the remanufacturing process are illustrated in Figure 2. The figure illustrates the forward supply chain of remanufactured products going from remanufacturer to customers. It also illustrates the incoming new products (newly manufactured) that are supplied to customers. When the products are discarded by the customer, the cores are subject to product recovery (including waste management and direct reuse), and some of the cores are remanufactured. When the core reaches the remanufacturer, it enters the remanufacturing process (described in further detail in Paper IV).

The remanufacturing system is in this dissertation defined as:

.. the system for collecting used/disclosed products, remanufacturing of the product, and the delivery of the remanufactured product to the customer
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Figure 2: The Remanufacturing System

The remanufacturing system is generally very different in comparison to the traditional manufacturing system. For example, the remanufacturing batch sizes are normally smaller, the degree of automation is lower and the amount of manual labour is higher in comparison to a manufacturing plant (Steinhilper, 1998). Furthermore, remanufacturing is a complex business due to the high degree of uncertainty in the production process (Guide 2000, Seitz et al. 2004) and mainly caused by two factors: the quantity and the quality of returned products (cores) (Atasu et al. 2005, Umeda et al. 2005). This uncertainty also creates variations regarding capacity requirements as well as the yield of the process. Guide (2000) defines these factors in detail and presents all together seven characteristics of remanufacturing found in the current research literature. These characteristics are:

- the uncertain timing and quantity of returns,
- the need to balance returns of used products with demand for remanufactured products,
- the need for disassembly of returned products,
- the uncertainty in materials recovered from returned items,
- the requirement for a reverse logistics network,
- the complication of material matching restrictions and,
- the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

The characteristics of the remanufacturing system are an important contribution to the understanding of the problems linked to remanufacturing. To continue to develop the
remanufacturing practice, it is important to address these characteristics. Some of the characteristics are more linked to system perspectives, as for example, the need to balance returns of used products suitable for remanufacturing with demand for remanufactured products. Other characteristics are more linked to the internal processes in the remanufacturing facility, e.g. the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times. To address these problems, a holistic approach is necessary to capture the effects of the different characteristics.

1.4 Dissertation Focus

In the remanufacturing system, the areas of interest are ultimately a result from the characteristics of remanufacturing, presented by Guide (2000). These characteristics address both the external processes, that simplified, can be referred to as the process of coordinating input of cores with the output of remanufactured products from the remanufacturing process. The other area is the internal processes that coordinate the operations within the factory walls. Thus, the material flow and the remanufacturing process will be the main study focus in this dissertation.

For the external process, the key activity is linked to acquiring the used products (cores) to the remanufacturing and matching the output to the demand for remanufactured products. This refers primarily to the remanufacturing characteristics of the need to balance returns of used products with the demand for remanufactured products, and the uncertain timing and quantity of returns.

In internal processes, the main activity is to remanufacture the incoming cores. The focus of this area is to make the remanufacturing process as effective as possible. This refers primarily to the characteristics of highly variable processing times and the uncertainty in materials recovered from returned items.

1.4.1 External Processes

For remanufacturing to be successful, Thierry et al. (1995) highlight the need to gain information on future market needs of remanufactured products, as well as to determine what drivers there are for remanufacturing in the first place. The problem then becomes matching the forecasted demand for remanufactured products with the anticipated magnitude of return flows. Toffel (2004) also concludes that one of the major impacting issues of remanufacturing is in the difficulty of obtaining used products (cores) that are suitable for remanufacturing. The timing and quantity of return of a product is dependent on the type of the product. Factors such as the mean product lifetime, rate of technical innovation, and failure rate of components all influence the return rate of products from end-of-use and end-of-life (Umeda et al., 2006). End-of-use returns refer to those situations where the user has a return opportunity at a certain life stage of the product. This refers to leasing cases and returnable containers like bottles, or returns to second-hand markets. Although end-of-
use products are not new, they are often in a good or reasonable state. In respect to end-of-use returns, end-of-life returns refer to those returns where the products are at the end of their economic or physical life. They are either returned to the OEM because of legal product-take-back obligations or “returned” to another company for value-added recovery. Customers can be more or less active concerning the returns, as illustrated respectively by returning bottles to the supermarket or by sending back toner cartridges via mail (de Brito et al., 2002).

The balance between product returns and demand for remanufactured products is clearly a function of many variables, were the rate of technological innovation and the expected life of a product are the major influencing characteristics (Guide, 2000). One conclusion that can clearly be drawn regarding this balance is that when a product is new on the market, the return rate of cores from end-of-use is generally lower than the potential demand for remanufactured products. Vice versa, after a point when the product has been on the market for an extended time, the returns of end-of-use products are generally higher than the demand for remanufactured products (Umeda et al., 2006).

For the performance of the remanufacturing system, the question of acquiring cores is an important issue for the remanufacturer in order to be able to satisfy the demand for remanufactured products. “The challenge within the industry is not just how to manage irregular reverse flows, but how to obtain them in the first place” (Seitz et al., 2004). To illustrate the importance of a close relationship, Seitz et al. (2004) provides an insight from a vehicle manufacturer:

“For vehicle manufacturers, a crucial issue is to maintain a relationship with customers so that when an engine fails, the customer returns to the retail network for a replacement. If the customer goes elsewhere, then the loop will not be closed and the manufacturer will not get access to the cores they need. Unfortunately, loyalty to OEM service schemes decreases noticeably over time.”

Here, the management of different types of relationships with the customer and suppliers is an important factor for the performance of the remanufacturing system. As Seitz and Peattie (2004) put it:

“Reverse logistics and remanufacturing are a customer relationship management challenge”.

1.4.2 Internal Processes

Just as for manufacturing companies, the remanufacturing industry is also subject to increased competition on markets and pressure from customers and suppliers. World-leading manufacturing companies are in a state of change towards a different view of manufacturing. The pressure on a company can be observed from its customers, demanding customized, cost-reduced and quality-enhanced products enabled within short lead times, and from its suppliers who demand reduced inventory levels and
increased demand variability (Mentzer et al. 2001). To respond to these demands, lean production, which is said to increase productivity, decrease lead-time and costs and enhance quality, has been widely adopted (Martinez Sanchez et al., 2001). The ideas for Lean Production (“Lean”) were developed by Toyota, and in their most basic form are the systematic elimination of waste - overproduction, waiting, transportation, inventory, motion, over-processing, defective units - and the implementation of the concepts of continuous flow and customer pull (Womack et al., 1996). In a study conducted by Sundin (2004) using mainly a Rapid Plant Assessments (RPA) ranking methodology (see Figure 3), an investigation was conducted concerning how lean remanufacturing companies perform in respect to a scale of manufacturing companies.

Figure 3: RPA scoring sheets of the remanufacturing companies (Sundin 2004)

The RPA is an assessment tool that ranks a company in 11 different categories that are traditionally linked to lean production thinking. The result from the Sundin study indicates that the additional complexities regarding material flows in remanufacturing may be a limiting factor for remanufacturing companies to apply lean production principles. In relation to the study by Sundin (2004), the poor performance of remanufacturing companies in the material flow motivates further research.

1.5 Objective, Aim and Research Questions

Remanufacturing companies are in a more complex and difficult position compared to traditional manufacturing companies (Guide, 2000). The additional complexity needs to be considered when organizing the remanufacturing system. If companies can find ways to manage the additional complexity, then the possibility to develop the industry sector further is great. This dissertation addresses the problem of how remanufacturing
can become more advantageous by developing different management principles and methods adapted for the remanufacturing context. The dissertation is therefore given the following overall objective:

*The objective of this dissertation is to explore how remanufacturing companies can become more competitive through analysing and managing material flows and remanufacturing processes.*

Many factors can contribute to the competitiveness of the remanufacturing system. In this dissertation, the aim is not to identify all of these factors, but rather to concentrate on the issues linked to the material flows and the remanufacturing processes.

Based on the purpose of the dissertation and the dissertation focus as described earlier in the introduction, a number of different key research questions have been identified during the course of this research. Firstly, to answer how companies can become more competitive, there is a demand to know about the foundation for competitive advantage in the remanufacturing system. Thus, understanding what the drivers are for the overall remanufacturing system is a key issue for developing competitiveness in the remanufacturing system. For example, when creating different management principles there has to be a purpose for the development of these principles. In other words, without knowing where we are going, we cannot deliver solutions to get there. Therefore, the identification of remanufacturing drivers becomes important for the direction of the forthcoming analysis. The first research question is formulated as follows:

**RQ 1. What are the drivers for companies to remanufacture products?**

The first research question addresses why companies remanufacture and what companies need to aim for to create a competitive advantage. In its essence, this research question is primarily focused on the demand side of the remanufacturing system. How this demand for remanufactured products is linked to the supply of cores is the focus of the next research question:

**RQ 2. What strategies can be used for balancing returns of products suitable for remanufacturing with demand for remanufactured products?**

The focus of the second research question is to explore how companies can balance the demand for remanufacturing products with the rate of product returns. The question addresses how to develop strategies that can aid companies in balancing supply and demand as well as providing insights for possible remanufacturing strategies in different supply and demand situations. To analyse the problem of balancing the supply and demand, the theory of the product life cycle (see definition in the theoretical framework section) will be used as a framework. For the balancing of the supply and demand in a remanufacturing system, there is also a need to consider the types of relationships between the remanufacturer and the customer:
RQ 3. What types of relationships exist between customer and remanufacturer, and what specific characteristics can be found in these relationships?

The third research question addresses the problem of the uncertain timing and quantity of returns as well as balancing returns of products suitable for remanufacturing with demand for remanufactured products. The focus of this research question is partly linked to the second research question, and aims to identify what kinds of relationships exist between remanufacturers and their customers/suppliers of cores, and how these relationships can be managed. Furthermore, an important issue is to explore how a customer/supplier relationship perspective can support product take-back for remanufacturing with a focus on the supply of cores. When considering the supply of cores to the remanufacturing process, the focus is on the relationships with the customers/suppliers of cores and how the supply of cores to the remanufacturer can be managed.

The first three research questions have a strong external focus on the processes outside of the operational part of the remanufacturing system – that is, the actual remanufacturing process. The remaining research questions will focus on the remanufacturing process. Firstly, the focus will be on the general remanufacturing process and the organisation of this process:

RQ 4. How is the organisation of the remanufacturing phases and the decisions taken linked to the remanufacturing process?

This research question focus is to describe the complexity of the material flow in the remanufacturing process. This complexity is based on a number of factors and decisions that have to be taken into account during the remanufacturing process. A discussion is needed on how different factors and decisions affect the organization of the remanufacturing process and the individual remanufacturing phases (see Figure 2). An additional intention with this research question is to develop a general overview of the internal remanufacturing process for further analysis in between different remanufacturing companies. The decisions taken in the remanufacturing process also have a major impact on the material flow, and also lead to the following research question:

RQ 5. How can lean principles for material planning and production planning be applied for remanufacturing?

Previous research clearly shows that the remanufacturing companies generally perform poorly in material flow and material handling issues (Sundin, 2004). The focus for this research question will be on how efficient material planning and production planning can be a means for making the remanufacturing process more competitive, especially by using principles from lean production,
**INTRODUCTION**

**RQ 6. What principles for material handling can be suitable in the reassembly phase?**

The last research question mainly relates to the problem of the uncertainty in components recovered from cores. In the remanufacturing process, this problem results in a need to replace faulty components with other (new or cannibalised) components. The focus is on exploring how the uncertainty in recovered components affects the material control and replenishment strategies for new components, material movement and storage for both new and reprocessed components in the reassembly phase.

**Figure 4:** Overview of the linkage between the remanufacturing system and the research questions.

Figure 4 provides an overview of the coupling between the remanufacturing system and the research questions, while further illustrating how the research questions focus on the remanufacturing system.

**1.6 Delimitations**

A number of interesting questions and factors regarding the remanufacturing system were chosen to be excluded from this dissertation. The design of the product to be remanufactured has a high degree of influence as to how the remanufacturing process will be organised (Sundin, 2004). Although this is an important factor, it is excluded from the scope of the study. This delimitation is also partly done due to the existence of previous research in this field (Sundin, 2004). Still, the importance of the design of the products should not to be neglected when considering the competitiveness of the remanufacturing system. In many situations, the design of the product has the major impact on the future possibility to economically remanufacture a product.
The potential environmental benefits related to the remanufacturing system have also been excluded from this study. Making this limitation does not exclude the potential environmental effects from a business aspect. For the interested reader, however, the environmental issues that are linked to some of the case studies presented here are further investigated in Lindahl et al. (2006) and Sundin (2004).

Another important characteristic in the closed-loop supply chain that was excluded is the reverse logistic network. The reverse logistic network, which is regarded as the logistical structure of the material flow, is organised between the customer and the remanufacturer. Logistics structures are, in this dissertation, the questions of e.g. where to place central inventories and which means of transportation that will be used. Reversed logistic networks for product recovery have previously been modelled by e.g. Kara et al. (2007), with the aim of calculating the total collecting costs in a predictable manner. Kim et al. (2006) also present a closed-loop supply chain model for remanufacturing to minimize the total cost of remanufacturing. Logistical structures have also been treated in the closed-loop supply chain by for example Huge Brodin (2002).
This part of the dissertation introduces the approach that was chosen to peruse the research aim and the specific research questions, discussing methodology theory as well as the practical data collection. In addition, the validity and the reliability of the research approach is discussed. The following section addresses previous research that has been used for developing the research questions, as well as providing a theoretical base for the empirical analysis.
When a researcher decides on the research methodology for a study, he or she is influenced by many factors. The purpose and the research question(s) that have been formulated have a direct link to the choice of research methodology, but there are other factors that also have a more indirect influence, such as available resources with which to perform the research and the research paradigm. The research methodology used for this dissertation is a case study methodology. Why this methodology has been chosen, as well as how it is used, is described in the case study design section. Before this discussion is made, however, a theoretical overview of the case study methodology is presented.

2.1 Case Study Methodology Theory

In situations where the issues that are under investigation cannot be easily separated from their context or environment, a case study research methodology can be an appropriate choice (Yin, 1994). By using case studies, one can gain a complex and holistic view of a specific issue or problem. A case study can be described as “problem-focused, small scale and entrepreneurial” (Merriam, 1994). As Yin states:

“In general, case studies are the preferred strategy when ‘how’ and ‘why’ questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context”.

(Yin, 1994)

When deciding on a methodology to investigate the research questions, Yin (1994) presents some general factors that influence the choice of method as seen in Table 1.
Table 1: On how to choose a research strategy (Yin 1994).

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Form of research Question</th>
<th>Requires control over behavioural events?</th>
<th>Focuses on contemporary events?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>how, why</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Survey</td>
<td>who, what, where, how many, how much</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Archival analysis</td>
<td>who, what, where, how many, how much</td>
<td>No</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Case study</td>
<td>how, why</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

When a researcher has chosen a case study approach for a study, there are five key components that are especially important when conducting the study (Yin, 1994):

- A study’s questions
- Its propositions, if any
- Its unit of analysis
- The logic linking the data to the propositions
- The criteria for interpreting the findings

2.1.1 Setting the Research Questions and Propositions

The first key component in the study is the research questions. In case study research the questions are normally “how” and “why” questions, as described earlier. The initial task for this component is to clarify the nature of the study question. The form of the study question results in different types of case study research; these are descriptive, explanatory and exploratory case studies. (Yin, 1994)

A descriptive case study is one that documents a particular action or series of actions. Thus, what is implied in this type of study is the formation of hypotheses of cause-effect relationships. Hence, the descriptive theory must cover the depth and scope of the case under study.

In exploratory case studies, fieldwork and data collection may be undertaken prior to definition of the research questions and hypotheses. This type of study has been considered as a prelude to some social research. However, the framework of the study must be created ahead of time. Pilot projects are very useful in determining the final protocols that will be used. Survey questions may be dropped or added based on the outcome of the pilot study.

Explanatory case studies are used to pursue an explanatory purpose. The researcher’s objective is to pose competing explanations for the same set of events and to indicate how these explanations may apply in other situations. In regard to the other types of case studies, the explanatory case study focuses on generating theories.
Deciding between the different descriptive, exploratory and explanatory designs is closely related to the richness of the related theories to the topic of the study. For example, if there is a vast body of literature regarding a specific topic, the greater the chance there is to formulate an explanatory case study. Therefore, a key issue for setting the research question is to search for the previous research in that area and to identify the theoretical propositions that cover the study questions. Important issues in this phase are to review literature, have discussions with key actors, ask challenging questions and think of what can be learned from the case study. (Yin, 1994)

Following this, the overall research questions are set and the potential study propositions are formulated. The research propositions can be seen as a further detailed development of the research questions down to an operational level. The main differences between research questions and study propositions are that research questions are formulated according to a gap in theory, whereas the study propositions begin to tell you where to look for relevant evidence. For the exploratory case study, there is a limitation of the possibility to apply the more detailed study propositions mainly due to the lack of existing theory with which to relate. Therefore, exploratory studies normally lack detailed study propositions. (Yin, 1994)

### 2.1.2 Selecting the Unit of Analysis

Once the research questions and the study propositions are set, the question becomes how to perform the actual research. This addresses what case companies are to be chosen; generally, the cases should somehow empirically represent the interesting topic of the study. Depending on the scope of the study, it can contain single or multiple case studies. Single case studies are preferable when critically testing existing theory, or to study rare or unique situations. Multiple case studies, on the other hand, are more favourable if replication logic is used to reveal support for a theory. When generating a theory linked to a case study, the aim is to identify the conditions when a particular phenomenon is likely to be found and when it is not. The theoretical framework is also the source for generalizing to other cases: if the empirical cases do not support the finding as predicted, modifications should be made to the theory. According to these criteria, the number of case replications depends upon factors such as the desired degree of certainty and the richness of the underlying theoretical propositions. (Yin, 1994)

### 2.1.3 Interpreting the Findings

After the data for a case study is gathered, the next step is to link the data to the propositions and interpret the findings. These components represent the data analysis step in the case study research, and the choice of research design has a major impact on the potential success of the analysis. The success of the analysis is also highly dependent on the researcher’s ability to perform the cross-case analysis for multiple case studies. Some formalised methods for data analysis exist, and they are often based on different methods of *pattern matching* and *explanation building*. (Yin, 1994)
The pattern matching principle is mostly common in explanatory and descriptive case studies. This analysis is based on comparing empirically-based patterns with predicted ones. This can be done by comparing if the initially predicted results have been found and alternative patterns are absent. Another method of pattern matching is to use rival explanations to compare the empirical data. (Yin, 1994)

The second source of analysis is based on explanation building. This is conducted through analysing case study data by building an explanation about the case and identifying a set of causal links. Explanation building is often a result of a series of iterations between an initial theoretical statement that are compared with empirical data that might result in a revised statement. After this, the other details of this case are analysed against the revision. This is then compared and revised in a series of interactions between the additional cases, and as many times as needed. (Yin, 1994)

In conclusion, the analysis should show that: it accounts for all the relevant empirical evidence; all major rival interpretations are dealt with; the most significant issue of the study is addressed; and that prior theoretical and expert knowledge is considered in the analysis. (Yin, 1994)

2.2 Case Study Advantages and Critique

Some specific advantages can be linked to case studies. According to Merriam (1994), case studies can:

- Give guidance to the reader in regards to what can be done, and what should not be done, in a similar situation.
- Address a specific situation(s) and still conclude to a general problem.
- Be frequently based on inductive reasoning.
- Have been influenced by the researcher’s own values. Although this does not necessarily have to be the case.

Merriam also discusses some general advantages that can be attained through the case study methodology. Case studies:

- Illustrate the complexity of a situation, e.g. the fact that not a single but a multiple of variables affect a given situation.
- Can describe a situation over time.
- Enable the collection of data from multiple sources, e.g. quotes, interviews and newspaper articles.
- Explain why a problem arises, give a background to a specific situation, what happened and why.
- Explain why some changes work and why others do not.
METHODODOLOGY

- Provide knowledge that is more concrete and connects better with our experience because it is more alive, concrete and direct in comparison to the abstract and theoretical.

There are, however, also some weaknesses linked to case studies. These weaknesses depend on the fact that case studies rely on analytical generalizations, whereas survey research relies on statistical generalizations. This raises a wide range of biases such as subjective and selective preconceptions, problems regarding the viewpoint of outsiders understanding group meanings, and bias surrounding the background, agenda and interests of the researcher. To avoid these types of biases, the issues regarding validity and reliability become important. Other negative comments are that case studies provide a poor basis for scientific generalization and that the studies take too long, often resulting in massive documents. This is the same set of arguments used against most methods of qualitative research. (Yin, 1994)

2.3 Validity and Reliability in Case Studies

Questions regarding issues like reliability and validity can be criteria that are used to value the quality of a given research; in case study research, the general validity can be divided into construct, internal and external validity. (Yin, 1994)

Construct validity – refers to the operational measures that are used, and if they are representative for the concepts that are being studied.

Internal validity – refers to the design of the study, and to what extent a researcher can draw the conclusions the researcher was interested in drawing. A simple example could be if a pharmaceutical given to a patient was actually the reason for the patient’s recovery. In this situation, it can be internally invalid because it failed to compensate for the factor of natural healing.

External validity – relates to if a result of a study can be applied to circumstances outside the specific setting in which the research was carried out.

Reliability – relates to if a study can be repeated with the same results. The goal of reliability is to minimize the errors and biases in a study.

A summary of how to increase validity and reliability and in what phases they can be influenced is given in Table 2.
Table 2: Validity and reliability in case studies (Yin, 1994).

<table>
<thead>
<tr>
<th>Tests</th>
<th>Case study tactic</th>
<th>Phases of research in which tactic occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construct validity</td>
<td>• Use multiple sources of evidence</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>• Establish chain of evidence</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>• Have key informants review draft case study report</td>
<td>Data collection</td>
</tr>
<tr>
<td>Internal validity</td>
<td>• Do pattern matching</td>
<td>Data analysis</td>
</tr>
<tr>
<td></td>
<td>• Do explanation building</td>
<td>Data analysis</td>
</tr>
<tr>
<td></td>
<td>• Do time-series analysis</td>
<td>Data analysis</td>
</tr>
<tr>
<td>External validity</td>
<td>• Use replication logic in multiple-case studies</td>
<td>Research design</td>
</tr>
<tr>
<td>Reliability</td>
<td>• Use case study protocol</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>• Develop case study data base</td>
<td>Data collection</td>
</tr>
</tbody>
</table>

Regarding the issue of reliability, Table 3 illustrates the strengths and weaknesses in the different methods of collecting empirical data (Yin, 1994).

Table 3: Strengths and weaknesses in the different sources of evidence (Yin, 1994).

<table>
<thead>
<tr>
<th>Source of Evidence</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation</td>
<td>• stable - repeated review</td>
<td>• retrievability - difficult</td>
</tr>
<tr>
<td></td>
<td>• unobtrusive - exist prior to case study</td>
<td>• biased selectivity</td>
</tr>
<tr>
<td></td>
<td>• exact - names etc.</td>
<td>• reporting bias - reflects author bias</td>
</tr>
<tr>
<td></td>
<td>• broad coverage - extended time span</td>
<td>• access - may be blocked</td>
</tr>
<tr>
<td>Archival Records</td>
<td>• same as above</td>
<td>• same as above</td>
</tr>
<tr>
<td></td>
<td>• precise and quantitative</td>
<td>• privacy might inhibit access</td>
</tr>
<tr>
<td>Interviews</td>
<td>• targeted - focuses on case study topic</td>
<td>• bias due to poor questions</td>
</tr>
<tr>
<td></td>
<td>• insightful - provides perceived causal inferences</td>
<td>• response bias</td>
</tr>
<tr>
<td></td>
<td>• incomplete recollection</td>
<td>• reflexivity - interviewee expresses what interviewer wants to hear</td>
</tr>
<tr>
<td>Direct Observation</td>
<td>• reality - covers events in real time</td>
<td>• time-consuming</td>
</tr>
<tr>
<td></td>
<td>• contextual - covers event context</td>
<td>• selectivity - might miss facts</td>
</tr>
<tr>
<td></td>
<td>• time-consuming</td>
<td>• reflexivity - observer’s presence might cause change</td>
</tr>
<tr>
<td></td>
<td>• cost - observers need time</td>
<td>• cost - observers need time</td>
</tr>
<tr>
<td>Participant</td>
<td>• same as above</td>
<td>• same as above</td>
</tr>
<tr>
<td>Observation</td>
<td>• insightful into interpersonal behaviour</td>
<td>• bias due to investigator’s actions</td>
</tr>
<tr>
<td>Physical Artefacts</td>
<td>• insightful into cultural features</td>
<td>• selectivity</td>
</tr>
<tr>
<td></td>
<td>• insightful into technical operations</td>
<td>• availability</td>
</tr>
</tbody>
</table>
2.4 Case Study Design

In the previous section of this chapter, the general theory regarding the design of the case study was presented. In this section and forward, the case study design of this dissertation will be explained and related to the general case study methodology theory. After the presentation of the general methodology, there will be a review of the choice of methodology in terms of validity and reliability.

2.4.1 Formulation of the Research Questions and Propositions

As previously stated, the purpose of the design of a research methodology is to support the purpose and the research questions of a study (Yin, 1994). The research made for this study is based on empirical data gathered linked to several case studies of different remanufacturing companies, as well as previously documented research in the area of remanufacturing. The research has its foundation in empirical data, and links are made to the existing theoretical base; hence, it follows a pattern of inductive reasoning. Inductive reasoning is based on a transition from specific observations to broader generalizations and ultimately theories. This is also called a “bottom-up” approach. In inductive reasoning, one begins with specific observations and measures, detecting patterns and regularities, formulating some tentative hypotheses that one can explore, and finally developing some general conclusions or theories (Hartman, 1998).

The purpose of the design of a research methodology is to support the purpose and the research questions of a study (Yin, 1994). The research questions for this study have been motivated both from an academic and industrial perspective in the introductory part of this dissertation. The formulated research questions are as follows:

RQ 1: What are the drivers for companies to remanufacture products?

RQ 2: What strategies can be used for balancing returns of products suitable for remanufacturing with demand for remanufactured products?

RQ 3: What types of relationships exist between customer and remanufacturer, and what specific characteristics can be found in these relationships?

RQ 4: How is the organisation of the remanufacturing phases and the decisions taken linked to the remanufacturing process?

RQ 5: How can lean principles for material planning and production planning be applied for remanufacturing?

RQ 6: What principles for material handling can be suitable in the reassembly phase?

Yin (1994) proposes that a case study approach is feasible if the research questions focus on “how and why” questions (see Table 1). Merriam (1994) also concludes that case studies are most suitable if the problems at hand are complex and demand a
holistic view of a specific issue. Yin also states that case studies are appropriate if the investigator has little control over events, and when the focus is on a contemporary phenomenon within some real-life context. According to the reasons given by Yin and Merriam for the choice of case studies, such a methodology seems to be the best choice. Another advantage with case studies is that a holistic view of the problems at hand can be taken, something that is considered essential when conducting research on the remanufacturing system. Based on the considerations above, a case study approach was chosen for this research.

Before the data collection began, the research questions were broken down into interview questions. The formulation of the interview questions can be seen in the Appendix section (see Table 6 for the linkage between the research questions and interview questions). Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions. The interview questions were reviewed and given feedback on by the research group linked to the research project (REKO, 2006).

Following the formulation of the questions, a pilot study was made to verify the validity and relevance of the questions. The main source of data for the case studies were semi-structured interviews, which were recorded. The length of the interviews varied from 1 to 4 hours, depending on how much information the interviewees contributed. The questions formulated for this type of study are normally open to give the respondents a chance to go into detail regarding the answers, i.e. the questions were prepared without specific sequence or answering options (Jacobsen, 1993). In each case, the interviews focused on specific areas of the remanufacturing systems, and an individual interview was held on each of these topics. The general topics for the interview questions had the following working titles (see further details in Appendix A):

- External logistics
- Production processes
- Remanufacturing characteristics
- Internal material handling
- Production planning
- Remanufacturing economics

Typically, the interviewees were facility managers, production managers, controllers and technicians. Other sources of data were direct observations made under the study visits to the companies, as well as documentation in the form of photographs, brochures and information from the Internet (independent as well as issued from the case companies). These sources were mainly used for data triangulation.

2.4.2 Determining the Unit of Analysis

The empirical data for this study is linked to the research project “REKO” (2006), and employs an explanatory, multiple-case study concerning multiple types of products.
The case company selection was made from companies that were found in the study of 
the remanufacturing industry in Sweden (Sundin et al., 2005). In this study, a 
multitude of potential companies were found. The choice of case companies was made 
based on variables concerning their annual remanufacturing volumes, relation to 
OEMs, product complexity and remanufacturing process. An attempt was made in the 
project to obtain as wide a distribution between the remanufacturing companies as 
possible, the reason being to gain as wide an empirical base as possible for theory 
generalisation purposes.

According to Eisenhardt (1989), there is no ideal number of cases, though a number 
between 6 and 10 is good for theory building. Empirical data was gathered primarily 
from different Swedish remanufacturing companies. The companies selected for the 
case studies are listed in Tables 4 and 5. In these tables, the size of the company is 
described according to its annual turnover.

Table 4: The primary companies in the study (REKO, 2006).

<table>
<thead>
<tr>
<th>Case Company</th>
<th>Size of the company</th>
<th>Remanufactured Products</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Industries</td>
<td>Large</td>
<td>Forklift trucks</td>
<td>OEM</td>
</tr>
<tr>
<td>Scandi-Toner</td>
<td>Small</td>
<td>Toner cartridges</td>
<td>Independent</td>
</tr>
<tr>
<td>Swepac International AB</td>
<td>Medium</td>
<td>Soil compactors</td>
<td>OEM</td>
</tr>
<tr>
<td>Tetra Pak and Wahlquists Verkstäder</td>
<td>Large</td>
<td>Filling machines</td>
<td>OEM</td>
</tr>
<tr>
<td>Volvo Parts</td>
<td>Large</td>
<td>Engines</td>
<td>OEM</td>
</tr>
<tr>
<td>UDB Cleantech</td>
<td>Medium</td>
<td>Automotive components</td>
<td>Contracted and independent</td>
</tr>
</tbody>
</table>

To further validate the findings of the case study, additional (interview) studies were 
performed at the following companies:

Table 5: The companies studied for further validation.

<table>
<thead>
<tr>
<th>Company</th>
<th>Size of the company</th>
<th>Remanufactured Products</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfa Laval</td>
<td>Large</td>
<td>Heat exchangers</td>
<td>OEM</td>
</tr>
<tr>
<td>Bättre Kontor</td>
<td>Small</td>
<td>Office furniture</td>
<td>Independent</td>
</tr>
<tr>
<td>Greenman Toners</td>
<td>Small</td>
<td>Toner cartridges</td>
<td>Independent</td>
</tr>
<tr>
<td>Inrego</td>
<td>Medium</td>
<td>Computers</td>
<td>Independent</td>
</tr>
<tr>
<td>Scania</td>
<td>Large</td>
<td>Engines</td>
<td>OEM</td>
</tr>
<tr>
<td>Turbo Tech</td>
<td>Small</td>
<td>Turbo chargers</td>
<td>Independent</td>
</tr>
</tbody>
</table>

It was found that these case companies were sufficient for this study, since they 
provided good in-depth knowledge to fulfil the purpose of the study. Further cases 
would take to much time to investigate. According to Voss et al. (2002), this skill of 
“knowing when to stop” is an important skill in theory building form case studies.
2.4.3 Interpreting the Findings

To find answers to these research questions, the main empirical data was gathered in the REKO study. The findings for each research question were also published in academic journal papers and conferences. These research results are presented in Papers I - VII. The way these individual papers are linked to the research questions and to the specific interview questions is summarised in Table 6 and described in the following paragraphs.

Table 6: Characteristics of the research questions, papers and the case studies linked to them.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Research question</th>
<th>Type of case study</th>
<th>Number of cases</th>
<th>Interview questions (see appendix)</th>
<th>Main theoretical analysis model</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1 Exploratory</td>
<td>Multiple</td>
<td>42-43, 61</td>
<td>Customer Value, Basic Marketing Theory</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>2 Explanatory</td>
<td>Multiple</td>
<td>14, 18-25, 47-48, 70-73</td>
<td>The product lifecycle</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>3 Exploratory</td>
<td>Multiple</td>
<td>5-27, 43-46</td>
<td>Typologies of core returns, General supply chain management theory</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>4 Descriptive</td>
<td>Multiple</td>
<td>29, 36-38, 49, 54-56, 74-83</td>
<td>Process mapping</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>5 Exploratory</td>
<td>Multiple</td>
<td>28-32, 49-63, 66-69, 84-124</td>
<td>Lean principles, Remanufacturing characteristics</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>5 Exploratory</td>
<td>Single</td>
<td>28-32, 49-63, 66-69, 84-124</td>
<td>Lean principles, Remanufacturing characteristics</td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>6 Exploratory</td>
<td>Single</td>
<td>64-66, 74-83, 84-92</td>
<td>The AC-Model for material control. General material handling theory</td>
<td></td>
</tr>
</tbody>
</table>

For research questions 1 to 5, the empirical results are based on all the REKO cases, whereas research question 6 is based on a single case from the REKO study (Volvo Parts), as shown in Table 6. For research questions 1, 5 and 6, the case studies are of an exploratory nature. The main reason for this is the lack of previous related literature found in the theoretical review. The main supporting theory for the research questions is given in Table 6. Regarding the analyses for these questions, they are mainly done with explanation building from the cases by analysing differences and similarities between the cases.

For research questions 2 and 3, the theoretical review provided more examples of cases and theory compared to the questions that demanded exploratory case studies.
Thus, there was a possibility to perform explanatory case studies. The analysis for the explanatory case study is also primarily based on explanation building, but it also contains some elements of pattern matching, especially for research question 2, where the patterns of the product lifecycle are analysed between the cases (see further about the product lifecycle in the theoretical framework and in Paper II).

The fourth research question is focused on describing the general remanufacturing process. In addition, for this question there are existing theories and previously described case studies to draw from. Since the question has a clear descriptive formulation, a descriptive case study approach was found appropriate. The analysis for this question is primarily based on identifying key factors and formulating a description of the general remanufacturing process. Therefore, the analysis is, in its major parts, based on pattern matching, i.e. trying to formalise a general process that corresponds to all of the cases.

2.5 Validity and Reliability in the REKO Case Study

To evaluate the research performed, one important aspect is to critically assess the validity and the reliability of the study. The first question that regards the validity of the study is the choice of scope, that is, if the purpose of the study is worth pursuing and if the research questions have been correctly formulated.

2.5.1 Formulation of the Research Questions

Before the REKO-project started, there was a formal research grant application process by a Swedish research council, the “Swedish Governmental Agency for Innovation Systems (VINNOVA)”. In this process, the formal research proposal was evaluated based on its relevance for both academic and industry stakeholders. Given that the research grant was approved provides strong evidence that the research plan has a valid scope. After the REKO project was initiated, a vast theoretical review was performed, the purpose of which was to identify gaps in the existing research that required further attention. By conducting the theoretical review, the scope of the research question was further validated. For the formulation of the specific interview questions, the researchers in the REKO project used each other as reviewers.

After the reviewing process, a pilot study was also performed for further evaluation of the interview questions. The review and the pilot study aims to increase the correspondence between the formulation of the interview questions and the underlying area of interest. Since the questions were semi-structured, there was still high flexibility for the respondent to expand on specific issues, as well as possibilities for the researcher to pursue additional interesting observations. Since the case study has exploratory and descriptive areas, it was also concluded that the freedom in the respondent answers is a major factor for the success of the study. All the interviews were recorded to maintain the possibly for the researchers to review details if necessary. During the project, there were some interviews that lead to some specific
questions that demanded special attention; for these questions, additional case-dependent studies were created. These case studies were more company-based, and provided further knowledge regarding individual situations, and how such situations can contribute to a general problem. The lack of generality in the single-case studies are therefore compensated by an additional level of detail. The validity of the additional case studies at the company has a pragmatic approach, and the scope of these studies was developed in consensus between the researchers and the companies. For further descriptions of the methodology for the individual case studies, see the related publications.

2.5.2 Determining the Unit of Analysis
To find appropriate companies for this specific case study, a background study was made with a focus on mapping the remanufacturing industry in Sweden (Sundin et al., 2005). From this study, a number of companies were identified. After that, a small empirical data collection was made through semi-structured interviews with a dozen companies; these interviews were conducted via telephone and ranged from 10 to 30 minutes in length. In addition, theoretical models and documentation from both brochures and the Internet were used. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and the extent of the remanufacturing process. After the study, a consensus scoring method was used to choose the case companies.

2.5.3 Interpreting the Findings
After the case studies were performed, the analysis of the results was initiated. One major difficulty in the analysis part is the potential biases that might exist both in the researchers’ and the respondents’ minds. For the researcher, the danger is linked to anticipated results, meaning that the researcher might have a previous vision of the results and attempt to match the collected data with that perception. A serious effect of this can be faulty conclusions and of the inability to identify important aspects. To reduce this risk, all the key informants from the case companies have reviewed the manuscripts for the papers in this dissertation. In this way, the validity of the conclusions has been further validated.

For the analysis itself, the previous knowledge and experience of the researcher has a major impact on the level of detail. The lack of theoretical knowledge in some areas might have limited the depth of the analysis, although this is a common problem in all types of research. For this study, the analysis was based on a number of theoretical areas that were found suitable. (For a detailed linkage between the research questions and the theoretical models that were used for the analysis, see Table 6.) In the respondents’ case, the major risk for bias in an interview situation is that the respondents answer with what he/she thinks is correct, and not according to actual practice. One way to reduce this bias is to ask the same question to multiple of respondents in the specific case company, and then see if the answers correlate. This was also done with a number of the interview questions. Another way is to use different data collection methods, and not only rely on interviews. In this study, other
sources of data were direct observations made under the study visits to the companies, as well as documentation in the form of photographs, brochures and information from the Internet (independent as well as issued from the case companies).

2.5.4 Discussion
The use of case studies as a source of theory generalisation has been a debated subject in the academic community (Yin, 1994). To summarise, the use of case studies as theory generation is most advantageous when the existing theory base is relatively small. This is also something that is relatively true for remanufacturing as an academic subject. To increase the general validity, a multiple case study approach was taken. This enabled the use of a cross-case analysis. The choice of case companies also influenced the possibility to generalise. In this study, the companies’ annual remanufacturing volumes, relation to OEMs, process complexity, and industrial branch were vastly different. The differences between the case companies were chosen with the aim to increase the external validity, that is, the possibility that the conclusions also apply in other industry settings. In respect to the positive effects of a vide array of companies from different industry sectors, there can also be a disadvantage for the level of detail. This negative effect is based on the fact that valid conclusions in respect to one industry are discarded due to opposing findings in another industry sector. The result can therefore be that the details of the conclusions made are described on such an aggregated level that they lose the appropriate level of detail. As this study had limited resources, the further investigations in specific industry sectors are referred to as potential future research. Another important issue that can have an impact on the conclusions is the use of companies with a Swedish origin. This can result in that different cultural aspects are neglected. Still, these effects are not seen as a major problem, since the majority of the companies are working in a global or at least in a European perspective.
THEORETICAL FRAMEWORK

In this chapter, the theoretical framework will be presented. As this dissertation focuses on the remanufacturing system from a holistic perspective, the discussion about the relevant theory will focus on a more general level, opposed to giving detailed explanations of specific areas of the remanufacturing. Generally, for detailed discussions, references will be given to the reader for further exploration in the related appended papers.

The structure of the theoretical framework is as follows. Firstly, remanufacturing will be addressed as a product recovery activity. The aim in the first part of the theory is to put remanufacturing on the “product recovery map”. Thereafter, the differences between remanufacturing and ordinary manufacturing will be further expanded, to provide a discussion for the forthcoming detailed discussions. The second part will principally address the external processes that are specifically linked to research questions 2 and 3. In this part of the theoretical framework, the issues of balancing the supply of cores for remanufacturing and demand for remanufactured products in relation to the product lifecycle will be addressed. The third part of the theoretical framework will address the internal processes that influence the remanufacturing process linking theory to research questions 4, 5 and 6.

3.1 Product Recovery Options

Products can be recovered in many ways, and this recovery can be performed at different levels. For example, at a lower level, it could be the product materials that are recovered. In this situation, it is often called “material recycling”. Product recovery on a higher level, where product, components or modules are reused, is often called “remanufacturing”, “reconditioning” or “refurbishment”. Hence, remanufacturing not only promotes the multiple reuse of materials, but it also allows for the steady upgrading of product quality and functionality, and does this without the need to manufacture completely new products and scrap used ones (Sundin 2004).
There exist many definitions for product recovery. An illustration of the linkage between different product recovery options can be seen in Figure 5. In reference to Figure 5, the following definitions can be found in theory:

**The installed base is...**

...the total number of placed units of a particular product in the entire primary market or product segment.

Krikke et al. (2004)

The following definitions of reuse, remanufacturing, reconditioning, refurbishment, component cannibalization and material recycling illustrate the complexity of describing the product recovery area:

**Reuse is...**

...the additional use of a component, part or product after it has been removed from a clearly defined service cycle.

(Keoleian et al., 1993).

**Reconditioning is ...**

... the process of restoring components to a functional and/or satisfactory state but not above original specification using such methods as resurfacing, repainting, sleeving, etc.

(Amezquita, 1996).
Refurbishment is …

... when a product is cleaned and repaired to return it to a ‘like new’ state.

(Rodgers et al., 1996).

Component cannibalization is …

... the process in which a limited number of components are extracted from a product for recovery.

(REVLOG, 1999).

Material recycling is …

... when a product is reduced to its basic elements, which are reused.

(Rogers et al., 1998).

Based on the definitions above, it is apparent that numerous definitions regarding product recovery can be found. The appropriate product recovery options are dependent on many factors and in many situations. This business aspect of remanufacturing and the situations where remanufacturing is advantageous will be discussed further in the following sections. The area of discussion in this section is what distinguishes the different product recovery options from remanufacturing.

The terms refurbishment and reconditioning are the product recovery options that relate the closest to remanufacturing. The product recovery process for refurbishment and reconditioning are similar to the one for the remanufacturing process; the main difference between them is the quality level of the products after recovery. The definition for remanufacturing given in this dissertation (see below) does not specify a specific quality standard regarding the original product, for example “as new” or “equal or better than new”. What it does say is that the “quality level desired by the customer” should be reached. In this dissertation, refurbishing and reconditioning terminology is not needed, as it is included in the definition for remanufacturing, which is stated as follows:

Remanufacturing is an industrial process whereby products, referred to as cores, are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, part reprocessing, reassembly, and testing to ensure it meets the desired product standards.

(Adapted from Sundin, 2004)

Another product recovery option that is close to remanufacturing is the reuse option. The main difference with remanufacturing is that the reuse does not involve any processing of the product. The processing of the product is in this case unnecessary since value of the product to the new consumer is sufficient. One similarity with the remanufactured and the reused product is that they are frequently sold in the same
marketplaces, and the quality of newer reused products can be in line with remanufactured products.

As a product recovery option, repairs are closer to the remanufacturing option. In the repair case, something is done to the product to put it in working order. The purpose of the repair operation is mainly to extend the product life for a low cost. In a normal situation when the product is broken down, the most frequent recovery option is to repair the product, since the functionality of the product is restored to working order with small inputs of resources as labour and new components. As a process, the repair is different from remanufacturing. In the remanufacturing case, the product is inspected to find potential weak components that might limit the quality level to be expected by the customer. In a repair operation, the identification process is limited to failure detection, and after failure detection, to restore the product to working order. From this perspective, the repair process can be considered as a craft and the remanufacturing operation as an industrial process. In addition, the warranty provided in the repair option is generally limited to the individual functions. In the case of remanufacturing, the warranty regards the entire product. Remanufacturing also creates the possibly to upgrade the product to future standards (Linton, 2005; Steinhilper, 1998).

**Figure 6:** The hierarchy of secondary market production processes (Ijomah, 2002).

A summary of the different product recovery operations of repair, reconditioning and remanufacturing is given in Figure 6. These options are ranked based on the work content that they typically require, the performance that can obtained from them and the value of the warranty that they normally supply.
3.2 **Product Life Cycle**

The concept of the “product life cycle” has been discussed widely in research (see the overview by Kotler, 2003). In the theory, at least two conflicting definitions about the product lifecycle can be found. The first refers to the progress of a product from raw material, through production and use, to its final disposal. The second definition of the product lifecycle, which will be used in this dissertation, describes the evolution of a product, measured by its sales over time, as seen in Figure 7.

![Product Life Cycle Diagram](image)

**Figure 7**: The product lifecycle for a VCR (Tibben-Lembke, 2002).

Every product passes through a series of phases in the course of its life, referred to as the product life cycle. The phases that a product goes through during its life cycle are the introduction, growth, maturity and decline stages (Cox, 1967). The product life cycle can be analysed on different levels from the main product type (product class) down to different product models; this is illustrated in Figure 1 (Tibben-Lembke, 2002). To use an example, consider the product class to be a VCR (Video Cassette Recorder). The components of the VCR also have their own life cycles, and are referred to as product form (in this example the 2-headed reader). Within the group of VCRs, there is also the development of different product models based on the 2-head technology, each with individual life cycles. In addition, the types of products can be divided into different types of categories according to technical innovation: (1) unquestionably new products, (2) partially new products, (3) major product changes and (4) minor product changes. The characteristics of the life cycle and its effects on the reversed supply chain have been discussed by Tibben-Lembke (2002), although it lacks a discussion on its effects on remanufacturing operations.

### 3.2.1 Forecasting Product and Component Returns

When the historical sales data (product distribution) is known, this data can be used as a basis for forecasting when these products are likely to be returned (product disposal distributions). Umeda et al. (2006) present a model based on empirical data from return rates for remanufacturing of a single-use camera and the remanufacturing of a
photocopier. In this model, a simple normal distribution function has shown sufficient results in predicting returns when using average life as an indicator for timing of returns. In the study by Umeda et al., the distribution of disposed products $S(t)$ is calculated as the historical sales data $D(t)$ over a limited timeframe $D(t)\Delta\tau$, distributed as a normal distribution function (NDist) with a standard derivation ($\sigma$) after an average usage time ($\mu$). This is illustrated in Figure 8 (Umeda et al., 2006):

Figure 8: Model of the linkage between the product distribution and the disposal distribution.

Another source of items suitable for remanufacturing is the components of a product. Here, the end product (e.g. a car) is not at its end-of-use but requires the exchange of a component to continue working properly (e.g. remanufacturing of the brake caliper). This disposal distribution of components (CD) is therefore a function of how many products there are in the market (the installed base (IB)) and the failure rate of the individual components $\lambda(t)$. This is shown in Equations 1 and 2 (Umeda et al., 2006):

$$IB(t) = \int_0^T D(\tau) - S(\tau)d\tau$$
$$CD(t) = IB(t) \times \lambda(t)$$

Potts (1988) defines the number of products in the installed base as follows:

*The installed base consists of the difference between total shipments and total 'decay' - that is, the reduction in number still in use.*

(Potts, 1998)
The relations between the different distributions are illustrated in Figure 9. In this figure, the upper line is the total amount of products on the market (the installed base). The installed base is the sum of the produced products to a given time subtracted by the sum of the disposed products during the given time (see Equation 1). Linked to the formulations of these distributions, Umeda et al. (2006) present a framework for product reuse based on three possible reuse scenarios: (1) product installation reuse, (2) spare part reuse from maintenance, and (3) Spare part reuse from disposed products.

The functions of the different distributions (production distributions, product disposal distribution, and component disposal distributions) can take many different forms, mainly depending on some key factors, where the average use period and the failure rate of individual components have the major impacts. As an example of the impact of the average usage period, Umeda et al. (2006) present real case data for two fundamentally different cases. The first case is a single use camera with a very short average usage period (4.2 months). In this case, the potential to remanufacture the products is very good, and more or less all of the products that are returned can be reused as seen in Figure 10.

The second case is a photocopier where the average usage period is about 7.6 years (see Figure 11). In the photocopier case, the potential for remanufacturing in the same
product version is limited to about 15%. If it is possible to remanufacture products and upgrade them to the next product version, the situation becomes more advantageous with 45% as illustrated in Table 7. This table illustrates the possible remanufacturing volumes as a percentage of the disposal distribution when products can be upgraded to a higher product version.

![Figure 11: Linkage between historical sales data and collected products for photocopiers. Adapted from Umeda et al. (2006).](image)

**Table 7:** Percentage of possible remanufacturing volumes when products can be upgraded to a higher product version from an earlier type of product.

<table>
<thead>
<tr>
<th>To</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>46.2%</td>
<td>14.5%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>24.4%</td>
<td>46.2%</td>
<td>14.5%</td>
</tr>
</tbody>
</table>

The disposal distributions in the Umeda *et al.* study are linked to end-of-use, end-of-life and reusable components, but there are also additional sources of cores that can be good sources for remanufacturing. Krikke *et al.* (2004) present commercial returns as another category, i.e. returns that are linked to the sales process. For a further discussion, see the forthcoming section regarding the different sources of cores for remanufacturing.

This previous research shows that the product life cycle and the technical and economic issues linked to the life cycle have a major impact on the ability to balance the returns and demand for remanufactured products. The characteristic of the life cycle provides a theoretical foundation regarding the possibilities of acquiring used products suitable for remanufacturing.
Different companies in different industries will apply different relations with the suppliers of the cores to get a sufficient number of cores for their remanufacturing operations. This is further developed in Paper III. Guide et al. (2000) present a number of management propositions on what to focus on when trying to balance the supply and demand for remanufacturing. Regarding core (used products or components) acquisition, one of the most important issues is to focus on identifying different sources of cores and rating them according to their characteristics. Forecasting core availability is critical in order to balance supply and demand. This reduces the need to purge the system of excess cores and reduces stock-outs of unavailable units. Managers should also try to synchronise return rates with demand rates, since doing so will lower the overall uncertainties in the system and lead to lower overall operating costs.

### 3.3 Closed-Loop Supply Chain

From a supply chain perspective, the logistical system regarding product recovery operations can be referred to as the closed-loop supply chain. As described earlier, the traditional view of the closed-loop supply chain is that it encompasses two distinct material supply chains: the forward and the reverse. Generally, the forward chain concerns the flow of physical products from producer to customer, while the reverse chain describes the flow of physical products from customer to producer. These flows are then “closed” by, for example, the remanufacturing operation (Krikke et al., 2004).

A reversed logistic flow is very different from the forward flow. In the forward flow, forecasts of future sales are used to project future requirements. At each level in the forward flow, forecasts can be used to help predict what will be needed. The scheduled incoming products to different levels in the supply chain can also be tracked, and the visibility of incoming products is high. In the reversed supply chain, the situation is different. Generally, the handling of returns is more reactive, with much less visibility. Reversed logistics activities are generally not initiated by companies’ planning and decision making. Instead, reversed logistic processes are generally initiated by the actions of customers or downstream channel members. In Table 8, a framework is presented with the basic differences between the forward and the reversed supply chains (Tibben-Lembke et al., 2002).
Table 8: Differences between forward and reversed supply chains (Tibben-Lembke et al., 2002).

<table>
<thead>
<tr>
<th></th>
<th><strong>Forward</strong></th>
<th><strong>Reversed</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecasting</td>
<td>Forecasting relatively straightforward</td>
<td>Forecasting more difficult</td>
</tr>
<tr>
<td>One-to-many transportation</td>
<td>One-to-many transportation</td>
<td>Many-to-one transportation</td>
</tr>
<tr>
<td>Product quality uniform</td>
<td>Product quality uniform</td>
<td>Product quality not uniform</td>
</tr>
<tr>
<td>Product packaging uniform</td>
<td>Product packaging uniform</td>
<td>Product packaging often damaged/missing</td>
</tr>
<tr>
<td>Destination/routing clear</td>
<td>Destination/routing clear</td>
<td>Destination/routing unclear</td>
</tr>
<tr>
<td>Standardised channel</td>
<td>Standardised channel</td>
<td>Exception driven</td>
</tr>
<tr>
<td>Disposition options clear</td>
<td>Disposition options clear</td>
<td>Disposition not clear</td>
</tr>
<tr>
<td>Pricing relatively uniform</td>
<td>Pricing relatively uniform</td>
<td>Pricing depends on many factors</td>
</tr>
<tr>
<td>Importance of speed recognised</td>
<td>Importance of speed recognised</td>
<td>Speed often not considered as a priority</td>
</tr>
<tr>
<td>Forward distribution costs closely monitored by accounting systems</td>
<td>Forward distribution costs closely monitored by accounting systems</td>
<td>Reverse costs less directly visible</td>
</tr>
<tr>
<td>Inventory management consistent</td>
<td>Inventory management consistent</td>
<td>Inventory management not consistently</td>
</tr>
<tr>
<td>Product life cycle manageable</td>
<td>Product life cycle manageable</td>
<td>Product life cycle issues more complex</td>
</tr>
<tr>
<td>Negotiation between parties straightforward</td>
<td>Negotiation between parties straightforward</td>
<td>Negotiation complicated by additional consequences</td>
</tr>
<tr>
<td>Marketing methods well-known</td>
<td>Marketing methods well-known</td>
<td>Marketing complicated by several factors</td>
</tr>
<tr>
<td>Real-time information readily available to track product</td>
<td>Real-time information readily available to track product</td>
<td>Visibility of processes less transparent</td>
</tr>
</tbody>
</table>

3.4 **Sources of Cores**

In the closed-loop supply chain, there are four main types of returns that can be a source of cores for remanufacturing (Krikke et al. 2004):

- **End-of-Life Returns.** These are returns that are taken back from the market to avoid environmental or commercial damage. These products are often returned as a result of take-back laws. These types of returns are often linked to electrical end electronic waste, end-of-life vehicles, packaging, batteries, tires, and construction waste. Normally, these products end up being recycled or placed in landfills.

- **End-of-Use Returns.** These are used products or components that have been returned after use by a customer. They are returned, for example, when a lease is terminated, with a trade-in, or when a product is replaced. These products are normally traded on an aftermarket or remanufactured.

- **Commercial Returns and Secondary Channel Goods.** These are returns that are linked to the sales process. These products can be returns from customers that return their products shortly after sales. Other reasons for the returns include problems with products under warranty or a product recall.
• **Re-Usable Components.** These returns are related to consumption, use, or distribution of the main product. This type concerns many different products, for example refillable cartridges, pallets, bottles and reusable containers. The common characteristic is that they are not part of the product itself, but contain and/or carry the actual product. For example, toner cartridges are frequently returned for remanufacture.

### 3.4.1 End-of-Use and Re-Usable Component Returns

Previous research has reported different systems and techniques for gathering cores for remanufacturing. A common observation is that off-lease and off-rent products are an important source of used products for remanufacturing. Thierry *et al.* (1995) have concluded that this type of return is more predictable than other types of returns due to the additional information that is available to the remanufacturing company. In the automotive industry, there is widespread use of “exchange cycles” where products are only sold if a core is given back (Seitz and Peattie, 2004). In this scenario, the customer must first act as a supplier of a core in order to become a customer of a remanufactured product. Other reported systems are voluntary, where e.g. the supplier freely returns the cores to a remanufacturer or where the cores are bought from core brokers or end customers. The company Lexmark uses a “prebate” program giving a discount on a product if the customer agrees to the return the product after use; this program prohibits the customers from returning or selling their used products to other companies.

The products returning from this category have not been addressed widely, and there is a clear research need to identify the linkages of these types of returns and how they may be acquired by remanufacturers. This research need is addressed by the formulation of Research Question 3.

### 3.4.2 Commercial Returns and Secondary Channel Goods

Commercial Returns and Secondary Channel Goods refer to returns that are linked to the sales process or products that newer leaves the sales process. These products can be returns from customers that return their products shortly after sales. Other reasons for the returns include problems with products under warranty or a product recall. The normal path for a product, as preferred by retailers and manufacturers, is shown by the solid lines in Figure 12.
The flow of products originates from the factory, travelling from the manufacturer distribution center to the retailer to the store, where it is can be sold to the customer. Some of the products are never sold to the customer, however; these products are sent through the reverse supply chain to an overstock broker. Some products can be sold and returned by the customer to the store; these reversed flows can be quite extensive, and for commercial returns in general, approximately 6% of all retail purchases are returned (Tibben-Lembke, 2004). When products are returned they are resold if possible, or they might be sent back in the reverse supply chain to a returns center. If no new customers can be found for a returned product, the last resolution is to sell the product to a salvage broker or send it to a landfill. When a product is sold outside the primary marketing channel, it enters what is known as the secondary market, illustrated in Figure 12 (Tibben-Lembke, 2004). As a complement to commercial returns, Guide et al. (2000) also reports “seed stock” as a possible solution for core acquisition. Seed stock is composed of products that failed OEM specifications at the manufacturing plant. These products can provide a fruitful source of cores for remanufacturing. In Table 9, the different sources of potential cores that can be used for remanufacturing and cannibalisation for components is presented. However, the possibility for independent remanufacturing companies to acquire commercial returns and secondary channel goods can be limited due to their frequent competition with OEMs (Hammond et al., 1998).

Table 9: Type of products in the secondary channel. (Tibben-Lembke, 2004).

<table>
<thead>
<tr>
<th>New Product in Secondary Market</th>
<th>Product that Cannot Be Sold as New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overproduction or Cancelled Orders</td>
<td>Second Quality or Irregular</td>
</tr>
<tr>
<td>Stock Balancing Returns</td>
<td>Freight or Insurance Damage</td>
</tr>
<tr>
<td>Shelf Pulls</td>
<td>Recalls</td>
</tr>
<tr>
<td>Marketing Returns</td>
<td>Customer Returns</td>
</tr>
<tr>
<td>Packaging Change</td>
<td>Used or Secondhand Product</td>
</tr>
<tr>
<td>End-of-Life Closeouts</td>
<td></td>
</tr>
<tr>
<td>End-of-Season Closeouts</td>
<td></td>
</tr>
</tbody>
</table>
3.5 The Remanufacturing Process

The process within which the used product is remanufactured is called the remanufacturing process. It is an industrial process where the core (defined as a used/broken product that is suitable for remanufacturing) is being returned to the remanufacturer where it passes through the typical steps of the remanufacturing process. A general remanufacturing process is illustrated in Figure 13:

![Diagram of remanufacturing process](image)

Figure 13: The generic remanufacturing process (Sundin, 2004).

When a core goes through a remanufacturing process, it may pass through a number of specific operations. In no specific order, these are (Sundin, 2004):

- Inspection
- Cleaning
- Storage
- Disassembly
- Reprocessing
- Reassembly
- Testing

The model in Figure 13 shows that the order of these operations is not defined, and that this order of operations is in fact dependent on the situation. Another important issue is that not all of these operations have to been undertaken in order to be classified as a remanufacturing process. As an example, the scheme in Figure 14 demonstrates the order of the operations in a remanufacturing process for home appliances.
Steinhilper (1998) arranges the process in the order of disassembly, cleaning, inspection, reconditioning, reassembly and testing. Disassembly and cleaning of used products/components can be viewed as new technologies on the industrial level, where industry itself has a pioneering role in setting new standards and creating new solutions. In disassembly, the product is disassembled to the single component level. The components are first identified and inspected, and the decision is made whether the individual components are reprocessable, can be reused in their current state or if they should be scrapped or recycled. Oil, dirt and rust can complicate disassembly operations and call for new solutions to be developed. Automation is rare, even though some experiments with robots have taken place in recent years. In the disassembly processes, the cores can also be cannibalized for components. Component cannibalization is when components are separated from the core and used to repair or rebuild another unit of the same product (Rogers et al., 1998). Thereafter, during inspection, it is decided if and how the components should be reprocessed. The uncertainty of the quality of a core, i.e. how many of its components can be recovered, is measured using the metric Material Recovery Rate (MRR) Equation (3) below (Guide 2000).

$$MRR = \frac{\text{Number of reusable components}}{\text{Number of total components}}$$  \hspace{1cm} (3)

According to (Steinhilper, 1998), the cleaning operation is the most time consuming, and entails much more than just removing dirt; it also means de-greasing, de-oiling, de-rusting and freeing components from paint. For this complex task, several methods have been developed for both sequential and concurrent execution, including sandblasting, steel brushing, baking ovens, cleaning petrol, chemical and hot water baths, etc. Following the cleaning operation, reprocessing has the aim of repairing or increasing the quality of the core. Geometrical change of the components through
metal cutting like grinding will change the dimensions. Sometimes after reprocessing, for example, a highly worn-out product will not match the standard tolerance, such as the diameter of a crankshaft, and must be scrapped. In the reassembly operation, the separated components are assembled. Reassembly can be done with components that are either reused, reprocessed, taken from previous cores (i.e. cannibalised components) or new components. The reassembly of components is often done with power tools and assembly equipment as in new product assembly. Thereafter, the final testing of the product is executed. During the reprocessing and operations, the component’s quality is continuously assured through applied measurements (Steinhilper, 1998).

Bras and Hammond (Sundin 2004) use an aggregated categorization of cleaning, damage correction, quality assurance (inspection and testing) and component interfacing (disassembly and reassembly). Arranging the steps in a standardized order, however, could be misguided, since every remanufacturing process is unique. For example, inspection should be performed before disassembly and cleaning in order to prevent cores with too many fatal errors from entering the production flow; conversely, inspection could be performed with greater detail after the core has been cleaned (Sundin, 2004).

3.6 Remanufacturing Characteristics

As mentioned in the introduction, the remanufacturing environment is very different to the traditional manufacturing environment of the same products. In previous research, seven characteristics of differences between remanufacturing and manufacturing have been observed (Guide, 2000). In all, these characteristics add different kinds of complexity and uncertainty in the remanufacturing process. In this section, these characteristics will be discussed.

3.6.1 Need to Balance Returns with Demand

In order to generate profit, the aim of a remanufacturer is to balance the return of cores to the demand of remanufactured products. It is also important for avoiding excessive inventory generated by exceeding returns, and low service levels generated by exceeding demand. Both problems of excessiveness and scarcity of cores are observed by Guide. To balance returns and final demand, a forecast or a real rate of demand can be used, or a mix of them. When only using real demand, the effects of demand uncertainty and lead times are buffered against by the use of work in process inventories. As it is reliant upon the quantity and condition of the cores, balancing problems affect the resource planning, materials management and lot sizing of replacing components, as well as production decisions such as scheduling (Guide, 2000).
3.6.2 Uncertain Timing and Quantity of Returns

The timing and amount of returned cores, caused by the uncertainty of the product’s life cycle and its rate of technological change, make the return process most uncertain. In the early phase of a product’s life cycle, there are few cores available on the market since few products are returned, making cores expensive. In the later phase, demand and supply become more balanced, and in the end of the life cycle there will be an excessive supply of cores and the price will fall (Steinhilper 1998). These problems should be suppressed by forecasting for planning purposes, and the forecast should be compared to the demand forecast. Activities to repress these problems are mainly core deposit systems, which generate a core when a manufactured product is sold. However, this reduces only the uncertainty of quantities returned. Due to variation of core supply and variability of demand, remanufacturers hold high levels of inventory (Guide, 2000).

3.6.3 Disassembly of Returned Products

The criticality of disassembly operations is significant since, they affect materials management, resource planning and production scheduling and control as well as shop floor control. If not coordinated with other functionalities, disassembly operations may lead to high inventories and poor customer service. Information from the disassembly phase for purchasing decisions is critical to ensure the supply of new parts. Disassembly activities are highly labour-intensive, and no optimal automated techniques are found in the literature. The coordination of disassembly and the remanufacturing shop is of high importance; to decrease and grant reactive lead times, planners have great responsibility to release disassembled parts to reprocessing in adequate time and quantity. The operations time required for disassembly has a high variability, ranging from minutes to weeks. Even within the same product group the average time is variable, with such a high coefficient of variance as 5.0. Due to this uncertainty, predicting production flow and lead times is difficult. (Guide, 2000)

3.6.4 Uncertainty in Materials Recovered from Returned Items

The uncertainty of the quality of a core, how many of its components that can be recovered, is forecasted by using the metric Material Recovery Rate (MRR) shown in Equation 3 (Guide 2000). A remanufactured product is generally estimated to consist of one third replacement parts. The MRR forecasts are often applied when determining batch sizes for purchasing and manufacturing. Simple methods to forecast the MRR, like an average, are most common in the industry but more refined regressive models are also employed. The options of input data to calculate the MRR use historical and statistical data or the procurer’s or planner’s subjective estimation, where the former is most common. When deciding on the size of purchase batches, dynamic lot sizing techniques are the most common; these are based on price, historical and statistical consumption patterns and service levels (Guide, 2000).

A number of problems have been identified in the purchasing process: uncertainty in demand, long lead times, and single suppliers for components and diminutive purchase
orders, which lead to unresponsive suppliers. Lead times are highly variable, varying from 0.5 weeks to 90 weeks, and purchased parts are a common origin of late orders (Guide, 2000).

3.6.5 Requirement for a Reverse Logistics Network
A network for collecting cores from the end user and returning them to the facility is a key function for balancing demand and return. Core acquisition ensures the adequate supply of cores. In the automotive industry, where the incentives for a customer to return the products, e.g. an engine, are high due to its high-value items, the trade organization is well-established, whereas in other industries it is not. It is common to call for a trade-in when the customer purchases a new engine, and a kind of exchange system is employed. The other options are core brokers, who serve as intermediaries for core collectors, third-party agencies, who arrange for the exchange of cores, and leasing and possibly also seed stock. Seed stock, consists of products that originally failed OEM specifications at the manufacturing plant (Guide, 2000).

3.6.6 Complication of Material Matching Restrictions
When the customer retains the ownership of the product and wants the same remanufactured unit back, something practiced e.g. by Xerox which as a part of its service program, the matching restrictions of the ingoing parts complicate the materials management and production process. This problem is also present when a unit consists of components that are marked with serial numbers, and obliges the coordination between disassembly, reprocessing and assembly operations. This is familiar for Make-to-Order-based production (MTO), which also has the observed problems with short planning horizons and poor visibility for replacement parts. Order release is common to be one-to-one, which makes setup reduction programs common, and to be able to offer reasonable lead times, excess capacity for critical resources is widespread. Lot-for-lot is a common lot sizing technique due to the complicated requirements of the operations. This characteristic also influences the information system and scheduling in order to keep track of the item. Purchase orders are problematic because of low volume and poor visibility of demand, and buffers are often used for high-volume replacement parts (Guide, 2000).

3.6.7 Stochastic Routings and Highly Variable Processing Times
Highly variable processing times are referred to as one of the most complicating factors for the internal process control in remanufacturing (Guide, 2000). At the operational level, the condition of a returned unit is a critical factor of the uncertainty of the production process and operation times, because of processing time and stochastic routings of operations. To estimate flow time and to plan both machine and labour resources are therefore extremely complicated. There is a set of maximum operations that a part can go through to get fully restored, but most parts only go through some of them and even between identical component types the routings are unique, which make processing time highly variable. The variety of the parts’ condition also complicates the machine setup times. Some operations are known with
certainty, but others are dependent on the age and condition of the cores. This makes remanufacturing more complex than traditional production in the perspective of capacity and resource planning, scheduling, shop floor and inventory control. Bottlenecks are a common problem, and they have a shifting nature in remanufacturing due to this characteristic, e.g. cleaning where parts might return to the cleaning station several times, and the MRR. This characteristic is also referred to as the single most complicating factor for lot sizing decisions and scheduling. There is no evidence for a best practice regarding lot sizing-method, but a size of one is common. When employing a fixed quantity, this is usually based on the Economic Order Quantity, the EOQ. Dynamic lot sizing techniques based on demand and capacity constrains are also common (Guide, 2000). For a detailed discussion regarding EOQ in remanufacturing, see the forthcoming section on material planning in remanufacturing.

3.7 Lean Production

Taiichi Ohno is often regarded as the founder of the Toyota Production System (TPS). TPS evolved out of need, as the marketplace in post-war Japan required small quantities of cars to be produced in many varieties, and this created a new type of production system at Toyota Motor Company. It was essentially the further development of the Ford principle of mass-producing the same automobiles in large production runs. Womack et al. (1990) coined the phrase Lean Production to describe TPS when they printed the results of a five-year study in the automotive industry in the book “The Machine That Changed the World”. Lean is in its essence an approach that eliminates waste by reducing costs in the overall production process, in operations within that process, and in the utilization of production labour. The focus is on making the entire process flow, not the improvement of one or more individual operations. According to these authors, “waste” can be categorized as anything that the customer is not willing to pay for (Womack et al., 1996).

The previous research in applying lean production principles in remanufacturing is scarce. The only known previously reported study in this area is a case study by Amezquita et al. (1998) that focuses on the remanufacturing of an automotive clutch. The main results from this case study were the development of techniques for lean automation and different methods for reduction of setup times. Another conclusion from this study is that different reprocessing technologies – e.g. additive technologies – need to be developed to be able to apply several lean principles, e.g. a one-piece flow.

3.7.1 Material Flow in Lean Production

The principle of Lean Production is to target these wastes in different ways with the aim of reducing them. Figure 15 illustrates an implementation plan of different Lean Production methods covering a vast number of issues in a manufacturing business. As the focus of this dissertation is not targeted towards Lean Production in general, but rather specifically towards material flow, the forthcoming analysis will address only
the relevant aspects of Lean Production that have the greatest impact on the material flow. These methods can be grouped in the following generic groups: (1) production to customer orders (customer pull); (2) create a levelled workload; (3) one-piece flow; (4) reduced setup times (costs for order preparation); (5) takt time; (6) just-in-time deliveries; and (7) stable production processes.

Figure 15: A roadmap on how to accomplish Lean Production using Lean Production methods. Adapted from Jacobs et al. (2006).

3.8 Material Planning in Manufacturing and Remanufacturing

Compared to ordinary manufacturing, production planning for remanufacturing is influenced by some additional complicating factors that have been presented (Guide, 2000). The effect of these characteristics are that the material and production planning becomes different from manufacturing situations. To support the forthcoming analysis, some of the main principles and methods for material planning in manufacturing and remanufacturing are presented.

3.8.1 Material planning in manufacturing

Regarding the field of material planning, the focus in this study is on replenishment policies. In ordinary manufacturing, there are some general methods concerning how
to handle replenishment, the most common of which are Reorder Point and Material Requirement Planning (see, for example, Blumenfeld (2001)).

**Reorder Point (ROP)**
ROP policies are one of the most common methods in materials management. One reason for their popularity can be their simplicity. The policy implies that when an inventory position of a component falls below a Reorder Point \( r \), then a new lot-size \( Q \) is ordered (see Figure 16). Here, the Reorder Point is set to cover the demand of products during the lead time for replenishment. The Reorder point can also include a safety stock to cover the risk of a higher demand during the lead time or a delay in the replenishment (Axsäter et al., 1994).

![Figure 16: The Reorder Point system (Blumenfeld, 2001).](image)

Reorder point policies can also be divided into two different categories of stock policies: *installation* and *echelon*. Installation stock polices \((Q, r)\) regard only the actual stock (installation) in a given level. The difference with echelon stock policies \((Q, r_e)\) is that the stock is calculated as a sum of multiple levels (installations) and the components in transit between levels (Axsäter et al., 1994).

**Two-bin System**
The two-bin system uses the principle of the Reorder Point for material replenishment. The difference is that the replenishment is based on visual control. The principle of the system is the creation of two bins, where one bin becomes the working bin and the other a spare bin. When the working bin is empty, an order request is created and the spare bin becomes the working bin while the former working bin generates a refill order (Chaneski, 2002). Two models of the system can be seen in Figure 17. The model to the left uses a single bin with a separator creating a working bin and a spare bin. In the model to the right, there are two bins of equal size where the spare bin becomes the work bin when the work bin runs out.
**Figure 17:** The principle of the two-bin system.

The two-bin system is a visual Reorder Point system with fixed reorder points (r) and order quantities (Q). Today, ROP systems are normally integrated in computerised systems; however, the two-bin systems are not. No components in a two-bin system are registered in the system, and therefore the number of components in the bins is unknown. One major advantage with the two-bin system is that it works both as a control system and as a material movement and storage solution (Hautanemi *et al.*, 1999).

**Material Requirement Planning (MRP)**

One of the disadvantages with Reorder Point systems is that they require relatively stable demand to be optimal. For example, if the demand for a product fluctuates over time and the demand can be predicted, a due-date policy (for example MRP) can be superior. MRP uses fixed planning horizons, and a production plan is generated based on the external requirements of components for each period, the lead time of components, product structures (BOM – Bill of Materials), safety stock of the component and the order quantity (Axsetter *et al.*, 1994). For a detailed description regarding the MRP and associates planning, see Browne (1996).

**3.8.2 Lot-sizing principles in manufacturing**

When determining what number of products to be produced (or ordered), the question of lot sizing technique arises. Two frequent principles for this calculation are to use fixed or variable order quantities. Economic Order Quantity (EOQ) uses fixed quantities. Because it is simple, EOQ is often used as a decision rule when orders are placed in a requirements planning system (Vollmann *et al.*, 2004).

EOQ is one of the simplest lot sizing techniques, and is helpful in deciding what order quantity should be used. EOQ is an equation that describes the connection between the costs of placing orders, the costs of carrying inventory and the order quantity. In using EOQ, some simplifying assumptions must be made, such as constant demand rate, non-fluctuating costs, and unlimited production and inventory capacity (Vollmann *et al.*, 2004).

**3.8.3 Material planning in remanufacturing**

Regarding material planning in remanufacturing, there is one particularly important difference when compared to manufacturing. This concerns the fact that there are a limited number of cores to be supplied. In manufacturing, the supply of raw materials...
or components can be regarded as relatively predictable; in remanufacturing, this is not
the situation (Guide, 2000).

One major reason for the insecure supply of cores is the many suppliers (the users of
the products) and the way that these products are collected (see Paper II).

When the complexities of a system become greater, the more difficult it becomes to
optimize; this is especially true in the remanufacturing environment. In this section,
two principles relating to how to plan for materials are presented: one of which is
similar to the ROP system, and the other which is linked to material requirement
planning (MRP).

**Reorder point in remanufacturing**
The Reorder Point system is in this situation linked to both the demand for products
and the supply of cores. Just as in the ROP for manufacturing, there is an order issued
when the inventory level drops below a given inventory position. If there are enough
cores in the inventory to fill a remanufacturing order quantity, the remanufacturing
order is released. If sufficient numbers of cores are not available, the next order point
issues a manufacturing/purchasing order in order to satisfy the demand for products
(see Figure 18). This strategy is ill suited when the return of cores is greater than the
demand for remanufactured products. If that happens, large stocks of remanufacturable
products will emerge (Teunter et al., 2005). The following abbreviations apply to
Figure 18:
THEORETICAL FRAMEWORK

\[ L = \text{Lead time} \]
\[ Q_m = \text{Order quantity for manufacturing} \]
\[ Q_r = \text{Order quantity for remanufacturing} \]
\[ r_m = \text{Order level for manufacturing} \]
\[ r_r = \text{Order level for remanufacturing} \]

Figure 18: The upper diagram shows the position of serviceability inventory, while the lower diagram shows the cores available on hand (Teunter et al. 2005).

**MRP in remanufacturing**

Compared to MRP in manufacturing, the remanufacturing situation includes additional input data such as the expected return flows and the current stock of remanufacturable cores. An example of MRP in remanufacturing is presented in Table 10. Here, the “remanufacturing first” priority rule is employed, and a disposal limit of 10 components is specified. Table 10 shows how planned order releases for all activities (disposal, remanufacturing and manufacturing) develop over time, taking into consideration the respective lead times (2 periods for remanufacturing and 1 period for manufacturing). Here, the numbers in bold are input data (Inderfurth et al., 2001).

It should be noted that alternative order release rules can also be used here. For instance, another alternative is to immediately remanufacture all units available. In addition, uncertainties in returns and lead times can be taken into account by using safety stocks and/or safety lead times as a means of security (Inderfurth et al., 2001).
Table 10: Example of a MRP table adapted to remanufacturing (Inderfurth et al., 2001).

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Gross Requirements</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Scheduled Receipts Manufacturing</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Scheduled Receipts Remanufacturing</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Projected Serviceables on Hand</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td>Net Requirements</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Expected Returns Remanufacturables</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Projected Remanufacturables on Hand</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Planned Order Receipts Remanufacturing</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Planned Order Receipts Manufacturing</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Planned Order Release Disposal</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Planned Order Release Remanufacturing</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Planned Order Release Manufacturing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.8.4 ABC analysis

Components in an inventory create costs; to minimise the costs associated with holding an inventory, efficient planning and control of the inventory can reduce these costs. The planning and control should be focused on the important components versus the unimportant ones; therefore, a classification of different components can be made to enable the focus on important components.

One tool to classify different objects is the Pareto analysis – or as it is commonly referred to, “the 80-20 rule”. This rule was created in 1906 by the Italian economist Vilfredo Pareto. He used a mathematical formula to describe the unequal distribution of wealth in his country, observing that twenty percent of the people owned eighty percent of the wealth. This logic is also the basis for the ABC analysis (not to be confused with Activity Based Costing, a supporting method for distributing costs and pricing products).

The ABC analysis is based on (1) the value of the component and (2) the demand for the same component (usage rate). Multiplied, they create the value of usage (or annual requirement value).

In a normal example, 10% of the components constitute 60% of the value of usage (see the A components in Figure 19). These components are especially important and demand a high degree of control. C components are less important, and represent about 60% of the components and only approximately 5% of the total value of usage as seen in Figure 19 (Partovi et al., 2002). The ABC analysis can be a valuable tool when the need to categorise components arises. Taking inventory as an example, close planning and control is more important for fast moving components with a high unit value. Conversely, for slow moving, low unit value components, the cost of inventory
planning and control systems may exceed the benefits to be gained, and simple methods of control should be substituted.

Figure 19: An example of the ABC analysis and value of usage.

3.8.5 AC model for material planning

With respect to the ABC analysis, the AC analysis simply does not consider the B components in a control perspective; instead, these components are spread to either the A or C group. The use of AC analysis as a tool when choosing replenishment polices has been documented by Hautaniemi et al. (1999), albeit in a make-to-order situation. First, the value of usage is used to find components with low value of usage. Then, the components that have a shorter lead time than the final assembly schedule (FAS) are identified. The components with a longer lead time than the FAS are then divided up depending on the demand pattern. The groups are then associated with different MRP and ROP systems for control. One of the reasons to identify C components is that the use of MRP creates higher administrative costs, and therefore other control methods can be more feasible. A summary of the framework can be seen in Figure 21 (Hautaniemi et al. 1999).
3.8.6 New components (spare parts)

Replacement Material
Another complicating factor for production planning is the coordination of replacement material that can come from both remanufactured and manufactured parts. In the situation when parts cannot be remanufactured, they have to be purchased. This leads to some problems, due to reasons like: (1) long lead times for purchased products, (2) single suppliers for parts or components, (3) poor visibility of requirements, (4) small purchase quantities leading to unresponsive vendors, (5) parts no longer in production, and (6) vendors’ minimal purchase requirements. Even

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**Figure 21:** A summary of the AC-analysis (Hautaniemi et al., 1999).
though purchase of material can be complicated, some protection can be gained against variability in material recovery as well as more predictable remanufacturing schedules (Guide et al., 2000).

**Obsolescence**

When the demand of a component decreases and finally is no longer desired or becomes out-of-date, it is considered as obsolete (Cobbaert et al., 1996). Obsolete components are no longer usable, and the remaining components have no value and result in a cost for the company, both in value and disposal. Obsolescence can occur either through an expected pattern or a sudden decrease in demand (also referred to as sudden death) (Teunter et al., 2002).

Some lot sizing and replenishment options for manufacturing have been created for both sudden death (Cobbaert et al., 1996) and expected decrease in the final phase of the product’s life cycle (Teunter et al., 2002). However, there is no existing model that focuses on the effects of obsolescence in remanufacturing environments.

**Spare Parts Inventory Management**

One main difference between ordinary inventory control and the control of spare parts is the usually low demand pattern for spare parts. In an ordinary situation, an ABC analysis is an appropriate tool, due to the fact that the products are more or less homogenous. However, the inventory control of spare parts differs, due to the more complex situations. For an effective analysis, the characteristics of criticality (process and control), specificity, demand patterns and value are good criterions when classifying spare parts (Huiskonen, 2001).

### 3.8.7 Material handling

**Line Storage and Kitting**

Material movement in the line storage solution is the transportation of a component from a warehouse position to a storage position in connection to the assembly operation. The kitting operation is when the components of a specific assembly are collected, often on a specific part carrier, and brought to one or more assembly operations (Brynzér et al., 1995).

Some pros and cons can be identified with each option. In an assembly situation, some advantages with kitting can be identified, such as: a liberation of space connected to the assembly operation, a simplification of the material movement (especially in the situation when components are stored at multiple positions, as in a parallel flow) and improved control and visibility in the system (Bozer et al., 1992). Another advantage is a reduction in lead time for the assembly operation (Brynzér et al., 1995). The disadvantages of kitting versus line stocking are: that the operation does not add any value to the product, that it creates an extra need for space in the warehouse, and that it increases the need for control and increases the risk of errors in the handling of components due to human errors (Brynzér, 1995).
The kitting operation can be done in many ways using different picking techniques. Some factors that influence the kitting activity are: the storage solution of the inventory, the number of components in a kit, the number of common components between kits, the lead time for the kitting operation, the resources demanded by the process and the type of components to be picked. For an overview, see for example Brynzér (1995).
PART III – ANALYSIS

This part of the dissertation presents the results of the individual research questions. In this section, the general analysis is presented as well as a discussion regarding the specific results. This section reports the major findings and provides some empirical evidence, although the major empirical data is further presented in the appended papers.
This section focuses on the first research question, that which targets the basic questions of why companies are involved in remanufacturing and what are the drivers that motivate companies to remanufacture products. Several authors have partly addressed this question in their previous research, and there are several case studies that contribute to answering this question. A main conclusion from these studies is that the motives for remanufacturing a product are very case-dependent (see for example Seitz (2007); Gray et al. (2007); Toffel (2004), Bras et al. (1999) and de Brito et al. (2004)). These previous studies, together with the empirical findings from this study, provide a good empirical base for further analysis. In this section, the first research question will be addressed, that is:

**RQ 1: What are the drivers for companies to remanufacture products?**

Understanding what the drivers are for the overall remanufacturing system is a key issue for developing competitiveness in the remanufacturing system. For example, when creating different management principles, there has to be a purpose for the development of these principles. Without knowing where we are going, we cannot deliver solutions to get there either. Therefore, the identification of remanufacturing drivers becomes important for the direction of the forthcoming analysis.

### 4.1 Profit as a Driver for Remanufacturing

One of the most frequent answers given when a company is asked why they are involved in remanufacturing is that remanufacturing is a profitable business for the company. In this section the identified profit drivers for remanufacturing are presented.

#### 4.1.1 General Cost Reductions

Remanufacturing as a solution for realising a product that meets the customer’s requirements can provide substantial cost savings in comparison to the new product
alternative. Remanufacturing can provide cost reductions, both for customers and for manufacturers. This is done by taking advantage of the resources that were used in the manufacturing of the product. By taking advantage of these resources, there is a potential that the costs of producing remanufactured products is lower than in the case of new production - in other words, providing a situation where remanufacturing can be profitable (Toffel, 2004). The reused resources consist of the material in the product, energy, machine time, labor and other costs that have been accumulated in the new production process (Bras et al., 1999).

This cost reduction is also the main criteria for making remanufacturing profitable. For example, Xerox Corporation saves hundreds of million of dollars a year by disassembling its end-of-life photocopiers and then cleaning, sorting, and reprocessing components and recycling residual materials (Toffel, 2004). Another example of remanufacturing becoming profitable is seen at Volvo, which uses remanufactured engines in warranty claims instead of new engines (Paper VII).

4.1.2 New Business Strategies

How companies formulate their business strategies to meet customer demands can also create opportunities for profitable remanufacturing. A trend today is that many manufacturing companies are moving from a focus of selling products to a perspective linked to optimising the use of the product during its lifetime. In this way, the focus is shifting from the cost at the point of sale to the life cycle cost. In this way, the focus shifts away from the price difference of a remanufactured product in comparison to a new product. One example of this thinking is when the product is linked to a functional sales offer. In the functional sales offer (e.g. a rental contract), the business strategy of a company is to sell the function of a product instead of the physical product itself. A formal definition of functional sales is: "To offer from a life-cycle-perspective a functional solution that fulfils a defined customer need. The focus is, with reference to the customer value (defined customer need), to optimize the functional solution from a life-cycle perspective. The functional solution can consist of combinations of systems, physical products and services" (Lindahl et al., 2001). One result from this is that the product can remain in the ownership of the company, and can then be remanufactured when returned from the customer (Jacobsson, 2000). In this case, remanufacturing can be a preferred product recovery option for products coming back after the lease or rental period (Toffel, 2004). One practical example of this is the rental agreements for forklift trucks offered by BT (Paper III). Normally, the forklifts are stationed at the customer for up to five years. When the product is returned, it is remanufactured before it is sent out to another customer or sold in the second-hand market.

4.1.3 New Product Sales and Entry into New Market Segments

This category refers to the practice of trading in old products when customers are buying a new product. When providing compensation for the old product, a drive for new product sales is made. If the company is involved in remanufacturing the product, the effect can be that the customer gets some discount for the new product, and the
remanufacturer gets a core that can be remanufactured. For the OEM remanufacturer, the result is a profit from the sale of the new products and a profit for the remanufactured product. One frequently cited reason for companies not to become involved in remanufacturing is that it can possibly reduce its new product sales. This does not have to be the case, since it is common that the new and the remanufactured products are sold to different markets, or are sold through different marketing channels, as well as that the new and the remanufactured products often target different market segments. One example of this is the case of remanufactured soil compactors from Swepac and forklift trucks from BT; both of these products are targeted towards different markets and market segments (Paper III). In each of these cases, the products that are sold as remanufactured are targeted towards customers with a lower demand of innovation level and to customers that are price sensitive. Targeting new market segments by offering remanufactured products is also one way for premium brands to address new customer groups that would not be able to buy new premium products.

4.1.4 Provide Spare Parts

For products that have been on the market for an extended period, the only option for the customer to replace a broken component might be with a remanufactured component. The main reason for this is that there are no new or reused components available on the market (Gray et al., 2007). Additionally, OEMs may be obliged to supply spare parts for products for a certain length of time after new production ceases; in many industry sectors, such as automotive, this timeframe can be up to 15 years, as for the case of Volvo and UBD (Paper III). By using a business model which provides these spare parts as remanufactured products, OEMs are able to cease production of small numbers of new spare parts for older product lines. This means that remanufacturing can offer a further cost savings to the OEM.

Another interesting point is that remanufacturing also provides an alternative to new production for spare parts. Hence, the dependency on sub-suppliers for spare parts can to some extent also be reduced by offering the remanufacturing option (Seitz, 2007). This is especially true for components that have been on the market for many years, making the costs for producing new components high due to the generally low production volumes (see Paper II).

4.2 Policy as a Driver for Remanufacturing

The drivers for remanufacturing can also be linked to non-direct economical issues. Policy issues, such as protecting a secondary market, promoting brand image, preventing legislation and other similar issues can motivate remanufacturing. The drivers that are presented here are drivers that have a positive economical impact on the company as a whole, even if the profit from the remanufacturing operations can be negative.
4.2.1 Protecting Aftermarket Volumes

The aftermarket is defined “as the market for components and accessories to maintain or enhance a previous purchase” (Toffel, 2004). The aftermarket is often a very lucrative business area for OEMs, and therefore it can be beneficial for the OEM to keep independent competitors away from this market. By collecting components and products from customers, the “risk” of independent remanufacturers targeting this area is reduced through limiting the supply of cores. Based on a study at an engine remanufacturer, Seitz (2007) provides the following insight:

*Officially a remanufactured engine can only bought if a core is returned. But if a customer offers us just the core without buying a remanufactured product, we tend to buy it anyway, because otherwise, the core would be “food” for our competitors. With regard to commercial vehicle engines, at one point, we even bought back used engines from scrap yards to avoid that competitors would get hold of them.*

Another example of protecting the aftermarket is the company Lexmark, which uses a “prebate” program giving a discount on a product if the customer agrees to the return the product after use. This program prohibits its customers from returning or selling their used products to other companies (Seitz et al., 2004).

4.2.2 Brand Protection

The image of a company is one of the most critical factors for a successful business. It is also something that demands a lot of time and investment to build, and it can quickly be destroyed by for example negative publicity. For high profile OEMs that target premium customer segments, it is very important that the quality of remanufactured products be under control. To maintain control over the product during its lifetime, the OEMs might want to restrict the supply of cores to the independent remanufacturing companies. The result can be that OEM does not want independent companies “playing around” with their branded products, resulting in a risk that the original brand gets the negative impact if something goes wrong with the remanufactured product from an independent remanufacturer. One example of this practice is the remanufacturing and upgrading of filling machines at Tetra Pak. By upgrading the products to the latest specifications, Tetra Pak is actively increasing the level of technology in its installed base, as described in Paper II. The reason for this is partly motivated by maintaining a company profile of innovative products and reducing the risk of inferior remanufacturing performance from independent remanufacturers.

4.2.3 Gaining Information of Customer Needs

Just as trading-in products can be a driver for new sales, information on remanufacturing needs and the status of the installed base can gain substantial advantages in respect to competitors. With the information about the status of the installed base gained from the customer, the seller can be one step ahead, realising the
REMANUFACTURING DRIVERS

needs of the customer before the customer themselves. If the information of the current situation can be gathered, there is a possibility to act proactive instead reactive. Acting proactively according to information can enable a company to control different activities according to the organisation’s ability to perform at its best. For example, a sale advantage can be gained when the products that are close to their end-of-use are to be replaced. This information can then initiate a proactive sales activity. Another example is when an innovation pushes the product out of its economic lifetime in the customer’s specific case. According to Holmlund (1997), the actions in these sequences have great influence on the perception of the relationship. With the information about the customers installed base, an information advantage over the competitors can be gained. (For a more detailed discussion about how this can be in ownership-based relations, see Paper III.)

4.2.4 Providing Additional After Market Solutions

Matching different customer needs for aftermarket services can also be a source for a positive company profile. Remanufacturing can then be a low-price option for the price-sensitive customer. In general, this reflects on the broader market appeal for customers, including the company’s ability to provide replacement components for a reasonable period, at a reasonable price. One remanufacturer puts it like this (Seitz, 2007):

One of the reasons why we remanufacture passenger car engines and engines for small commercial vehicles is the fact that we want to offer the customer the option to purchase remanufactured engines. It all boils down to customer orientation and customer satisfaction.

4.2.5 Feedback to new Product Design

Engaging in a remanufacturing activity can also provide additional knowledge about how the products are performing during the later parts of their usage periods. Products that are subject to warranty claims have previously been reported to be a good feedback source in new product design. When engaging in remanufacturing there is an additional advantage, since older products that are not returned under warranty considerations can easily be analysed. By remanufacturing, companies can get good insight into what happens to the product in the later phases of its life. A practical example of this is the close collaboration between the design and remanufacturing departments at household apparatus manufacturer Electrolux (Sundin, 2004).

4.3 Environment as a Driver for Remanufacturing

From an environmental perspective, remanufacturing can in many cases offer superior material recovery due to additional reused resources (Smith et al., 2004). From an environmental perspective, it is still important to consider the impact of prolonging the life of products with obsolete or polluting technologies. Remanufacturing products with less environmentally-sound technology can have a negative impact, especially if
the major environmental impact is concentrated in the use phase. Still, remanufacturing in the proper scenario can lead to substantial environmental advantages (Bras et al., 1999).

4.3.1 Legislation

Environmental considerations and corporate social responsibility are putting pressure on governments and other institutions to react. A result of this is that the environmental legislative pressure from institutions like the European Union (EU) is growing. Examples of this include the launching of the WEEE and ELV directives, which are currently being implemented in the EU member countries in either an “industry collective” or “company individual” manner. From a remanufacturing viewpoint, the effects of these directives can become a significant driver for the remanufacturing industry. How these directives are implemented will have a significant effect on the future remanufacturing industry. According to Webster and Mitra (2007), in a collective implementation situation, the specific industry branches are collectively responsible, and would make a structural change to the industry – creating an environment where remanufacturing becomes profitable, if not already profitable without a take-back law. On the other hand, if these directives are implemented company individually, i.e. if each company will be responsible for its own products, then the companies will gain better control of their own remanufacturing businesses.

One example of legislation as a driver for remanufacturing can be taken from the toner cartridge business. Toner cartridges are regulated under the WEEE directive; as a result, toner cartridges cannot be treated as ordinary office supplies. This creates a recycling problem for the customer. Scandi-Toner recognizes the embedded value in the discarded product that can be realized through remanufacturing. A recycling service is provided to the customer free-of-charge, and results in the access to used toner cartridges. The relationship is established by providing a take-back system that is realized with a return box that is (when full) sent to the company free-of-charge. The boxes are sent to the company randomly and can contain several cartridges. According to Scandi-Toner, the take-back system also motivates customers to remain customers, and provides a sales opportunity since a customer is more likely to purchase remanufactured cartridges when they are supplying the used ones through the take-back system.

4.3.2 Moral and Ethical Considerations and Green Marketing

When Kodak started to produce single-use cameras, they really were just “single use”. As a result, the customers started to refer to them as “throwaways” and “disposables”. This, in combination with environmental groups addressing concerns of this wastefulness, resulted in a remanufacturing program that took care of these single-use cameras. This environmental driver was the start of one of the most successful remanufacturing programs in the world, with millions of cameras being remanufactured each year (Toffel, 2004).
Remanufacturing can also be a way of promoting a green image of a company. Green marketing can therefore be a way of promoting environmental issues in the company marketing efforts. The main aim with the green marketing idea is that the customer is informed of the environmental effect of the products they are considering buying. As a result, green marketing aims to make the customer aware of this information in the decision on which product to purchase (Rex et al., 2007).

4.4 Discussion

This study shows that there are three main business drivers for remanufacturing: profit, company policy and environmental drivers. For remanufacturing to be successful, these drivers are crucial, although not all of these drivers need be present for a successful remanufacturing business. The main drivers for remanufacturing can be very different across different industries as well as between individual companies. When combining the profit, policy and environmental factors, there is great potential for a win-win-win situation, meaning that the customer gets a quality product at a lower price, the manufacturer reduces its manufacturing costs, and the environment gains from a lower environmental impact, as seen in Figure 21.

Figure 21: The potential for win-win-win situations through remanufacturing

In a general sense, the profit motivation is the most prevalent business driver, but still there are situations where this motivation is secondary to policy and environmental issues. This is especially true for OEMs that are involved in remanufacturing to enhance their image, to promote new product sales or to offer other types of after-sales offerings.

The identification of the different business drivers is also important to determine which aspects need to be optimised in order to create a competitive advantage. When developing and managing the remanufacturing system, the main point might not be to focus on cost as a primary objective. For example, if a main driver for remanufacturing is to protect the aftermarket, acquiring cores should be the priority.
5

BALANCING SUPPLY AND DEMAND OVER THE PRODUCT LIFECYCLE

In this section, the second research question is addressed, that is:

RQ 2: What strategies can be used for balancing returns of products suitable for remanufacturing with demand for remanufactured products?

In the remanufacturing environment, the life cycle of a product and the disposal rate for both products and components have a great impact on the possibility to perform profitable remanufacturing. Previous research has shown that that issues such as the age of the generation of the product, the expected life (reliability), the rate of technological development and the willingness to return products for remanufacturing will influence these distributions (Guide et al., 2000). This section will focus on shedding light on these issues, as well proposing strategies that can possibly make the overall remanufacturing system more competitive. In the following section, the stages of the life cycle are addressed according to three different remanufacturing scenarios (adapted from Umeda et al. (2006)).

- **Product remanufacturing** – Used products are remanufactured to “as new” or upgraded status; an example of this category is the remanufacturing and upgrading of Tetra Pak filling machines.

- **Component remanufacturing** – Used components are remanufactured to “as new” or upgraded status; an example of this category is the remanufacturing of automotive components (UBD case) and toner cartridges (Scandi-Toner case).

- **Component cannibalisation** – Used products are cannibalised for components, and the components are then remanufactured “to new” or upgraded status. An example of this category is the cannibalisation of components from heavy trucks (Scania) and forklift trucks (BT Industries). In these cases, the component cannibalisation option is mainly a supporting activity for the product and component remanufacturing scenarios.
Each of these different remanufacturing scenarios will be discussed in detail in the forthcoming analysis, starting with the product remanufacturing scenario. In each of these scenarios, the empirical data in presented in further detail in Paper II.

5.1 **Product Remanufacturing**

In this section, the basics for the demand and supply for remanufacturing will be analysed. After this, the linkage between the supply and demand will be analysed from a product life cycle perspective.

5.1.1 **Demand for Remanufacturing**

The shape of the product distribution for newly produced products has a major impact on the demand for remanufactured products with equal characteristics. A theoretical illustration of the linkage between demand for new and remanufactured products is seen in Figure 22.

![Figure 22: Linkage between new product sales and demand for manufactured products.](image-url)

Figure 22 illustrates that the demand for remanufactured products generally follows the trends of newly manufactured products. Just as for new manufacturing, there is a possibility to affect the shape of the demand for remanufactured products by different remanufacturing offers; this is illustrated by the dotted lines in Figure 22. For example, if no marketing of the remanufacturing product is possible, then the demand of remanufactured products often tends to be lower, due to customers’ poor knowledge of the availability of remanufactured products. In addition, the pricing strategy of remanufactured products has a major effect on the shape of the demand for remanufactured products. For example, in traditional manufacturing a major reason for the drop in sales is that once new products with better performance are introduced, and that the price for the older version of the products cannot compete with the price of the newer product. In the case of remanufacturing, some products can still be attractive for a longer period of time due to the traditionally lower price for remanufactured products. This is especially true for products with low technological development, or within customer segments that are not sensitive to new technology. One factor that limits the demand for remanufactured products is other types of product recovery options; reuse is one example. In the secondary market, resale can be a more viable
solution in the eye of the customer if the product at hand is in working order and the expected lifetime of the product is sufficient (the quality of the used product). In practice, this is largely a matter of the cost of the reuse and the remanufacturing options, a detailed discussion of which is found in Paper II. Hence, the competition from other recovery options limits the demand for remanufacturing volumes over the life cycle, as illustrated in Figure 23.

In Figure 23, the cost and benefit from the remanufacturing option is compared with the product recovery options of reuse and recycling. When the core quality is high, the cost for the remanufacturing operation is not motivated according to the market price for a remanufactured product. In this situation, the logical option from a profit perspective is to reuse the product. Later, when the quality of the core is decreasing, the benefit for remanufacturing becomes greater and is logically motivated from a profit perspective. After a point, the quality of the returning core becomes so low that the cost for remanufacturing becomes too high according to the potential market price. In these situations, it can be motivated to recycle the product, especially if the desire is to protect the aftermarket or to protect the brand image. However, in situations where the quality of the used product is sufficient, the option of reusing the product “as is” on a secondary market can be motivated – especially for low-performance tasks.

5.1.2 Supply for Remanufacturing

To match the demand for remanufactured products there is a need to forecast the future supply of cores suitable for remanufacturing. The potential supply of cores from end-of-use and end-of-life can be forecasted according to historical OEM production data as explained in the theoretical framework (Umeda et al., 2007). One problem with this is that the forecast is made for the total disposal distributions of all products. The disposed products are also subject to reuse/repair (if the quality level is high enough) and recycling/waste treatment (if the quality is too low), as illustrated in Figure 23. As a result and as seen in Figure 24, the supply of cores suitable for remanufacturing will always be lower than the disposal distribution. In addition, the supply of cores will fluctuate according to the quality level of the disposed products over time, due to the
logic of the economically preferred product recovery option as a function of core quality, as illustrated in Figure 23.

Figure 24: Linkage between the disposal distribution and the distribution of products suitable for remanufacturing.

5.1.3 Life Cycle Aspects for Balancing Supply and Demand

The possible remanufacturing volumes for a product are dependent on the relation between the supply and demand curves. The case when remanufacturing is generated from end-of-use returns is illustrated in Figure 25. The shape of the potential remanufacturing volumes is dependent on the shape of supply and demand distributions. The exact shape of the distributions differs between different types of products. For example, the potential remanufacturing volumes of single-use cameras are high, as described in section 3.2, due to the short average usage period that pushes the supply distribution to the left in Figure 25. Another example is the remanufacturing of filling machines to “as when produced status”; in this case, the machines are returned after an extended period of time, and the supply distribution is pushed to the right.

Figure 25: Potential remanufacturing volumes.

In product remanufacturing, there is one special case were this reasoning does not apply: when the supplier of the core is also the customer of the remanufactured product as in a direct-order customer relationship (Paper III), as for example in remanufacturing as a service. In this case, the customer supplies the core directly according to a make-to-order principle, and there is potentially a perfect match.
between supply and demand. A practical example of this is the remanufacturing service provided for soil compactors (Swepac case), where the customer (often rental companies) supplies the compactor and gets it back within two weeks.

In the case when remanufactured products are being upgraded to the latest specifications from cores based on a previous version (illustrated as $A^{-1}$ in Figure 26), the situation can become advantageous from a potential remanufacturing volume perspective, as illustrated in Figure 26. The possibilities to do so are limited according to the upgrading cost it generates, but also according to the level of technology of the core to be upgraded. In conclusion, upgrading products can be a very effective strategy for matching supply and demand and increasing remanufacturing volumes.

**Figure 26:** Potential remanufacturing volumes when upgrade to latest technology is a viable option.

**Life cycle aspects in the introduction phase**

Before remanufacturing can be undertaken, there can be difficulty in identifying the potential products for which remanufacturing is profitable and technically feasible (Zwolinski et al., 2006). One important competitive mean for remanufacturing companies in this phase is to quickly develop and present remanufactured products to the market once a new type of product has been introduced. With closer cooperation between remanufacturing stakeholders, new manufacturing and potential customers, the following advantages can result:

- Better identification of potential remanufactured products can stimulate increased remanufacturing of products.
- A faster time-to-market for remanufactured products, gaining a first-movers’ advantage in respect of competitors.
- An earlier start of remanufacturing has the potential to better match underlying demand for remanufactured products, and hence increase remanufacturing volumes.
- Demands regarding quality and technical specifications of cores/components can be distributed from the OEMs to the remanufacturing industry.

In this phase, the possibility to identify potential products and shorten the time-to-market is largely dependent on the ability to act in a network of actors such as OEMs,
component suppliers and customers. Hence, relationships between partners become important. Previous research reports that competition between OEM remanufacturers and independent remanufacturers can be a major limitation for collaboration, although this is not always the case (Hammond et al., 1998). In this study, there have been examples of fruitful collaboration between OEMs and independent/contracted remanufacturers. In the UBD case, the remanufacturer is contracted by the OEM, but it also competes with the OEMs as they also provide remanufactured products to the independent market. Additionally, if the products have been designed for remanufacturing in the first place, the possibilities to identify and motivate remanufacturing will be greater.

**Growth phase**
This is the phase when remanufacturing volumes emerge and increase over time. Here, the core returns from end-of-use are limited, and the potential demand for products is high. In this phase, the possibilities for generating good profit margins are high, mainly due to the high demand for remanufactured products with respect to the lower supply of products suitable for remanufacturing. The companies that have a better ability to acquire cores in this phase will have a major competitive advantage (Paper II). As the end-of-use and end-of-life disposal rates are limited to failure rates and average usage periods, the possibility to manage the returns is low. In this phase, the greatest potential for acquiring cores is from other sources such as seed stock, commercial returns and other Secondary Channel Goods, as for example warranty claims and transportation damage.

**Maturity phase**
In this phase, the return rates from end-of-use increase more and more, to the extent that they start to meet and extend the demand for remanufactured products. As volumes increase and a more stable remanufacturing process is developed, efficiency and cost-consciousness become important issues. Important in this phase is to manage the inventory levels of returned products in relation to the demand for remanufactured products. Another important issue is how to make the processes become even more efficient, e.g. through lean production principles.

As illustrated in Figure 25, there is a breakpoint between supply and demand. This breakpoint also has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on e.g. identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important, while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing. Another characteristic in the later stages of this phase, as well as in the decline phase, is that the quality of the cores can become lower; this in turn can cause a demand for new types of reprocessing operations.
Decline phase
In this phase, the need for remanufacturing decreases, and there is normally an abundance of cores available on the market. The main danger in this phase is having excessively high inventory levels of cores and remanufactured products when demand for remanufactured products decreases. This can result in high obsolescence costs, both for end products as well as for components that are kept in inventory as spare parts. This is especially important for complex, low-volume products with many product-specific components, as for example diesel engines (as in the Volvo case). Knowing when this drop is about to happen is critical in reducing the risk and cost of obsolescence.

5.2 Component Remanufacturing

The cases of component remanufacturing and product remanufacturing are quite different. In the case of component remanufacturing, the demand for remanufacturing activities is primarily linked to the characteristics of the installed base and the failure rate of individual components. One example of this is that the need for break calliper remanufacturing is dependent on the number of installed cars (UBD case). Just as in the case of product remanufacturing, the component remanufacturing volumes are not directly correlated to the disposal distribution of components from a product. Competition from other after-market options such as component replacement by new components (spare parts) influences the remanufacturing volumes. Just as for product remanufacturing, component remanufacturing volumes are sensitive to new component pricing (spare parts pricing), something which is further discussed in Paper II. For example, as shown in Figure 27 the increase in remanufacturing volumes late in the life cycle is a result of component replacement options being reduced to buying a remanufactured or a reused one.

As a general conclusion, the competition arising from replacement volumes by new components is generally higher in the early life cycle; vice versa, completion from component cannibalisation/reuse occurs later in the life cycle (see reasoning in the forthcoming component cannibalisation section).

Figure 27: Potential remanufacturing volumes for component remanufacturing.
5.2.1 Life Cycle Aspects on Balancing Supply and Demand

In a perspective of matching supply and demand, component remanufacturing is a lot different from product remanufacturing. In component remanufacturing, the supply of cores has a direct link to the demand for remanufacturing. Simply put, when a customer needs a remanufactured component they supply the old component (which will be the core in the remanufacturing process), and in return the customer receives a remanufactured component. From this perspective, the need to balance supply and demand is not as prevalent as in the product remanufacturing case. Still, in the introduction phase there is a shortage of cores to be remanufactured for the simple reason that not every core is remanufacturable. Another issue to consider is that the number of available cores from remanufacturing can also be decreased by losses of cores in the supply chain, as further addressed in Paper II. There are also differences between make-to-order cases (as in Figure 27) and deposit or a credit-based relationship based on a make-to-stock policy (as in Figure 28). In the make-to-stock situation, there is a lag between the supply of a component and the delivery of a remanufactured product. In this situation, the customer returns the used component and receives a different remanufactured component immediately. The problem with this system is the existence of a lead-time between the supplying of cores until the time the product is remanufactured and put into inventory, ready for sale (See Paper II).

Figure 28: Potential remanufacturing volumes for component remanufacturing with additional lag in lead-time for the supply of cores.

Introduction and growth phases

Just as for product remanufacturing, there is a need to find potential components for remanufacturing; here, the same type of reasoning used for product remanufacturing is valid. Once new products have been introduced into the market, there is a specific problem for companies using deposit-based relationships (make-to-stock). Before being able to sell remanufactured products, there is a need to acquire cores; with no sale of remanufactured products, however, there is no incoming flow of used cores. In this phase, the producers will have to make an investment in cores before they can begin to sell remanufactured products. This need for investment can be quite large if e.g. a remanufacturer is to put an inventory of remanufactured products at each retailer
(as for example in the UBD case). One way of minimizing the number of components to be used as an investment is to try to minimize the lead-times between when products are returned from the customer and when they are available for sales. Hence, in order to decrease lead-times there is a need to minimise the number of products listed as work in process in the supply chain. Examples of causes that can generate high work in process are infrequent transports between retailer and the remanufacturing facility, the need to batch products together, and a lack of new replacement components.

Just as for product remanufacturing, a key factor for competitive advantage is to gain access to component cores suitable for remanufacturing. Cannibalization of components from end-of-use and end-of-life is a potential source of cores, but it appears much later in the life cycle (see discussion about component cannibalization). For a discussion regarding acquiring cores in this phase, see further in Paper II.

### Maturity phase
In this phase, the product returns from end-of-use and end-of-life life start to increase. Acquiring component cores that have been cannibalised from end products begins to be a viable source. In the automotive industry, scrap yards are a frequent source of component cores for remanufacture.

### Decline and cancellation
Just as with product remanufacturing, the risks of obsolescence are great in this phase, especially for companies with make-to-stock polices. One solution to become less sensitive towards obsolescence is to apply a direct-order relationship (make-to-order) policy on some components, thereby reducing the need to keep a finished product inventory. The disadvantage with the direct-order relationship (Paper III) is that the customer has to wait while the product is being remanufactured. As a result, this option is only viable when (1) the product can be sent off for a longer period of time, (2) when no cores are available, and (3) when the customers want the same product back as they sent in (e.g. customized products).

### 5.3 Component Cannibalisation

This last category is based on the idea that products are cannibalised for components that are later remanufactured. Cannibalisation of components for reuse, in e.g. scrap yards, is a frequent activity in the automotive industry. Cannibalised components are also a source of components for both component remanufacturing and for product remanufacturing.

### Balancing supply and demand
The supply of used products suitable for component cannibalisation is dependent on the other product recovery options that are available. Figure 23 presented a framework regarding the economically preferred product recovery option as a function of core

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quality; a similar approach can be taken for the case of component cannibalisation. For cannibalisation to be economically motivated, the earnings must be higher than the earnings from other product recovery options such as remanufacturing, recycling, and reuse. The earnings from component cannibalisation can be calculated as Equation 4 (example taken from component cannibalisation of forklift trucks).

\[ \text{Earnings} = \sum_{x} p(x) + \sum_{y} r(y) - \sum_{i} ic(x) - DC - MP \]  

(4)

\( x \) = number of components that can be reused  
\( y \) = number of components that cannot be reused  
\( p \) = market price of disassembled components  
\( r \) = gain/cost for recycling/waste treatment of disassembled components  
\( ic \) = inventory carrying cost for cannibalised components  
\( DC \) = total disassembly cost  
\( MP \) = market price or cost for lost sales for the core in an “as is” status

There are two main variables that change according to the quality of the core and which determine the outcome of Equation 4: the number of reusable components and the cost for acquiring the core or cost for the lost sales. For cannibalisation to be a viable option, the market price of the core should not be too great, and secondly the number and value of the reusable components should be sufficient. As a result, cannibalisation has the greatest potential late in the life cycle (Figure 29), something discussed in further detail in Paper II. The timeframe in which the possibilities to cannibalise components can therefore be quite limited, something which increases the risks of obsolescence in reused components. A technical hindrance linked to cannibalisation is that components that are usually in demand for remanufacturing operations are also in such bad shape in the object for cannibalisation that they cannot be reused in remanufactured products. As a result, there might be a need to dissemble several cores to find one component that can be remanufactured or reused in a satisfactory manner. As a general conclusion, component cannibalisation is generally feasible for components with a generally high material recovery rate, mainly due to the purchasing difficulties of this category of components, (see Paper IV). The possibility to reuse and remanufacture cannibalised components is also a question of compatibility between different versions of a product. If the components can be reused between the different versions, the window in which cannibalisation is possible is expanded, and the chance that the components will be reused is greater.

**Figure 29:** Potential component cannibalization volumes to be reused in product remanufacturing.
Component cannibalisation can also be motivated even though the potential earnings are low or negative. As far as brand image (see Papers I and II), there can be legitimate reasons for keeping the end-of-use and end-of-life products off the market; in this case, cannibalisation can be a solution for restoring some value. Other motivation factors for taking a product off the market are that the resale option is competing with other, more profitable solutions, such as new sales and remanufacturing.

5.4 Discussion

This analysis is in its essence focused on how to provide remanufactured products in an effective way during the product’s life cycle. The problem is focused on a supply and demand balancing problem that also creates variations in remanufacturing volumes. The life cycle theory can be effective when trying to forecast the general trends of remanufacturing volumes. When going into further detail, the problem becomes more difficult and addresses the problem of uncertainty in timing and quantity. The difficulty in applying a life cycle perspective in more detailed forecasting is that the variables used to calculate future returns are insecure. The average use and life of a product/component can be forecasted beforehand, but this factor is also dependent on complex factors, for example, to what extent the product has been used and in which environment (to mention some variables). Another factor is the willingness to return old products for reuse. In addition, the demand for remanufactured products can be said to follow new product demands, but is also sensitive to prices of substitute products such as brand-new products and reused second-hand products (if available). The rate of technical development also has a major impact on the demand for remanufactured products, in some cases resulting in a sudden drop in sales for remanufactured products. In all, these insecurities make it difficult to accurately forecast the supply and demand for calculating exact return quantities and timing. The major advantage of using the life cycle as a foundation for balancing supply and demand is the insights it brings on a general/strategic level.

5.5 Conclusions

At a general level, some additional conclusions can also be made. The OEMs are generally in a more favourable position to perform remanufacturing with respect to independent remanufacturers, especially in the earlier phases of the life cycle when access to commercial returns and seed stock are a competitive advantage.

Upgrading products to the latest standard is one possible solution for increasing the potential remanufacturing volumes for the product remanufacturing case, using for example modular design strategies. For component cannibalization, this is not an as important issue; for this category to expand further, component remanufacturing has to become a more attractive option with respect to the new component alternative. Also,
a more standardized and modularized use of components could increase the possibilities to cannibalize components for remanufacturing and reuse.

The ability to attract cores for remanufacturing in the early life cycle phases is a source for competitive advantage. Later in the life cycle, only the most suitable cores should be acquired for remanufacturing. These conflicting ways of looking at cores may introduce difficulties for companies. Normally remanufacturers handle a vast amount of products that are in different life cycle phases, but they have to be coordinated in the same supply chain; the coordination and administration of different take-back systems is an important aspect in managing this. The mix of different marketing channels for product returns is also an important aspect for matching the different needs over the life cycle.

Furthermore, remanufacturers should focus on the development of methods that can make returns predictable. In remanufacturing, the source of cores is the current users of the desired cores. Each of these users is a potential supplier, but with a limited supply capacity and usually very long lead-times for core production. To identify and communicate continuously with all of these potential suppliers is simply perceived as impossible. The result of this lack of communication is that the user comes to the remanufacturer with the core only “when they think if it” (if they come back at all), thus displaying a stochastic return rate. The problem of sourcing cores becomes a question of which of these potential suppliers can supply a core at the right time, at the right quality and at the right price. To be able to find the right cores, different marketing channels and business concepts provide communication solutions with potential suppliers. For example, off-lease products have been rated more predictable than other types of returns due to the additional information that is available to the remanufacturing company (Thierry et al., 1995; Sundin et al., 2005). The off-lease product provides some degree of security that the product be returned at the right time and at a known price (and hopefully the right price). Using different contracts that result in the take-back of cores can be one solution for securing that products are returned at the right time and for the right price, although the quality of the returned product cannot be contracted that easily.

The problem of balancing supply and demand can also be limited or aided depending on the business solution. Remanufacturing of single-use cameras with fast exchange cycles are, for example, aided by the policy of returning the entire camera for development, resulting in faster returns. Coordination of leasing and rental contracts according to average usage age, as in the Xerox and Tetra Pak cases, can also aid a balance between supply and demand. As a result, the more thought about the business solution and how it can aid in balancing returns with demand, the greater the possibilities for successful remanufacturing.
The previous two sections have focused on (1) the general business drivers for remanufacturing and (2) how to manage the remanufacturing system for balancing the need for remanufactured products with the demand for remanufactured products. In this section, the focus will be on how to interact with the customer in order to be able to collect the returned products. To be specific, the third research question is:

RQ 3: What types of relationships exist between customer and remanufacturer, and what specific characteristics can be found in these relationships?

Previous research has highlighted that there are some major differences between the “normal-forward” supply chains and the closed-loop supply chain with remanufacturing (e.g. Guide et al., 2003). By applying a relationship perspective to the area of remanufacturing and the closed-loop supply chain, important insights can be gained. The importance of managing relationships has also been proven a prosperous and important issue in the supply chain management literature. Christopher (2005) adapts the following definition of supply chain management:

“The management of upstream and downstream relationships with supplier and customers to deliver superior customer value at less cost to the supply chain as a whole.”

In a closed-loop supply chain, the management of relationships becomes even more important as the supplier of cores and the customer often are the same person or company. In the remanufacturing industry, there are many different types of relationships with customers and core suppliers. Some relationships are very close, such as where the amount of trust, commitment and collaboration is high; in other relationships, the linkage is rather weak. Even in the latter case, the relationship still exists and constitutes an important issue for the remanufacturers as well as the customers. In this study, seven different types of structural relationships have been identified:
Ownership-based. This type of relationship is common when the product is owned by the manufacturer and operated by the customer, as for example in a rental, lease or product-service offer. Here, the control of the installed base is high and often regulated by contracts.

Service contract. This type of relationship is based on a service contract between a manufacturer and a customer that includes remanufacturing.

Direct-order. The customer returns the used product to the remanufacturer, the product is remanufactured and the customer gets the same product back (if it is possible to perform a remanufacturing operation)

Deposit-based. This type of relationship is common in the automotive industry. When the customers buy a remanufactured product, they are obligated to return a similar used product, thus also acting as a supplier to the remanufacturer.

Credit-based. When the customer returns a used product, they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.

Buy-back. The remanufacturer simply buys the desired used products from a “supplier”; which can be the end user, a scrap yard or similar, or a core dealer.

Voluntary-based. The supplier gives the used products to the remanufacturer. The supplier can also be a customer, but does not have to be.

Concerning these different types of relationships, some disadvantages and advantages can be identified. As will be shown, these relationship structures are not used individually but they can also complement each other, as discussed in Paper III. For example, the deposit-based relationship will have to be complemented with another alternative, due to the inevitable fact that not all cores can be remanufactured. The following paragraphs describe the seven identified customer take-back relationships for remanufacturing companies. A summary of these different findings is given in Table 11.

6.1 Ownership-Based Relationships

An ownership-based relationship is often related to a leasing, rental or a product-service offering as in the forklift truck (BT Industries) case. The basis for the ownership-based relationship is that some sort of ownership is still present for the seller, and that the product is returned to the seller after the end-of-use; it is also in this phase that the remanufacturing operation is undertaken.

The use phase of a product in a leasing or a rental offer, for example, can vary in length from a couple of weeks to several years. The intensity of the interactions with the customer can also vary depending on the situation of the customer (see Paper III). In some cases, the product is rented to a customer for many years with regular servicing; other times, the products are rented for shorter periods, following for example seasonal demands. BT Industries, which provides many of its forklift trucks through rental programs, explains it to its customers as follows:
“Think of the advantages. You avoid all the risks of ownership. You don’t consume capital – not even a deposit is required. We take care of the equipment and make sure it’s always reliable, and we work with you to manage your fluctuating need – we call it capacity management. Rental from BT means flexibility for the future and all of your costs are predictable.”

(BT Industries, 2004)

During the use phase, the seller is responsible for maintenance and repairs of the product; the maintenance technicians handle this commitment. By providing regular service and maintenance operations at the customer’s location, a relationship is established through the service/maintenance personnel. Maintaining the relationship is an important factor of the BT policy of basing its service technicians at its major customers.

Another effect of a close relationship such as found in the BT case is that the service/maintenance personnel gain detailed information as to whether or not there is a need for a future remanufacturing operation. This information can make the return flow of products easier to control and provide information on the forklift truck status to the remanufacturing process. A high degree of control can for example be gained by high control of the products that are in operation at the customer, also called the installed base. By using information gathered from the installed base, the supply chain can be effectively coordinated. This information can be gathered by, for example, service/maintenance personnel as in the BT case, or by software solutions integrated in the product (used by for example Xerox in photocopiers).

The installed base of a rental/lease or functional provider is often called the “fleet”, and this term is also used at BT. The products in this fleet are either in operation at the customer (in-use fleet) or waiting for a customer (buffer fleet), as shown in Figure 30. High use of the installed base leads to a low size of the buffer fleet; vice versa, a low degree of use will indicate a larger buffer fleet. If the use of the installed base is too high (i.e. a small-sized buffer fleet), the company tends to have problems in supplying the demanded products and only the unneeded products are available. If the use of the installed base is too low, there are too many products in the buffer fleet.

**Figure 30:** The product flows between customer and remanufacturer in an ownership-based relationship.
In Figure 30, the size of the buffer fleet is dependent on the inputs (the return of cores) and the output (the need for products). Information about planned returns in combination with demand for remanufactured products can enable a more accurate fleet management. Balancing the size of the buffer has proven to be a difficult task due to the high number of variables that influence the need for the buffer. Some important variables are:

Uncertainty in returns – A close relationship between the customer and the seller can reduce this insecurity. Still, there are situations where the customer wants to prolong the contract; this, however, will delay the return of the products. Furthermore, sometimes the used products are not returned immediately after the contract has ended. This also increases the delay of returning cores (product take-back).

Uncertain demand for products – Accurately forecasting the needs for products is always a difficult task. This uncertainty can be reduced if the buffer fleets are coordinated in a wider perspective – for example on an international or national level as opposed to a regional level. By distributing products between regions and countries according to demand, the total buffer size required can be reduced. This is especially true for seasonal demands where a large number of specific products are needed for a limited period.

A high number of customized products that target a specific segment of customers – When dealing with leasing or product-service offerings, the physical product tends to remain at the customer for a long period. This first customer carries the major part of financing for the product. For this reason, the sales department tends to be willing to customize the product, the result being that the product can become ill suited for other applications. For example, a customer might want a specific reach height for their forklift truck. This makes the mast of the forklift truck taller than normal and unusable for other customers because it will not fit into their environment, limiting the forklift to a narrower range of customer. Here, remanufacturing can provide a solution by changing the specifications of the forklift truck in the remanufacturing process, either to a standard or according to another customer’s specification. Having this in mind, a standardization and/or modularization of product types would facilitate the downstream remanufacturing processes. Remanufacturing provides an opportunity to modify the specifications according to the customer’s needs, given that the design of the product allows for modification.

Gaining control of the installed base provides more than just support for fleet management issues; the information gathered from the customer also provides detailed information about the life cycle of the products in use by the customer. In this way, the company can plan its sales activities according to the needs of the customer.
6.2 Service Contract Relationships

This type of relationship has a high degree of similarity with the ownership-based relationship. The main difference is that the product is owned by the customer, thereby reducing the level of control over the products compared to an ownership-based situation. The service contract type of relationship is based on the formulation of a contract for aftermarket service. In the Swepac case, this contract contained clauses for repairs and maintenance as well as remanufacturing after a set period. A major similarity between the cases is that the offers are still regulated by a contract that has the major influence on the relationship. Given these similarities, the characteristics of the ownership-based relationships is still valid, although the lack of ownership and the characteristics of a service contract add some differences to this type of relationship.

For Swepac, coordinating returns for remanufacturing has proven to be a difficult task, mainly because of the unwillingness to return products at a specified date. This problem is rooted in the reduction of the customer’s capacity when a product is being remanufactured. When a product is sent for remanufacturing, it is unusable by the customer; consequently, this leads to unwillingness to return the product for remanufacturing at a specific time. As a result, the timing of the returns becomes unpredictable.

In this type of relationship, it is important to manage the remanufacturing activity of the customer relationship. If the remanufacturer pushes the remanufacturing operation according to a contract, this can result in a negative response from the customer, depending on if the customer needs the product at that time. This can result in a negative perception of the relationship from a customer perspective. One way to reduce this risk is to plan remanufacturing at a time when the utilisation of the product or the fleet of products is low. For example, Swepac performs its remanufacturing operations during the winter, when demand for compactors is lower due to the ground frost. This is fundamentally the same problem as the companies that have a direct-order relationship have, which is further described in the following section regarding direct-order relationships.

6.3 Direct-order Relationships

In this situation, the customer gives an order for the remanufacture of a used product. Generally, in the eyes of the customer there is a problem in determining if there is a technical possibility to remanufacture the used product (core). Another uncertainty is what the price of the remanufacturing will be. The cost of the remanufacturing is dependent on the quality of the core and how much new material and labour is needed in the process, something that is difficult to determine before remanufacturing is undertaken. Regarding the pricing of the remanufacturing operation, there are different practises from company to company, and pricing can be variable to fixed. If fixed
prices are used for remanufacturing, the risks of sending the used product to
remanufacturing will be transferred to the remanufacturer.

In the case where the customer orders the remanufacturing, there is not normally a
need to keep an inventory of cores; this is because the cores are supplied directly by
the customer. Using a make-to-order system also reduces the need for a finished goods
inventory. In some cases, remanufacturing to a direct order is the only alternative due
to for example a lack of spare parts (normally due to the age, and consequentially the
low volumes, of the product).

In the situation of a direct-order, the cores from a customer have to be sent away for
remanufacturing. Say, for example, that the core for remanufacturing is a component
of a product; the result will be that the product will be non-usable for the time when
the component is being remanufactured. This is not preferable for many situations, as
discussed in Paper III. These disadvantages make this type of relationship only suited
for a limited range of situations, mainly when:

- The product can be sent off for a longer period of time
- When no other type of spare parts is available
- When the price of remanufacturing is an important issue
- When the customers want the same product back as they sent in (e.g.
customized products with high value).

### 6.4 Deposit-Based Relationships

In this situation, the customer is obligated to return the core when buying a
remanufactured product, thus becoming the supplier of cores. This system is common
in the automotive industry, where the remanufacturer normally supplies a product to a
sort of “middleman”, for example, an automotive part retailer as in the UBD example.
The retailer pays a price and a deposit for the remanufactured product. When the
retailers sell the product, they collect the used core from the customers; later, they
return the core to the remanufacturer and their deposit is refunded, resulting in the one-
for-one (1:1) take-back relationship illustrated in Figure 31.

![Figure 31: Illustration of the core and deposit flow in a deposit-based relationship.](image)
This system creates a theoretical match between the supply of cores and the demand for remanufactured products due to the one-for-one link. However, in practice UBD reports that the 1:1 link is not valid. In reality, some of the cores are still not being demanded due to many random actions, for example sales clerks failing to demand the take-back of the core. Another factor that reduces the theoretical 1:1 relationship is that a percentage of the cores that are retuned cannot economically be remanufactured due to extensive damage that would require extensive reprocessing. The result of this mismatch is that the company must use alternative systems to gather the missing cores, something that is discussed further in Paper III.

In relation to the direct-order relationship, the deposit-based relationship enables the customer to get a remanufactured product back at the same time as the used product is given back. This has proven to be a strategically important ability, especially for business-to-business relations where maintaining functionality is a critical factor. Another important issue not to be neglected is that this type of relationship is common when dealing with warranty claims. To be able to provide a remanufactured product immediately once a product breaks down during warranty can help to create a positive relationship with a potentially unsatisfied customer.

With a deposit-based system, no consideration is taken about the quality of the core that is supplied to the remanufacturer. The result may be that the perceived cost of remanufacturing, according to the customer, becomes too high if a high-quality core is supplied. Vice versa, the value of remanufacturing for a customer supplying a low-quality core becomes higher.

### 6.5 Credit-Based Relationships

This type of relationship is similar to the deposit-based relationship, but provides a higher level of sophistication (Volvo Parts case). Instead of a deposit fee, the customers receive credits for the type of cores they supply to the company. As a result, this means that the customer can return cores without purchasing a remanufactured product. The number of credits the customers gain from the supplied cores is dependent on the state of the core, and the credit they have acquired gives them a discount when ordering a new remanufactured product as seen in Figure 32. This credit system, however, does not have the same 1:1 relationship as the deposit-based system. This enables the customers to return as many cores as they wish.

![Illustration of the core and credit flow in a deposit-based relationship.](image-url)

**Figure 32:** Illustration of the core and credit flow in a deposit-based relationship.
In the deposit-based system, no considerations are taken for the quality level of the returned core; it also does not motivate the customer to return more cores than the one-for-one principle. With a credit-based system, these considerations are taken into account. Credits are given according to two factors: first, the quality level of the core, and if any of the specific components in the core are missing; second, the number of credits given, which is also variable between different types of products, with highly-demanded cores given a higher credit, and low credit given for cores with low demand. In this way, the remanufacturer gets a high variety of cores and can practice some level of control through the credit system, while the customer can return cores for credits. This type of system enables the remanufacturer to control the balance between the supply and demand. The credit system can also work as a method for assessing the incoming quality level of the cores according to the number of credits given for returned cores.

The credit-based system prove ineffective as well: this type of system provides the customer with a high degree of flexibility to return cores, but the control and predictability is more complex in comparison with the deposit-based system. The system can also be taken advantage of by the customer; respondents have reported cases where customers have given back twenty cores of low value (e.g. a water pump) and used the credits to order a high value item (e.g. a remanufactured engine), resulting in a major loss for the remanufacturer. In this situation, a lack of long-term commitment and cooperation is needed for this system. One major disadvantage with this system is that it also creates a higher administrative cost for the remanufacturer. The customers also have an uncertainty in the number of credits they will receive for a specific core; this can result in a situation where price-sensitive customers hesitate to remanufacture, due to the uncertainty in price.

6.6 Buy-Back Relationships

Buy-back is as simple as it sounds; the remanufacturer simply pays out money for the cores. The sellers of a core, or multiples of cores, can vary greatly, and range from core brokers/dealers that specialize in the trading of cores, scrap yards, or end customers. This type of relationship is present in most cases of remanufacturing, and it is used as a compliment to some other type of relationship. It is common that the cores that are difficult to find are acquired in this way.

In many cases, buy-back is considered to be the last option if no other alternatives are present. For example, buying a product on a spot market is one way of buying cores; other more advanced systems are also used. One way is through core brokers, who have a close relation with their suppliers, often scrap yards. They are specialized in what they do and they have their own channels for acquiring cores. These core brokers are relatively frequent in the toner and automotive industries; the disadvantage can be the higher price paid (UBD and Greenman Toners), as discussed in Paper III. In some situations, the OEMs have their own facilities for cannibalisation of components. The
Company Scania has a facility that buys trucks that are in some way damaged, and cannibalises them for valuable components for reuse and remanufacturing. The main source of trucks in this case is those that have been damaged and are supplied by insurance companies.

Buy-back of products mainly results in customers getting money for their cores, although other systems do exist. Toffel (2004) reports a case where Lexmark uses a “prebate” program, giving a discount on a product if the customer agrees to return the product after use. This program prohibits the customers from returning or sell products to other companies. According to Lexmark, this program has boosted its product returns, although no reports about the efficiency of the program are given (Toffel, 2004). The ability to gather “hard-to-get” cores is especially important when there are many independent remanufacturers that want to retrieve cores for their business.

6.7 Voluntary-Based Relationships

This sort of system is common in the recycling of different types of material such as newspapers. It also exists in the closed-loop supply chain with remanufacturing (Scandi-Toner case). This system is based on the idea that the customer will voluntarily give back the core. This system can also be forced on the customer and the original equipment manufacturer. This is done for example through take-back laws stimulated by EU directives like the waste electrical and electronic equipment directive (WEEE) (EU, 2002) and the end-of-life vehicles directive (EU, 2000).

One example of this is the toner business that is regulated under the WEEE directive; as a result, toner cartridges cannot be treated as ordinary office items, and this creates a problem for the customer. A product recovery service is provided to the customer free-of-charge, and results in the access to used toner cartridges. The relationship is established by providing a take-back system with a return box that is (when full) sent to the remanufacturer free-of-charge. According to Scandi-Toner, the take-back system also motivates customers to remain customers, and provides a sales opportunity since a customer is more likely to purchase remanufactured cartridges when they are supplying the used ones through the take-back system. The environmental advantages of remanufacturing are strongly promoted as a motivational factor due to the lack of financial stimuli. This is done both to acquire cores and for use in motivating sales. Of course, the environmental issues count as a sales motivation in the other types of relationships as well, and not just in the Scandi-Toner case; it is here where this issue is most actively marketed to the customer.

The voluntary take-back relationships can generate a large supply of cores that in many situations have low demands for remanufacturing, which can lead to high levels of obsolete cores in inventory. A key issue is to keep this tendency at a minimum, continuously reviewing core inventory according to long-term forecasted needs. This type of relationship can also lack the ability to motivate the return of valuable cores that have a high demand for remanufacturing. The cores that are the most valuable do
have a value and are subject to buy-back from competitors. A challenge here is to make the customer committed to the company for the long-term.

6.8 Discussion

This research has focused on building theory based on case study research. By identifying the closed-loop supply chain relationships, a greater understanding can be gained about the structure of the remanufacturing industry and the characteristics of its relationships. The identified general relationships are ownership-based, service contract, direct-order, deposit-based, credit-based, buy-back, and voluntary-based relationships. These individual relationships have different characteristics and are suitable in different situations, as described earlier in this section.

Each company has different resources and abilities that limit it to some specific relationships. For example, the ownership-based and the service-based relationships are mainly linked to original equipment manufacturers, and are less common among independent remanufacturers. As a result, none of these relationships is suited for every company. Another important issue is that these relationship structures are not used individually; in reality, some of these relationships are used simultaneously to complement each other. One general observation from this study is that buy-back relationships are generally present in all companies that are involved in remanufacturing. Although buy-back is normally not the major source of cores, it is used for the “hard-to-get” cores and cores that they are lacking. The buy-back of cores also serves other strategic issues. For example, the buy-back of a product can both provide a sales opportunity as well as protect sales in the aftermarket (Paper I). The ability to adapt a specific type of relationship is dependent on multiple factors. Issues such as the type of product and the interest from the customer to have a relationship will influence the success of a specific type of relationship. Regarding the different relationships and their characteristics, a summary is given in Table 11.

Regarding the different types of relationships, the ownership and the service-based relationships have the highest control over the installed base, and have a favourable position in gaining information about the installed base. The higher degree of control gained by the detailed information can decrease uncertainty in the quality level of the incoming product (core). This information, combined with detailed contracts about the duration of the contracts and the point of return, makes the remanufacturer able to predict the timing and quantity of the returns and ease the need to balance returns with demand. In an earlier study, Thierry et al. (1995) arrive at the same conclusion when they write, “companies that lease their products are generally in a more favourable position than companies that only sell products. Lease companies usually have more information on the quality and return of used products”.


Table 11: A summary of the relationship characteristics

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Core control</th>
<th>Relationship focus</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ownership</td>
<td>High, returns are often regulated by contracts</td>
<td>High, long-term relationships, focus on integrating products and services</td>
<td>Used by OEMs with a high degree of interaction with customers that focus on the function (e.g. reliability) of products</td>
</tr>
<tr>
<td>Service contract</td>
<td>Medium-high, return probability is dependent on different contracts</td>
<td>High, long-term relationships, focus on adding services to the products</td>
<td>Used by OEMs with a high degree of interaction with customers that want to own the products</td>
</tr>
<tr>
<td>Direct-order</td>
<td>High, cores are supplied to an order</td>
<td>Low to medium, according to the importance of the product in respect to customer operations</td>
<td>Suitable in situations where: the product can be sent off for a longer period of time, no new parts are available, the price of remanufacturing is an important issue, and the customers want the same product back as sent in</td>
</tr>
<tr>
<td>Deposit-based</td>
<td>Medium, a theoretical 1:1 relation exists</td>
<td>Low, transactional focus</td>
<td>Can provide a remanufactured product immediately once a product breaks down, e.g. during warranty. No considerations about the quality of the core are needed. Commonly used in the automotive industry</td>
</tr>
<tr>
<td>Credit-based</td>
<td>Medium, enables some control opportunity, no strict 1:1 relation</td>
<td>Medium to high, based on long-term cooperation</td>
<td>Considers and compensates for different quality levels of the core</td>
</tr>
<tr>
<td>Buyback</td>
<td>Medium, one can control what one wants to buy</td>
<td>Low to high, ranges from buying cores at spot price to long-term collaboration with e.g. insurance companies</td>
<td>Used mainly as a compliment to some other types of relationship. Used especially for acquiring hard-to-get cores</td>
</tr>
<tr>
<td>Voluntary</td>
<td>Low, the company gets what the customer is willing to give</td>
<td>Low to high, focus on providing the customer with a positive environmental profile</td>
<td>Minimising the cost for acquiring cores</td>
</tr>
</tbody>
</table>

Regarding deposit and credit-based relationships, the major difference is the level of sophistication. The credit-based system has an additional function of stimulating the customer to return specific cores. From a customer-relationships perspective, this system will be the most fair. This system also stimulates cooperation between the parties, and the accumulation of credits stimulates a long-term commitment to the remanufacturer. Overall, the credit-based system relies on commitment, trust and the win-win situation, compared to the more transaction-based and deposit-based relationships. In this type of relationship, the gatekeeping function is very important. Gatekeeping in this context refers to the screening of cores that are coming back to the
entry point of the reversed logistics network. The foremost important issue of the gatekeeping function is inspecting cores and giving the appropriate number of credits.

Voluntary-based relationships are based on the idea that the customers will voluntarily give back the core. This relationship system can also be forced on the customer and the OEM with take-back laws. To stimulate customers into giving back their used products, relationship management becomes important. Some negative effects of this system are that it can generate a high supply of cores that in many situations have a low demand for remanufacturing. It can also lack the ability to motivate the return of valuable cores that have a high demand for remanufacturing. The environmental advantages of remanufacturing are strongly promoted as a motivational factor due to the lack of financial stimuli.

6.9 Conclusions

The more general conclusions about how the relationships can be managed are as follows:

Firstly, one should understand that these relationship structures are not used individually; in reality, some of these relationships are used simultaneously to complement each other.

Secondly, a proposition is that the more important a product is for the customer’s operation, the greater the will to have a closer relationship in an ownership or service-contract relationship. In addition, the perceived risk of the remanufacturing operation has a strong influence on the willingness to become involved in a closer relationship. Issues like cooperation, trust, and long-term commitment are important in these types of relationships. When managing these types of relationships, the focus should be on reducing risk and the perceived relationship costs.

Thirdly, a higher degree of control over the installed base can enable the seller to control the timing of activities in the relationship (as in an ownership or service contract relationship). The remanufacturer can be one step ahead, realising the needs of the customer before the customer themselves. Hereby, a seller can control the timing of different activities according to its ability to perform at its best.

Fourthly, remanufacturing can be a source of negative responses in the relationship. This is especially apparent when the remanufacturing operation results in a loss of functionality in the customer’s value-adding process. One way of reducing the risk of a bad response is to plan remanufacturing at a time when the utilisation of the product or the fleet of products is low, and thus reduce the perceived cost of the relationship.

Fifthly, one proposition is that remanufacturing becomes more effective when there is a clear win-win situation for both the customer and the remanufacturer. The customer
enables the low cost option of remanufacturing by supplying, from their perspective, a low-value core, at the same time as the remanufacturer gets a supply of cores.

To conclude this section, the success of a remanufacturing business is very dependent on the relationship between the remanufacturer and the customer, since the customer can act both as supplier and customer to the remanufacturing company. Since the retrieval of used products is crucial for the remanufacturer, the management of these supplier/customer relations is very important. The companies studied in this case study all recognise that the management of the relationship with their suppliers and customers has contributed to their business success.
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In the previous three chapters, the focus has been on external processes, mainly focused on securing the supply and demand in a supply chain. From this point forward, the attention will be on the internal remanufacturing process. In this chapter, an analysis is provided to answer the following research question:

RQ 4: How is the organisation of the remanufacturing phases and the decisions taken linked to the remanufacturing process?

Sundin (2004) has formulated a general remanufacturing process, shown in Figure 33. In this description of the general remanufacturing process, the order of the individual operations is not specified. The results from Paper IV show that the remanufacturing process can divided into five different remanufacturing phases. In these five phases, there are some key decisions in the process, decisions that will be elaborated on in the following analysis.

Figure 33: The generic remanufacturing process (Sundin, 2004).

7.1 The Five Remanufacturing Phases

According to previous research and empirical data regarding the different remanufacturing cases, there are many ways to logically organise a remanufacturing
process. Even though there are some general characteristics that appear to be valid in all situations – such as disassembly being conducted before reprocessing, and reprocessing being done before reassembly – the order of the operations in remanufacturing, such as inspection, testing, cleaning etc., are case-dependent (Paper IV). Compared to the general remanufacturing process described by Sundin (2004), the main difference is that the remanufacturing process can be divided into the following five phases due to the linkage between disassembly, reprocessing and reassembly (see Figure 34):

- Pre-disassembly phase
- Disassembly phase
- Reprocessing phase
- Reassembly phase
- Post-assembly phase

The specific order and purpose of the operations that define the process is dependent on a number of factors and decisions. In each phase of the remanufacturing process, there can be one or may operations, just as specified by the general process described by Sundin (2004). In Figures 23–26, the specific set of operations will be illustrated in the same manner as the generic remanufacturing process described by Sundin (2004); the difference, however, is that they will be limited to one of the a specific phases. This can be illustrated as in Figure 34, where each of the different remanufacturing phases contains a set of case-dependent operations as described by Sundin (2004).

**Figure 34:** An overview of the five remanufacturing phases (Paper IV).

Figure 34 is an overview of the general material flow in the remanufacturing process. This is a summary of the five phases, which will be explained in detail in the following analysis.
7.2 Pre-Disassembly Phase

The pre-disassembly phase can be described as a preparatory phase before the disassembly process begins. When a core is returned from a customer, the state of the core must be assessed; this is important in order to decide whether to remanufacture, cannibalize components or recycle the core. This decision is taken in the decision point 1 in Figure 35.

In the UBD case, there is no need to rank the quality level of the core; in this example, only the type of core is identified as there is a higher demand for products than the supply of cores, and thus all of the cores are used. This is an effect of that components are remanufactured (see reasoning in Paper II) and with a deposit-based system (see Paper III).

In the Scandi-Toner case, in contrast, the cores are inspected to maintain better control of the process. Just as in the UBD case, it is a component that is remanufactured, although there is no 1:1 linkage with supply and demand since a voluntary take back system is used.

In the BT case, the inspection is important in order to make a correct valuation of the market value of the core and to obtain an estimate of the costs for remanufacturing. This is then considered in regard to the market value of a remanufactured product. In the BT case, some of the information regarding the state of the product is known in advance, due to a specified service record.

In this phase, inspection and testing are made to identify the correct quality level of a core, or its market value, as illustrated in Figure 35. Sorting is also performed to be able to control the process in later phases, for example by using high-quality cores when free capacity is low, as in the Scandi-Toner case, something explained further in Papers IV and V. Sorting is also done in order to determine what economic potential a core has for remanufacturing.

When information about the core is retrieved, there is a decision point concerning what to do with the core. The alternatives are to remanufacture, cannibalize components, recycle the core or keep it in inventory for future needs. The decision about what to do with the core is based on a number of different factors.

Figure 35: The Pre-Disassembly Phase (Paper IV).
To be able to motivate remanufacturing for profit purposes, the costs for remanufacturing have to be considered (see Paper II). Here, the information about the cores can be of great use when deciding if to remanufacture the core. In this situation, many different contributing economic factors (direct and indirect) influence the choice of remanufacturing the core; Paper I describes the indirect economic factors. Examples of important remanufacturing decision variables in the process are:

- Costs for acquiring the cores
- Potential costs for disassembly, reprocessing and reassembly as well as the cost for new components
- Inventory levels and values of components (new, used and reprocessed components) in the disassembly and reassembly phases
- Minimal order quantities in relation to future needs
- Cost for logistical and marketing activities
- Quality level required by the customer
- The customer demand to keep the product in the portfolio of remanufactured products

The main decision variables are case-dependent, and all of these factors add to the complexity of the remanufacturing process. By gaining information about the core, the decision can be simplified; therefore, making it easier to retrieve this information can aid in making a correct decision.

For the decision whether to cannibalize the core for components, the inventory levels and the need for individual components later in the disassembly and the reassembly processes need to be put in relation to the costs associated with cannibalisation, as further discussed in Papers II and IV.

Deciding whether to recycle the core is a question of if the core can be useful in the future. This depends on if there will be a potential market demand in the future, and if there are other cores available to be remanufactured or cannibalized, as well as the status of these cores with respect to the present core.

### 7.3 Disassembly Phase

After the decision is taken to remanufacture a core or cannibalize it for components, the cores are sent to disassembly. When the component has been disassembled from the core, another important decision must be made regarding the state of the individual components: if they are reusable in their current status or are reprocessable. This decision is made in Decision Point 2 in Figure 36.
The disassembly of a core can possibly involve a number of different activities where different separating operations are the most prevalent as seen in Figure 36. In the Volvo Parts case, the complete core is disassembled. During the disassembly operation, the components are inspected to determine if they are reusable or reprocessable; if not, they are sent to recycling. Some of the components may be reusable or reprocessable, but are still recycled. For example, all of the case companies have policies in place to always exchange certain components. These policies can be driven by reliability or security reasons, (see Paper IV). In all, the different characteristics of the components are important factors for the overall material flow.

For the decision of what to do with the components, there are several economical factors that influence the choice. Take, for example, a battery from a forklift truck in the BT case. Here, the battery may be in working condition, although it could have only 30% of its normal capacity. Installing this used battery in a remanufactured product will mean that the customer must replace it after a short period, potentially creating a warranty claim or badwill. Alternatively, the battery could go through a reprocessing activity that, for example, would change a cell of the battery and return the battery’s work capacity to 60%, or the battery could be recycled. Some customers might demand the highest standard; in that situation, a new battery would be the only option. This issue and the effects on the remanufacturing process are further elaborated on in Paper V. As for the core, the appropriate way to handle the individual component depends, just as in the pre-disassembly phase, on many different decision variables such as:

- The cost for new components
- Potential costs for reprocessing
- Inventory carrying costs
- Inventory levels and values of components in the reassembly phases (new, used and reprocessed components)
- Lead-time to reprocess or to purchase new components
- Minimal order quantities in relation to future needs and the risk for obsolescence
- Quality level needed by the customer
- Availability of an upgraded version of the component.

**Figure 36:** The Disassembly Phase (Paper IV).
7.4 Reprocessing Phase

The components that are planned to be reprocessed can undergo a variety of different operations that aim to reprocess or raise the quality of a component. However, in some situations, the component might be found to be non-reprocessable; in this case, it is recycled, as seen in Figure 37. An example of this is a hidden crack in the housing of a brake caliper in the UBD case (Paper V).

In some situations, the reprocessing activities might make changes in the component that makes it incompatible with a standard core or a component. An example of this is when a cylinder in an engine is damaged and can be reprocessed by expanding the diameter. Here, the result is that a wider diameter for the piston has to be used compared to the standard. When doing so, the complexity of the process increases since the bill of materials (BOM) is changed (due to the difference in piston diameter). UBD has chosen not to remanufacture a product if it changes its BOM, as such a change creates excessive administration. This is not the situation in all cases. Volvo uses “over dimensions” as in the cylinder example. The difference between Volvo and UBD is that an engine has a higher value than a brake caliper, and thereby the additional cost is compensated for. In this phase, the major decision on if the component should be reprocessed is normally taken in the disassembly phase. Still, there are situations where the decision needs to be changed, due to for example the results of further testing of the component.

The extent of component reprocessing varies significantly between the different situations. The trend is that the more value in each component, the more feasible it is to reprocess. This is mainly due to the higher cost reduction potential; this depends, however, on the desired level of quality demanded by customers.

7.5 Reassembly Phase

In the reassembly operation, the individual components that have been separated from the core need to be reassembled. This can be done in four ways: with a reprocessed component, with the replenishment of a new component, with a reused component or with a component taken from a cannibalized product by ordering a disassembly
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operation. The mix of components to be reassembled is determined in the third decision point in Figure 37. The new component can be an exact copy of the original component or an upgraded one, depending on the customer’s needs.

In the UBD case, all of the components that are to be reused and have been reprocessed are stored together. Here, the challenge is to have the right number of each component. The missing components are replaced with mostly new components, but in some situations with used ones. Another alternative used by Volvo is that new, used and reprocessed components are stored together, and the specific amount is gathered from this common inventory. The advantage of the UBD scenario is that some material handling is avoided. In the Volvo case, the gathering process is simplified.

Regarding the decision of what components to use in the reassembly of the remanufactured product, the used components should be used in the first hand, because, ideally, they should have the lowest cost (if not, they should have been recycled in earlier phases). Even so, some of the components might need to be replaced with a new component due to differences in customer needs (as, for example, in the battery example presented earlier). Once a component is discarded, it needs to be replaced with another component; here, the first priority is the reprocessed components, if they are available. It is possible that the lead time for reprocessing may be too long, meaning that components might not be available in time. Some components can also be cannibalized from cores if the new component cost is too high.

One of the major obstacles in controlling the remanufacturing is the uncertain material recovery rates. Ordering and storing new components is used to compensate for the lack of reusable components. This solution, however, is not ideal for all components, because it demands inventories, and thereby capital, and thus it could lead to obsolescence problems. One solution made by Volvo is to forecast the material recovery rate (MRR) of each component; this is set by experience. Based on this, a percentage of the components is ordered for a specific order. An example of this can be when 12 engines are to be remanufactured and 40% of the 12 camshafts are predicted to be recycled; in this situation, the company would order five new ones. The material flow and the planning of the process in this phase is further discussed in the analysis for research questions 5 and 6, and described in Papers V and VII.

7.6 Post-Assembly Phase

When the core is reassembled, it is ready to become a finished remanufactured product. In this phase, the products are put into working order. For example, software might be upgraded to the latest standard (as in the Volvo case). The functionality might also be tested. Other operations can include painting and preparations to send the remanufactured product to the customer.
7.7 Discussion

The main contribution of the general remanufacturing process is the descriptive nature of the results. The result from this section provides an important tool for further analysis. The formulation and the distinction of the five remanufacturing phases is a clear effect of the three major questions in the process. These decisions are made at the decision points in the remanufacturing process shown in Figures 34 – 37, and are as follows:

1. Whether to remanufacture the core, cannibalize components or recycle the core.
2. Whether to reuse, reprocess, or recycle the individual components.
3. Which components to reassemble into a remanufactured product.

In this dissertation, five distinct phases have been identified, phases which are always present in a complete remanufacturing process:

- Pre-disassembly phase
- Disassembly phase
- Reprocessing phase
- Reassembly phase
- Post-assembly phase

How the decisions taken in the remanufacturing processes are linked to the material flow can be seen in Figure 34. An evaluation of how these decisions affect the remanufacturing phases and the operations within these phases has been made in the analysis. Some general conclusions regarding these decisions are as follows:

The main purpose in the pre-disassembly phase is to evaluate what to do with the core. This is done to support the first decision in the process (Whether to remanufacture, cannibalize components or recycle the core). This decision is taken in the first decision point in Figure 31. Given the purpose of this phase, there are some specific operations that can be used, such as inspecting, testing, cleaning and sorting. The decision taken in this phase has a major influence on the overall result of the remanufacturing process.

When the first decision is made, the core enters the disassembly phase with the main purpose to separate and evaluate the individual components. This is made to enable the second decision (Whether to reuse, reprocess, or recycle the individual components). This decision is taken in the second decision point in Figure 34. The decision that is taken in this phase also has a high degree of influence regarding the material flow.

The reprocessing phase has the purpose of restoring the functionality of a component from the core to a specific quality level. This process is highly dependent on the result of the second decision.
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The purpose of the reassembly phase is to assemble the components into a remanufactured product. This phase is dependent on the third decision *(Which components are to be reassembled into a remanufactured product)*, which is made in the third decision point in Figure 34. In this phase, the planning of the material flows is a key issue for success.

The post-assembly phase has as its purpose to ensure that the remanufactured product corresponds to the quality level required by the customer.

These decisions not only concern the organisation of the process, but also the management of the material flows. Concerning the decisions in the process, the second and third decisions have the highest influence on the material flow. This is because the components are separated from the core, thereby increasing the complexity as well as the planning needs. In the remanufacturing process, this is linked to the disassembly, reprocessing and reassembly phases.
The previous chapter addressed the remanufacturing process as a process model with distinct phases and important process decisions that have to be made. In the following two chapters, the focus will be on how to make this process more competitive. In this chapter, the focus will be on how material planning and production planning can be a solution for making the remanufacturing process more competitive, especially by using principles from lean manufacturing, thus addressing the question of:

**RQ 5:** How can lean principles for material planning and production planning be applied for remanufacturing?

The analysis in this study regarding the material flow will focus on two categories: material planning and production planning. In this study, material planning refers to the coordination of incoming material, both cores and new replacement components, with the customer demand for remanufactured products. Production planning is defined as the coordination of the different processing phases (pre-disassembly, disassembly, reprocessing, reassembly and post-assembly).

### 8.1 Material Planning on an Aggregated Product Level

In the remanufacturing environment, one of the characteristics is that the demand for remanufactured products (output) and the returns of cores (input) is not always synchronised. Rather, the rate of product returns is dependent on the characteristics of the product life cycle. The balance between product returns and demands for products is a function of many variables, where the rate of technological innovation and the expected life of a product are the major influencing properties. (For further details regarding the research about balancing supply and demand, see Guide (2000); Umeda et al. (2006) and Paper II.)

Another major difference between the remanufacturing and manufacturing process is the disassembly phase of the process. In manufacturing, the majority of the components for a product can be sourced independently of the other components. In
remanufacturing, the sourcing of components is a result of the disassembly of a core, thus becoming dependent of each other. This is illustrated in Figure 37.

![Figure 37: The dependency between a core and a product in remanufacturing.](image)

The dependency between the components combined with variations in the amount of components recovered for a core are a limiting factor for using the principle of a demand pull on a component level. An example of this is an engine to be remanufacture, which when after disassembly and inspection, it becomes obvious that some components cannot be reprocessed, for example the crankshaft, fuel pump and the cylinder head. The result is that these components then must be replaced. This can be done either by cannibalizing a core for components, or by using new components. If the cannibalisation alternative is used, disassembly will generate the needed components, but it will also generate a lot of other components due to the interdependency between the components. In the remanufacturing environment, this becomes a planning issue. In the remanufacturing cases observed for this study, the solution used by all of the case companies is to first plan according to the supply and demand of a core to remanufactured product level, and then to break it down to component level.

There are principally two ways to plan material flows: (a) planning for the demand of remanufactured products (Make-To-Order) and (b) planning according to availability of cores (Make-To-Stock). This is illustrated in Figure 38.

![Figure 38: The aggregated planning perspective.](image)
8.1.1 Planning for Remanufactured Product Demand

In the Volvo, Tetra Pak, Swepak and BT cases, the planning focus was on the number of remanufactured products to be produced; this means that the number of remanufactured products that are produced are fixed according to customer orders (Illustrated as an X in Figure 38). Still, due to the option of cannibalizing components there are situations where more cores are used in respect to the demand for remanufactured products, hence, the number of products that enter the process are variable (illustrated as a “?” in Figure 38). For example, the production planning might demand four products to be remanufactured, but six cores enter the process. Hence, the extra two cores that enter the process are cannibalized for components instead of being remanufactured. However, in the observed cases there was more or less a one-in and one-out (1:1) relation between cores entering and products leaving the process. This was especially true when the products were new to the market; that is, when the supply of cores suitable for cannibalization was low. Later in the life cycle, when cores were easier to find and less expensive, the companies reported that they tended to use cannibalization as a planning option more often.

8.1.2 Planning according to Availability of Cores

Both UBD and Scandi-Toner used a reorder-point system for initiating remanufacturing orders. The planned remanufacturing orders were dependent on the number of cores that were available in inventory when the order arrived, thereby becoming fixed (illustrated with an “X” in Figure 38). These cores were then sent through the process, and the numbers of recovered products from the process was dependent on the quality of the incoming cores and the possibility to remanufacture them according to the objectives of the company. This variability is generally not considered as a critical from a material control perspective, since the remanufactured products are used to fill up an inventory (although variation in capacity usage does influence production planning, as discussed in the following section).

8.2 Material Planning at Component Level

On the aggregated level, the material planning problems were focused on balancing demand for remanufactured products and the supply of cores. On the component level, the problems addressed the uncertainty in the number of components recovered from the returned items. The components that were broken or faulty needed to be reprocessed or exchanged by a new component. From the material planning perspective, the components can be separated into different planning categories. These categories, shown in Figure 39, are:

1. Components that are always replaced
2. Components that can be reused or reprocessed
3. Components that are found unusable, but can be ordered before the reassembly start date
4. Components that are found unusable, but have to be ordered according to forecasts
8.2.1 Components that are Always Replaced

Some components in a remanufactured product are always replaced with a new component. Normally these components are wear-and-tear components, for example, pistons and roller bearings in an engine. The components in a remanufactured product can also be upgraded to the latest standards; one example is the electronic control units in the filling machine (Tetra Pak) case that are replaced by components of the latest standard. When components are always replaced, there is no need to consider the specific characteristics of remanufacturing, as for example variations in the material recovery rate (MRR), since no components in this category is reused. As a result, all of these components can be sourced independently of what happens in the forthcoming remanufacturing process. Material planning for this category of component is the most predictable. When the customer orders for remanufactured products are issued, the exact demand for components can be calculated without any need for disassembly or inspection, just as in a manufacturing situation (Figure 39). Still, some complicating factors might cause planning problems. One practical example of this is that ordering lead-times for new components can be longer then the time between the confirmation of a remanufacturing order and the reassembly start date; this is illustrated as a
“additional planning horizon due to ordering limitations” in Figure 40. In these situations, the components have to be ordered according to forecast and placed in inventory. Minimal order quantities accepted by vendors can also pose disadvantages when higher than the confirmed demand for components (confirmed demand of products refers to the orders from customers opposed to orders generated by forecasts); as a result, some of the components are ordered according to forecasted demands.

**Figure 40:** Planning horizons for the different component categories.

### 8.2.2 Components that can be Reused or Reprocessed

These are the components that in some situations can be reused or reprocessed; this decision is dependent on the quality of the single component. An example of these components is broken housings for the brake callipers (UBD case) that can be reprocessed in some situations. The ratio between reusable and non-reusable components is described as the material recovery rate (MRR), as shown in Equation 3 in the theoretical framework. For these components, the confirmed demands are not known until the components have been inspected and approved for reuse/reprocessing. For some types of components, the status of the component can be assessed before disassembly is undertaken (pre-disassembly phase). For other components, the components might need to be disassembled from the core before inspection/testing can be done (disassembly phase). From the planning perspective, the result is a shorter planning horizon for the components inspected in the disassembly phase.

For components that are being reprocessed, the reprocessing operation has to be done within the timeframe between disassembly/inspection/testing and the time in which reassembly is undertaken; this can be referred to as the *reprocessing window* as seen in Figure 41. If the components can be reprocessed before reassembly is undertaken
(within the reprocessing window), they can be reused in the same core; otherwise these components need to be sourced in a different manner, e.g. from a reprocessed component inventory or as new components. Therefore, performing inspection as soon as possible can increase the timeframe for both ordering new components and the time available for reprocessing.

An example of the impact of the reprocessing window is taken from the remanufacturing of engines at Volvo Parts, as illustrated in Figure 41. In this case, the engines are remanufactured according to customer orders. The lead-time for customer delivery is three weeks. Hence, all customer orders within a timeframe of three weeks before the remanufacturing due date are confirmed. This three-week timeframe with confirmed customer orders is referred to as the “freeze window” in the lean literature. Customers also provide demand forecasts that consider future demands outside of the freeze window. The needed cores are delivered to the facility before the 3 weeks of freeze window, according to customer forecasts. Reassembly of one weeks’ production (deliveries to customers are performed once a week) are then planned to start about 1.5 weeks before the delivery due date. The disassembly of cores is planned to begin three weeks before the remanufacturing due date. As a result, the reprocessing window becomes less than 1.5 weeks, depending on how soon the disassembly operation can be performed. In the Volvo study, a value stream mapping investigation showed that some of the components could not be reprocessed within the reprocessing window, mainly due to high amounts of work in process. The main reasons for the high amount of work in process were unmotivated high batch sizes in combination with sequential operations with long throughput times, for example cleaning and drying operations (see the forthcoming section about production planning for additional details.)

![Figure 41: An example of the remanufacturing lead-time and the effect on the reprocessing window.](image)

### 8.2.3 Components that can be Ordered within the Lead-Time for Reassembly

This category of components is the components that have been inspected/tested and found faulty, and which are not economically viable to reprocess. In this situation, the preferable situation is to order the lacking components and have them delivered before the reassembly start date. If the inspection can be performed as early as possible, the chance to order according to confirmed need of components is higher. The information
about confirmed component demands can be used to create a customer pull for this category of components.

8.2.4 Components that cannot be Ordered Within the Lead-Time for Reassembly

The components in this category are the most difficult components to plan, and their lead-time is longer than the time available before reassembly, as seen in Figure 40. The components in this category can also be divided into two sub-groups. The first group is the components that are ordered according to the forecast of remanufacturing orders. In the Volvo example, this would be components that have to be ordered three weeks before the due date (outside of the freeze window). The second group is the components that can be ordered due to confirmed remanufacturing orders (within the freeze window); in the Volvo example, these are the components that can be ordered three weeks before the remanufacturing due-date and delivered before the reassembly is undertaken. Ordering components according to demand forecast for remanufactured products is, in comparison, a less favourable option since this group of components is sensitive to both uncertainties in future demand for remanufactured products as well as uncertainties in the number of recovered components (those subject to MRR). When ordering according to the confirmed demand for remanufactured products, the uncertainties in future demand are reduced. From a lean perspective, ordering components without confirmed customer demand (push principle) can result in unwanted waste.

8.3 Lean Implementation Solutions for Material Planning

In the previous section, four different component categories were presented, each of which had different characteristics that had different effects on material planning. Considering a lean perspective, it is important to actively adapt to these characteristics and to develop lean principles that are specific to the remanufacturing characteristics. Among the categories of components, the one with the worst implications for lean practice are the components that cannot be ordered within reassembly lead-time and have to be placed in inventory according to forecasts. One solution to make the remanufacturing process leaner is to try to transfer these components into the other “better” planning categories. A company can, for example, invest in reprocessing technologies and reprocess the component instead of manufacturing or purchasing it. The result of a reprocessing activity is that components can be moved to the reprocessable component planning category. The alternatives for adapting lean principles to the remanufacturing environment found in this study include:
• Improved reprocessing processes
• Component inspection as soon as possible to determine actual component recovery possibilities
• Cannibalization of components for some lacking components
• Reduction of sourcing lead-time for new components
• Reduction of minimal order quantities
• Expanding the freeze window in order to produce according to confirmed needs

These points will be described in detail in the forthcoming analysis. In Table 12, a summary is given regarding these different ways of implementing a more lean material flow and the effects on the individual component categories.

Table 12: Proposed improvement solution and the effect on the component categories.
8.3.1 Reprocessing Technologies
Reprocessing aims to process broken or worn components back to original specifications or better. By doing so, the costs for new components can be reduced. Reprocessing is generally an advantageous strategy for components with high purchasing/manufacturing prices, long purchasing lead-times and when there is low annual demand for new components that have to be kept in inventory. One disadvantage with this solution is that the possibilities for using reprocessing technologies are limited to some specific areas. Most of the reprocessing technologies that have been observed are additive technologies that add new material to broken or worn-out materials; these components are then machined to original specifications. The use of additive technologies is frequent in, for example, the automotive industry, with many mechanical components (as seen for example in the UBD and Volvo cases presented in Paper IV).

8.3.2 Inspection as soon as Possible
One of the major sources for instability in material planning is the effect of insecure material recovery rates (MRR). Planning according to a preset MRR is a frequent practice at remanufacturing companies, but from a lean perspective, preset MRR should be avoided. The main reason for using preset MRR is that components cannot be inspected before replacement components have to be ordered (due to e.g. long sourcing lead times). Therefore, they have to be ordered beforehand according to a preset MRR. If components can be inspected earlier, the time gap between inspection and reassembly can be extended. The earlier inspection can be undertaken, the more components can be ordered according to confirmed demands on a component level. The result of this is a higher opportunity to generate a customer pull. One major obstacle in many cases is that the status of the individual components cannot be inspected until disassembly is undertaken. Different techniques, such as on-line monitoring and other monitoring devices, can be used to communicate faulty components and therefore ease the material planning.

Even though the inspection operation gives information that is useful for the forthcoming material planning and production planning (see the following section), the studies at the companies show that normally this information is not collected and used as in practice (e.g. as in the Volvo case). The main reason for this is that there are no efficient ways of gathering and analyzing the information, and that the cost for administration is perceived as greater than the gains. One reason for this is that the use of MRR calculations for future new component demand shows a “good enough” result. Another important insight is that even if inspection can be performed earlier, the sourcing lead-times will still be too long. Another limiting factor is the minimal ordering quantities that force the remanufacturer to order batches of components that also cover forecasted demands. As a result, the category of components that can gain the most planning advantages from inspection operations are components with low sourcing lead-times and low minimal order quantities, which instead of being kept in inventory can be ordered just-in-time.
8.3.3 Cannibalization

Cannibalization of components from a core is a debated subject. The principle of cannibalization is based on two scenarios. In the first scenario, a demand for some components arises and all of the components from a core are disassembled. If the entire core is disassembled, it generates components with no demand and that have to be put into inventory for future demand or scrapped. In the second scenario, the cores are kept in inventory, and when the demand for component arises, a specific component is disassembled from the core. After the disassembly of the component, the core is placed in the core inventory again. However, when specific components are taken from a core it generates an administrative problem of keeping track of what components have been taken from what core.

If component cannibalization is to be regarded as an economically viable option for product recovery, then the cost savings of cannibalizing a core for components should be higher than the gain from other product recovery options, as discussed in Paper II. These options can e.g. include remanufacturing the core or selling the core on the second-hand market. In practice, this means that for cannibalization to be a viable option, there has to be an excess of cores on the market compared to the demand of remanufactured or reusable products. This situation is mostly common when the product has been on the market for a while and the product is in the later phases of its life cycle. However, under specific characteristics cannibalization is a viable solution. This is especially true for components with a high chance of retrieving a reusable component from a core (high MRR). In the case of components with a low MRR, the opposite is true; in many cases, several cores have to be cannibalized before a reusable component can be found. For components with a high MRR, the general demand for new components is generally low – simply because the component seldom breaks. The low demand for new components will also generally have a negative impact on the ability to purchase new components at a competitive price and lead-time for sourcing.

8.3.4 Reduction of Ordering Lead-Time and Minimal Ordering Quantities for New Components

The long purchasing lead-times for new components are a hinder for employing a just-in-time principle. If the sourcing lead-times can be lowered, the possibilities for ordering more according to confirmed demands will increase. Guide et al. (2000) report that the main reasons for long lead-times are that: 1) components are no longer in production; 2) the component has a sole supplier; and 3) the purchase orders are small (resulting in unresponsive vendors). Another issue for many components is that the minimal order quantities force the remanufacturer to order batches of products that are greater than the actual demands. A result of the minimal ordering quantities is that a part of the order will be made according to forecast. To be able to reduce ordering lead-time and minimal ordering quantities, remanufacturing companies have to work together and develop relations with their suppliers.
8.3.5 Expanding the Freeze Window

To compensate for long ordering lead-times and long reprocessing throughput times, one solution is to expand the freeze window. The result is that more components can be ordered according to confirmed demands enabling a customer pull. There is also a greater chance that reusable components can be reprocessed within the reprocessing window and be used in the same core as from which it was disassembled. Negative impacts are that the ordering lead-time in a make-to-order case will be extended. In a make-to-stock environment, the amount of safety stock will have to be increased due to an increase in remanufacturing lead-time.

8.3.6 Inventories

Some components simply have to be put into inventory. Generally, components with long ordering lead-times have to be ordered and put into inventory according to forecast. A negative impact on lean practice is that components are pushed forward instead of being pulled according to confirmed customer orders. The result is a need for keeping components in inventory, something that also results in additional costs. Components with long lead-times are normally components that no longer are in production and with generally low annual demands; as a result, these components become sensitive to obsolescence. Another reason for storing new components in inventories concerns minimal order quantities, where orders have to account for future forecasted demands. Still, keeping components in inventory is a key cost driver in many remanufacturing companies (Guide et al., 2000). In the research there has been a strong focus on adapting different rule-based optimization models (e.g. heuristics for determining economic ordering quantities) for inventory management; for an overview, see e.g. van der Laan (2005).

8.4 Production Planning

To analyse the remanufacturing process from a lean perspective, the framework for the general remanufacturing process, as presented in Chapter 7, has been used. The framework from this chapter divides the process into five phases: pre-disassembly, disassembly, reprocessing, reassembly and post-assembly (Paper IV). In this part of the chapter, the remanufacturing process will be analysed.

8.4.1 Pre-Disassembly Phase

This phase can be described as a preparatory phase before the disassembly process begins. Normal activities in this phase include inspection, testing and sorting of the cores. The major purpose of this phase is to receive information about incoming cores in order to control the forthcoming process. One important aspect of this information is decision support in order to decide whether to remanufacture, cannibalize components or recycle the individual cores.
By inspecting cores and sorting them into quality categories, a capacity control mechanism can be created. Through the use of different quality categories, “hard” or time-consuming cores are remanufactured when the capacity utilisation is low; when capacity utilisation is high, “easy” cores are remanufactured. By sorting cores into different quality categories, a solution for levelling the workload is created. These quality categories can be used to control the effects of the uncertainty in MRR as well as the stochastic routings and variable processing times in the forthcoming phases. The variability cannot be reduced per se, but the information helps to balance the remanufacturing capacity on an aggregated level.

8.4.2 Disassembly Phase
After the decision is made to remanufacture a core or cannibalize a core for components, the cores are sent to disassembly. The disassembly phase can involve a number of different operations where separating is the most prevalent. Other operations in this phase are e.g. inspection and sorting. This phase is highly exposed to stochastic processing times due to different quality levels of the incoming cores. Broken, dirty, and rusty cores can be very hard to disassemble, and as a result, the cycle times for disassembly operations can be highly variable. This variation in cycle time strongly limits the possibility to introduce the lean principles of a fixed takt time and a levelled workload, and it limits a stable production process. The main reason for not being able to employ a takt time is mainly due to the waiting time that is generated due to variations in cycle times, resulting in major risk for balancing losses. Still, the possibilities for a levelled workload are not excluded due to the possibility of sorting cores into quality categories.

During disassembly, the majority of components can be inspected and the defective components are scrapped or sent to recycling; the remaining components are then reused or reprocessed. Information concerning the recovered components can potentially aid in both material planning and production planning. In material planning, this will confirm demands for replacement components, as discussed in the previous section. For production planning, information regarding confirmed reprocessing demands can be used to balance capacity in forthcoming process phases. Still, just as for material planning, the use of MRR calculations for capacity planning can be sufficiently shown. One reason for this is the short planning horizon between inspection and the reprocessing operations that limit the planning possibilities (see Figure 41 regarding planning horizons in the Volvo Parts case).

8.4.3 Reprocessing Phase
After the components have been disassembled they are reprocessed (or reused) if the quality level of the components is sufficient. The reprocessing phase aims to raise the quality of a component. The components can undergo a variety of different operations in this phase, such as testing, cleaning, different machining operations, painting, etc., all depending on the type of component.
From a planning perspective, the ideal situation is that the reprocessing operations of each component should be performed within the reprocessing window (time between disassembly and reassembly). If components cannot be delivered to reassembly before reprocessing has been initiated, a component from the inventory must be used (if available). Taking a lean perspective, this will constrain the use of a customer pull; thus, it is important to design the reprocessing phase so that the highest degree of components possible can be reused in the same core.

The reprocessing of components can be organised in two principal ways: either in parallel or in sequence. In the parallel situation, the components from a core are separated and reprocessed independently of each other. In the sequential situation, all of the components from a core are kept together and operations are undertaken one at a time, as illustrated in Figure 42. In the observed cases, none of the companies used purely sequential or parallel strategies; they applied a mix of both. The choice of reprocessing organisation has a substantial impact on important variables such as lead-time and material-handling efficiency.

**Figure 42:** Differences in accumulated lead-time in the reprocessing phase with a parallel and sequential flow.

**Parallel reprocessing**
When applying a parallel reprocessing organisation, the minimal theoretical reprocessing lead-time of the operations becomes equal to the throughput time of the longest component, as shown in Figure 42. From a material flow perspective, parallel reprocessing has the potential for a low throughput time and low levels of work in process (WIP). The negative aspects are that when separating components from a core it can create non-value adding activities in the form of extensive administration and complex material handling.

Normally, when the individual components are separated from the core they are placed in material holders that often are specialised according to the type of components. The components are then transferred to different reprocessing workshops. The possibility to apply a one-piece flow in a parallel material flow can be limited by material handling. The major limiting factor to employ a one-piece flow in the Volvo Parts case was the transportation costs between disassembly cells and the specific reprocessing workshops. The transportation between the workshops generated material handling costs, which in turn generated a need to batch components from multiple cores together to reduce the material handling costs. Other material handling activities that result in “ordering costs” can be the need to switch between specialised material carriers in between product categories. The reduction of material handling between
disassembly and reprocessing workshops is therefore important to work against a one-piece flow; this is the same logic as when reducing set-up times in machining operations. In practise, high material handling cost can result in material carriers that contain several days of production before transferred to reprocessing operations. In fact, cases have been observed with even higher levels, accounting for several weeks of production. Overall, this has a major impact on the lead-time of the system.

The parallel material flow can also generate many non-value adding activities. When separating the components, the natural link to the bill of materials (BOM) of the original core is lost, and several inspections might have to be done during the reprocessing operations just to keep track of the components. One solution to avoid multiple inspection requirements is to attach different types of labels that ease identification, although the labelling itself becomes a non-value adding activity. Another difficulty with inspection is that cores with material matching restrictions, meaning that the components from a core need to be used in the same remanufactured product, will demand additional administration.

Sequential reprocessing
Instead of separating the components, a second solution is to have components from the same core stored together on a material carrier that is transported through reprocessing in a sequential manner. The employment of such a strategy poses a number of advantages with respect to the parallel organisation. Firstly, it reduces the need for identification, sorting and handling in the disassembly operation. Secondly, it enables a one-piece flow. Thirdly, it reduces setup times in the disassembly operation because of a reduction in the material carriers needed. Fourthly, it solves the problems with material matching restrictions. A disadvantage of keeping components together in a material carrier proceeding sequentially between different reprocessing cells for different components is that the theoretical throughput time becomes the sum of the throughput times of all components.

For some components, the only opportunity from a lean perspective is to use a sequential material flow, especially when applying takt time, as discussed in Paper V.

Variation in processing times and effect of the material recovery rate (MRR)
The quality level of the incoming cores has a major impact on the reprocessing phase of the remanufacturing process, resulting in variances in processing times for example in the cleaning and machining operations. The variances in quality levels also have an impact on the material recovery rate. An example of this can be taken from the reprocessing of crankshafts at Volvo. To make the crankshafts reusable there is a need to smoothen specific surfaces, which is done by grinding the surface material. Depending on the amount of surface unevenness, there will be different processing times according to the amount of material that has to be removed. In the case of crankshafts, there is also a limitation on how much material that can be removed. For instance, if the unevenness of the surface is too high, the component cannot be reused.
In a situation applying a one-piece flow through the reprocessing operations, the impact of the variations in processing times and the MRR can be illustrated as in Figure 43. This figure illustrates the case of a component from eight cores entering one workstation in a one-piece flow. The figure illustrates the unevenness in processing times for the individual objects as well as the effect when the object has previously been rejected (e.g. in the disassembly phase). From a lean perspective, these characteristics have a negative impact on the possibility of implementing principles like stable production processes and a levelled workload. The MRR will create a waiting time when the component from the (scrapped) fourth and sixth cores are supposed to be reprocessed; this will then demand WIP buffers. When applying a takt time, the takt is calculated according to the maximum processing times, resulting in balancing losses when components requiring shorter processing times are processed. From a lean perspective, the possibility of implementing principles of a one-piece flow and takt time are constrained.

Figure 43: Simulation of an operation time outcome of 8 cores in a one-piece flow.

Lean implementation solutions for reprocessing operations
In the reprocessing phase, highly variable processing times and stochastic routings imply limitations of the flow. The effects of the characteristic uncertainty in materials recovered add additional complexity. These two characteristics can be derived from the quality of the core and have to be considered, although division of cores into quality categories can partly mitigate the effects of uncertainties in MRR. From a lean perspective, it becomes important to try to reduce the effects of the MRR and the variations in cycle time. Some solutions that can be used to reduce the effects are:

- Reprocessing technologies
- Work in process buffers
- Solutions for a levelled workload
  - Cannibalisation
  - Compensating low capacity with new components
Reprocessing technologies
The use of reprocessing technologies can possibly increase the MRR – reducing balancing losses in a one-piece flow. Taking a one-piece flow perspective, the use of reprocessing technologies can also result in some negative effects. For example, the use of additive technologies will demand additional operations where material is added onto the component before machining can be undertaken. These additional operations are not used on every reprocessed component, thus adding variations in processing time and the introduction of stochastic routings. Still, the reprocessing activity addresses the wastes of scraping reusable components and is a value-adding process.

Work in process buffers
Using a one-piece flow with a takt time can create a large amount of waiting time in workstations due to balancing losses. If the use of a takt time is discarded and buffers of work in progress can be placed between workstations, then the buffers can work as a hedge against both variations in processing times as well as MRR. The negative effects with adding WIP is that it prolongs the throughput of the components and adds inventory carrying costs. The use of batches in production can be positive for the components with high variations in MRR or processing times due to the balancing losses that otherwise can occur.

Cannibalisation
Using cannibalised components as a replacement for scraped components can reduce the effects of variations in MRR. This will enable the use of a takt time in this respect. It would also provide a solution for maintaining a levelled workload, at least in the sense that capacity is utilised. The disadvantage with this solution is that it does not reduce the variations in processing times.

Compensating low reprocessing capacity with new components
When the reprocessing capacity becomes scarce, as for example at remanufacturing volume peaks or when incoming quality is low (resulting in additional reprocessing demands), there is always the possibility to source new components or to use cannibalised components that have been previously reprocessed and put into inventory. The existing inventory of components ready for reassembly (new or cannibalised components) can then serve as security against fluctuations in capacity requirements. The components that cannot be processed due to lack of reprocessing capacity are then rescheduled to periods with lower capacity utilisation. The negative effects of this practise are that components are placed in inventory. Hence, one important question is to decide which components are to be rescheduled. This is mainly a question of balancing costs for carrying inventory and the costs for capacity utilisation. Components that are well-adapted for rescheduling can, for example, be low-value components, with a low risk of obsolescence, high turnover and that also have a high strain on reprocessing capacity.
Quality categories
The effects of the MRR and variable processing times could partly be suppressed by inspection and quality categorization, making the capacity demands predictable. Sorting of cores enables a capacity control, i.e. when there is available production capacity, remanufacturing “hard” or time-consuming cores, and when capacity utilisation is high, remanufacturing “easy” cores. The negative impact when applying this principle is that there has to be an inventory of cores available. Therefore, this option is only suitable in situations where the supply chain characteristics result in a core inventory.

Work organisation
In situations where capacity demands can be increased by increased man-hours, a possible solution is to rearrange operators in the flow according to actual demands. Another solution is to reorganise the work content so that operators can perform value-adding tasks when waiting time arises, e.g. perform setups when switching between orders. This can reduce balancing losses and therefore reduce the effects of an uneven workload.

8.4.4 Reassembly and Post-Assembly
In the reassembly phase, the components are assembled. The components to be assembled can be taken from four sources: reused components, reprocessed components, new components or cannibalized components. In this phase, processing (assembly) times are not variable as in the disassembly and the reprocessing phases. When all components are available for reassembly, the remanufactured products can be reassembled in a procedure similar to manufacturing. Hence, the foundations for applying lean principles are equal to manufacturing environments, given that all components are available for reassembly. Although a general difference is that many more (different) products and versions are to be handled in the flow, this is especially true for the independent remanufacturers that remanufacture many different brands of products.

Complications in previous phases can result in not all of the required components being available for reassembly, which in turn will negatively influence stability in this phase. When demands for a new component are calculated using MRR, problems can occur if the estimated MRR is false. The result in a false MRR is either a component shortage or excess inventories of new components. Therefore, a correct estimate of the MRR will have a great impact on the inventory management.

The possibility to create a customer pull for new components is also limited, mainly due to long purchasing lead-times and high minimal order quantities from suppliers. If a purchase lead-time extends the freeze window for orders, the products must be ordered according to forecasts or kept stocked, thereby hindering a just-in-time material flow. If just-in-time deliveries and contracts could be used the principle of customer pull could be realized, although, according to management, the negotiation position for remanufacturing companies is not high when forming purchase contracts with suppliers.
The specific characteristics of the reassembly phase and the material handling in this phase will be further developed in the next section addressing material handling.

### 8.5 Discussion

In this section, the focus has been on the material flow and how different solutions that specifically target the remanufacturing system, can make the process more competitive. In the analysis section, the material planning and production planning were addressed independently, but the linkage between the two was shown to be strong. For example, one factor that has a major impact on the material flow is the setup of customer order to delivery process, and especially the time between fixed order deliveries for the remanufactured product. This puts major limitations on the organisation and planning of the remanufacturing process in general, and sequentially also on the material planning horizons.

Applying lean principles in a remanufacturing environment can be difficult. One foundation for implementing lean principles is the existence of standardised processes that are stable and predictable. In the remanufacturing process, the possibility to realise such a predictable process is limited by the “normal” variations in quantity and quality of returned cores. An important conclusion that can be drawn from this study is that the inherent characteristics of variable processing times and uncertainty in materials recovered have the major negative impact for implementing a lean production process. Vice-versa, given an accurate supply of cores for reassembly, all the principles of a lean material flow in normal manufacturing can be implemented in the phases of reassembly and testing.

The analysis section of this chapter presents different solutions that can be used to reduce the hindering characteristics of remanufacturing. Each of these solutions has different effects on different process phases and categories of components. To summarise, the proposed solutions for making the material flow lean can be a source of inspiration to the lean practitioners in their daily task of reducing different types of waste.
In the previous section, the material flow in the remanufacturing process was addressed. One major conclusion from the previous section was that the uncertainty in recoverable components puts limitations on the efficiency of the process, something that has implications for both the reprocessing phase (as described in the previous section) as well as the reassembly phase. In this section, the focus is on the reassembly phase. In the reassembly phase, the major difficulty linked to the uncertainty of recoverable components is to coordinate the replacement material for the components that have been found non-reusable. The formal research question was formulated as:

RQ 6: What principles for material handling can be suitable in the reassembly phase?

According to the Material Handling Industry of America (2005), “material handling and logistics is the movement, protection, storage and control of materials and products throughout the process of their manufacture and distribution, consumption and disposal.”

In Paper VII, there is a focus on coordination of the reassembly phase and its implications on material control and replenishment strategies for new components, material movement, and storage for both new and reprocessed components. This was investigated in the Volvo Parts case.

Compared to ordinary manufacturing, remanufacturing in the Volvo case suffers from low inventory turnover and large amounts of tied-up inventory. One reason for the inventory levels is the obsolete components that have been accumulated over the years; another is the relatively large number of components with a low demand (see Paper VII).

The components from a core can be divided in to different material control categories as explained in the previous section. For this case, the interesting categories are the categories that are subject to uncertainties in materials recovered. These categories are the components that undergo some sort of reprocessing or reuse without
remanufacturing (Paper V). The only category of components that is not effected by this characteristic is the category of components that are always replaced or upgraded.

The components that are subject to reprocessing or are reused demand special attention; see an illustration of the material flow of these components in Figure 44. In the following sections, the focus will be on this category of components.

![Figure 44: Components that undergo some sort of reprocessing or reuse (gray, dotted lines) and may have to be replaced by new components (black, solid line).](image)

### 9.1 Material Planning Principles

The components that undergo some sort of reprocessing or are reused have some specific characteristics. These characteristics can be a basis for making decisions regarding how to control these components.

![Figure 45: The separation of components in material handling groups.](image)
By using the principles of the ABC analysis (i.e. the Pareto principle, not Activity Based Costing) and the AC model for material planning described in the theoretical framework, some general groups of components can be identified. (For further details concerning this analysis, see Svensson et al. (2004) or Paper VII.) Firstly, the valuable components with a low demand are identified. These are referred to as problem components, and are the first category to be sorted out according to Criteria I as illustrated in Figure 45. This group should try to capture the components that have a high risk for obsolescence or that are critical in the material planning (long lead-time, high price, etc.).

Secondly, the focus is on the components that need to be planned with sophisticated methods, using for example MRR forecasts. For these components, the value and general advantages of using sophisticated methods surpass the cost of these methods. The other category of components and those that can be planned using more simple methods are generally bulk components that are ordered frequently or cheaper products with low demand that have limited effect for material handling cost.

To sort components into these material handling categories, the ABC analysis is used with value of usage as the key variable (value of the component multiplied by the annual demand of the component). To identify the components that need to be controlled with sophisticated methods, the value of usage has to be high enough to motivate the cost for the control. To exclude some high-volume components with low value, a constraint is that the value of the component should be sufficient. These components are here forward referred to as “A-components”.

The components that have not been listed as A-components are regarded as components that can be controlled with simpler control methods and are referred to as “C-components”. We also make a distinction between the C-components based on the demand pattern. Components with a higher and more stabile demand rate on an aggregated level could be treated as independent, as further discussed in Paper VII.

### 9.2 Material Planning Framework

After the identification of the characteristics, a framework is created with four groups. The principle of the AC analysis is to sort out the components in different groups. This is done by using different criteria for each sorting as seen in Figure 45. The variables used are value, demand and value of usage. Value of usage is the sum of the value of a component multiplied by the demand for the same component. These criteria are also presented in the second to the fourth rows of Table 13.
Table 13: A summary of the material handling framework

<table>
<thead>
<tr>
<th></th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>Group IV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Problem</td>
<td>A</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td><strong>Value</strong></td>
<td>&gt; X (high)</td>
<td>&gt; Y (high)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Demand</strong></td>
<td>&lt; P (low)</td>
<td>&lt; D (low)</td>
<td>&gt; D (high)</td>
<td></td>
</tr>
<tr>
<td><strong>Value of Usage</strong></td>
<td>&gt; V (high)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Planning</strong></td>
<td>Manually influenced, based on MRP</td>
<td>MRP based on forecast</td>
<td>Reorder point</td>
<td>Reorder point</td>
</tr>
<tr>
<td><strong>Movement</strong></td>
<td>Kitting</td>
<td>Kitting</td>
<td>Kitting</td>
<td>Two-bin system</td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td>Depending on situation</td>
<td>Central storage</td>
<td>Central/automated storage</td>
<td>Two-bins and automated/central storage</td>
</tr>
<tr>
<td><strong>Planning Priorities</strong></td>
<td>Minimise obsolescence, order quantities, cannibalisation</td>
<td>High control of processes, correct order quantities, effective safety stocks, forecasting, supplier collaboration</td>
<td>Minimise material handling and storekeeping costs, cost-effective control, stock-out costs</td>
<td>Stock out costs, safety stock, cost-effective control</td>
</tr>
<tr>
<td><strong>Storage Comments</strong></td>
<td>Cost effective storage</td>
<td>Dividing storage into high and low flow zones according to demand</td>
<td>Easily accessible</td>
<td>Stored in connection with the assembly operation</td>
</tr>
</tbody>
</table>

For sorting the components into the categories, a series of criteria testing is used. First, the first criterion (Group I - with a high value and a low demand) is used to sort out the components for Group I. The components that fit in with the criteria for Group I are placed in this planning group. Then, the remaining components not applicable for Group I are then tested for the remaining groups, as illustrated in Figure 45.

The method for using the model is as follows. First, Group I components are identified; these are the problem components and are sorted out first by the criteria sufficient high value and then by relatively low demand. Group II components are identified from the remaining components that have not been associated to Group I components. The remaining groups are also sorted out in the same manner. Group II is sorted out using a sufficient value of usage; this is made according to the ABC method, although for material handling issues the components must also have a relatively high value. The remaining C-components are then sorted into two groups based on if they have a high or low annual demand.

A summary of the proposed framework is given in Table 13. (For further details about the principles, see Paper VII.)
9.3 Material Movement and Storage

The analysis of the material movement and storage is concentrated on the reassembly phase, hence involving reused, reprocessed, and new components. For the movement of components from the inventory to the assembly facility, there are two major options: transportation of components to a designated location (line storage), and the kitting operation that transports unique sets of components to be combined in the reassembly operation. The choice of material movement and the material control principles together affects the appropriate solution storage.

Two-bin System
The two-bin system is a common tool for material movement and storage in assembly situations. The method is cheap and easy-to-use. The system is used in situations where there is a high demand for the components, and in many situations where the turnarounds in the bins are high. In the remanufacturing situation, this type of handling is feasible for Group IV components with a high demand and low value. Typical components in this group can be screws and plugs. The components are stored in a central warehouse and then refilled when the refill order arrives. The inventory position in the central storage is known, but not in the two-bin system. This makes the inventory levels in the two-bin system unknown, and can create a planning problem if the turnaround is low.

For Group III components, the low demand, the high inventory levels, the invisibility and the obsolescence risk make the two-bin system infeasible.

Two-bin Storage
The area of the two-bin system is limited, and thus the amount of space for components is limited. Some components in Group IV that are suited for two-bin control can be unsuitable for two-bin storage, since they are too large or demand excessive space. The components in the two-bin system are usually quite small and take up limited amounts of space. In this case, the use of a central inventory is required. The reason for this inventory is that the order quantity is larger than the quantity in the bins. There can be situations when the order quantity is less than the order quantity in the bin; here, the order could be initiated directly without passing through the central inventory (if lead time for replenishment is shorter than the time for usage of a order quantity) or handled by a kitting policy. An illustration of a two-bin system from Volvo Parts can be seen in Figure 46.
Figure 46: An example of the two-bin system in the reassembly line at Volvo (right image) and two examples of the working bin and the spare bin (left images).

**Kitting and Storage Keeping**

For components that demand more control and total visibility, the use of a kitting system is superior to the two-bin solution, especially for components with low demand. Groups I, II and III are thus most suitable for this type of material movement.

The parts that are most suitable for picking into kits are the ones that are ordered to be picked the most times. The number of times depends on the demand for the component, but also on the “normal” order quantity of a component. There are a number of different practical storage solutions for inventory (see e.g. Pareschi et al. (2002)).

Some components cannot be picked from storage due to some practical issues; for example, they can be too spacious or too heavy. These components have to be moved straight to the assembly operation, for example by a forklift. When moving a single unit from the inventory to the assembly operation, a cost arises and that has to be minimised. One way to minimise this cost is to minimise the time to find and retrieve a component. The use of an ABC-divided inventory, where the most frequent components are placed closest to the ground and the input/output point can be used as a tool to create a cost effective material storage and movement by minimising the total time to find and retrieve a component. Generally, Group I components are placed far
away from the input/output point, while Group II components are placed close to the input/output point, due to their demand pattern.

**Figure 47:** A material kit in remanufacturing (example taken from Volvo Parts).

### 9.4 Product examples

In order to show how the model can be applied in practice, some examples from the case study are presented. The components that are used in these examples are a belt pulley, a fuel injection pump, a screw and a camshaft.

**Belt Pulley**

The first step is to check for Group I; in this case, the value is medium-high and the demand low, although not low enough to be a problem component. Then Group II is checked. Here, the value of usage is low and therefore the demand pattern must be checked in order to decide between Groups III and IV. The demand is low and singular; therefore, Group III is appropriate for the belt pulley. Regarding the material handling, a Reorder Point option is preferred. The component should also be kitted and stored in a central storage facility.

**Fuel Injection Pump**

This is an expensive component with a low demand. Therefore, it should be considered as a problem component and controlled as a Group I component. This component should be under tight observation and controlled by MRP. Regarding material movement and storage, it should be kitted and stored, preferably in a cost-effective way.
**Screw**
This component is of low value and has a high demand. After checking the criteria for Groups I, II and III, we see that this component should be a Group IV component. This component should be controlled by the two-bin system in connection with the reassembly operation, and in our example, an upstream automated storage solution using an echelon inventory should be implemented. This should be done in order to create a cost-effective material handling and minimise the stock-out costs.

**Camshaft**
The value of this component is high, although not as high as that of the fuel injection pump, and the demand is medium-high. This makes the value of usage quite high, and the component is associated to Group II. This component should be closely watched using the MRP system. Close attention should be given to correct order quantities, effective safety stocks, forecasting, and good supplier collaboration. This component should also be kitted.

### 9.5 Discussion

One way to manage the material flows is to divide the components into several material handling groups. In this study, a framework for material handling is presented based on four different groups (see Figure 45). These groups are sorted into their respective groups by the use of four different quantitative criteria:

- Problem components – with a high value and a low demand (Criteria I)
- A–Components – with a high value of usage (Criteria II)
- C–Components – with a low annual demand (Criteria III)
- C–Components – with a high annual demand (Criteria IV)

Each of these groups has its own characteristics. To set the quantitative criteria for the material handling groups, the ABC analysis can be used. A list of how these groups can be managed is provided in Table 13.

The planning consideration in this framework is a further development of a method that is used in manufacturing (Hautaniemi et al., 1999); in this study, it has been adapted to the specific environment of remanufacturing.
PART IV – DISCUSSION AND CONCLUSIONS

In this section the results of the analysis part of this dissertation is discussed in relation to the overall aim of the dissertation. In this section there will be a more general discussion regarding the linkage between the individual research questions and what main conclusions that can be drawn from the research results. This section does also include a section on the future challenges for further studies in remanufacturing.
DISCUSSION AND CONCLUSIONS

In this section, the results of the analysis part of this dissertation will be discussed in relation to the overall objective of the dissertation:

The objective of this dissertation is to explore how remanufacturing companies can become more competitive through analysing and managing material flows and remanufacturing processes.

The objective of the dissertation was broken down into six different research questions that address some key areas identified in the overall remanufacturing system. The research questions that were formulated are as follows:

RQ 1: What are the drivers for companies to remanufacture products?

RQ 2: What strategies can be used for balancing returns of products suitable for remanufacturing with demand for remanufactured products?

RQ 3: What types of relationships exist between customer and remanufacturer, and what specific characteristics can be found in these relationships?

RQ 4: How is the organisation of the remanufacturing phases and the decisions taken linked to the remanufacturing process?

RQ 5: How can lean principles for material planning and production planning be applied for remanufacturing?

RQ 6: What principles for material handling can be suitable in the reassembly phase?

These research questions have been analysed and discussed in the previous sections. In this section, there will be a more summarised discussion regarding the linkage between
the individual research questions and the main conclusions and contributions that can be drawn from the research results. Starting with research question one:

RQ 1: What are the drivers for companies to remanufacture products?

The first research question addresses the drivers for remanufacturing. The analysis regarding this research question identifies that the potential for competitive remanufacturing is great when there is a clear win-win-win potential. Win-win-win situations can be described as when all actors gain from remanufacturing, meaning that the customer gets a quality product at a lower price, the manufacturer reduces its manufacturing costs and increases profit, and the environment gains from a lower environmental impact. The drivers for remanufacturers can be generalised to profit, company policy and the environmental drivers, as seen in Figure 48. For remanufacturing to be successful, these drivers are crucial, although this model does not propose that all of these drivers have to be present for a successful remanufacturing business.

**Profit**
- Cost reductions
- New business strategies
- Driver for new product sales
- Targeting new market segment
- Providing Spare Parts

**Environment**
- Legislation
- Moral and ethical considerations
- Green marketing

**Policy**
- Protecting aftermarket
- Brand protection
- Providing additional after market solutions
- Feedback to new product design

**REMANUFACTURING**

In a general sense, the profit motivation is the most prevalent business driver, but still there are situations where this motivation is secondary to policy and environmental drivers. This is especially true for OEMs that are involved in remanufacturing for policy reasons, for example, to promote new product sales, protecting after-sales as well as protecting brand image.

Linked to the overall objective, the results of the first research question are important for understanding what to aim for when developing a competitive remanufacturing system. The main contribution of this research result is that it is not only the traditional lower cost of remanufacturing that motivates companies to remanufacture products; other drivers can also be present. Another important contribution from this research result is the identification and the classification of the different drivers. In the existing body of literature, there have been case studies addressing similar research questions. Still, this study provides additional drivers that haven’t been identified previously, as well as integrating results from past research. By identifying the drivers for remanufacturing, the objective of the first research question is satisfied.
DISCUSSION AND CONCLUSIONS

The knowledge of the basic drivers that create a demand for remanufacturing is also an important input to the second research question that was formulated as follows:

RQ 2: What strategies can be used for balancing returns of products suitable for remanufacturing with demand for remanufactured products?

The second research question is in its essence focused on how to provide remanufactured products in a competitive way during all the phases of the product’s life cycle, that is, when the product is new on the market, reaches the peak of its sales and starts to decrease its sales. This question is focused on the problem of balancing the supply of cores suitable for remanufacturing with the demand of remanufactured products. Different authors have concluded that forecasting as a mean for reducing uncertainty in the exact timing and quantity of returned products is less effective than trying to forecast the general trends of remanufacturing volumes. The average use and life of a product or component can be tested and validated beforehand with different experiments, but this factor also depends on complex factors, for example, to what extent the product has been used and in which environment (to mention some variables). The rate of technical development also has a major impact on the demand for remanufactured products, and in some cases results in a sudden drop of sales for remanufactured products. In all, these insecurities make it difficult to accurately forecast the supply and demand for calculating exact return quantities and timing. The major advantage of using the life cycle as a foundation for balancing supply and demand is the insights it brings on a general/strategic level. To analyse remanufacturing and the supply and demand situations three different remanufacturing scenarios are used:

- **Product remanufacturing** – Used products are remanufactured to “as new” or “upgraded” status; an example of this category is the remanufacturing and upgrading of Tetra Pak filling machines.

- **Component remanufacturing** – Used components are remanufactured to “as new” or “upgraded” status; an example of this category is the remanufacturing of automotive components (UBD case) and toner cartridges (Scandi-Toner case).

- **Component cannibalisation** – Used products are cannibalised for components, and the components are then remanufactured to “new” or “upgraded” status. An example of this category is the cannibalisation of components from heavy trucks (Scania) and forklift trucks (BT Industries). In these cases, the component cannibalisation option is mainly a supporting activity for the product and component remanufacturing scenarios.

The possible remanufacturing volumes for a product are dependent on the relation and the shape of the supply and demand distributions. The case when remanufacturing is generated from end-of-use returns is illustrated in Figure 49. The exact shape of the distributions differs between different types of products. For example, the potential remanufacturing volumes of single-use cameras are high, as described in Section 3.2, due to the short average usage period that “pushes” the supply distribution to the left in
Figure 49. An opposite example is the remanufacturing of photocopiers to “as when produced status”, as described in Section 3.2; in this case, the machines are returned after an extended period of time, and the supply distribution is pushed to the right.

As illustrated in Figure 49, there is a breakpoint between supply and demand. This breakpoint also has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on e.g. identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing.

To increase the possible remanufacturing volumes, upgrading products to the latest standard is one possible solution for the product remanufacturing case. To make this a competitive option, the use of modular design strategies can prove to be promising solutions for upgrading key components. For component remanufacturing to become more competitive, it has to become a more attractive option with respect to the new component alternative. In addition, a more standardized and modularized use of components could increase the possibilities to cannibalize components for remanufacturing and reuse.

The main contributions from research question two are the support that it provides in different supply and demand situations. By using a product life cycle perspective, the supply and demand situations can be foreseen, and support given for possible strategies in these situations. The product lifecycle as a theoretical model has been the subject of numerous publications concerning new products (Kotler, 2003); the same, however, cannot be said for remanufactured products. In the literature review for this research question, there where only limited studies on the life cycle for remanufactured products, with the study made by Umeda et al. (2005) as the most prominent. Therefore, the results from the second research question and Paper II are an important contribution to the existing research in the area. By identifying and discussing the different supply and demand scenarios for remanufacturing, the objective of the second research question is satisfied.
DISCUSSION AND CONCLUSIONS

Before remanufacturing can take place, there have to be cores available for remanufacturing; before cores are available, they have to be supplied by customers. This, along with the take-back relationship between the remanufacturer and the customer, is addressed in research question three:

RQ 3: What types of relationships exist between customer and remanufacturer, and what specific characteristics can be found in these relationships?

As a conclusion, this study identifies seven general types of relationships between remanufacturer and customer:

- **Ownership-based.** This type of relationship is based on the product being owned by the manufacturer and operated by the customer, as for example in a rental, lease or product-service offer. Here, the control of the installed base is high and often regulated by contracts.
- **Service contract.** This type of relationship is based on a service contract between a manufacturer and a customer that includes remanufacturing.
- **Direct-order.** The customer returns the used product to the remanufacturer, the product is remanufactured and the customer gets the same product back (if it is possible to perform a remanufacturing operation).
- **Deposit-based.** This type of relationship is common in the automotive industry. When the customers buy a remanufactured product, they are obligated return a similar used product, thus also acting as a supplier to the remanufacturer.
- **Credit-based.** When the customers return a used product, they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.
- **Buy-back.** The remanufacturer simply buys the wanted used products from a “supplier”, e.g. the end user, a scrap yard or similar, or a core dealer.
- **Voluntary-based.** The supplier gives the used products to the remanufacturer. The supplier can also be a customer, but does not have to be.

Each company has different resources and abilities that limit it to some specific relationships. For example, the ownership-based and the service-based relationships are mainly linked to original equipment manufacturers, and are less common among the independent remanufacturers. As a result, none of these relationships are suited for every company. Another important issue is that these relationship structures are not used individually; in reality, some of these relationships are used simultaneously to complement each other. The ability to adapt a specific type of relationship is dependent on multiple factors. Issues such as the type of product and the interest from the customer to have a relationship will influence the success of a specific type of relationship.

Regarding the different types of relationships, the ownership and the service-based relationships have the highest control over the installed base, and have a favourable position in gaining information about the installed base. The higher degree of control gained by the detailed information can decrease uncertainty in the quality level of the
incoming core. This information, combined with detailed contracts about the duration of the contracts and the point of return, makes the remanufacturer able to predict the timing and quantity of the returns and ease the need to balance returns with demand.

Regarding deposit and credit-based relationships, the major difference is the level of control. The credit-based system has an additional function of stimulating the customer to return specific cores. This system also stimulates cooperation between the parties. The accumulation of credits also stimulates a long-term commitment to the remanufacturer. Overall, the credit-based system relies on commitment, trust and a win-win situation, compared to the more transaction-based and deposit-based relationships. In this type of relationship, the gatekeeping function is very important. Gatekeeping in this context means the screening of the cores that are coming back to the entry point of the reversed logistics network. The foremost important issue of the gatekeeping function is inspecting cores and giving the appropriate number of credits. These kinds of relationships are mostly used for component remanufacturing, since they are used in make-to-stock situations where remanufactured components often are sold from a retailer’s inventory.

Voluntary-based relationships are based on the idea that the customers will voluntarily give back the core. This relationship system can also be forced on the customer and the OEM with take-back laws. To stimulate customers to return their used products, relationship management becomes important. Some negative effects of this system are that it can generate a high supply of cores that in many situations has a low demand for remanufacturing. It can also lack the ability to motivate the return of valuable cores that have a high demand for remanufacturing. The environmental advantages of remanufacturing are strongly promoted as a motivational factor due to the lack of financial stimuli.

The main contributions of answering the third research question is the general categorization of the different kinds of customer relationships. An additional contribution is the description of the characteristics of these relationships. In previous research for the take-back of products, the focus has been on quite technical issues, as for example what product properties are suitable for remanufacturing and how these are collected and transported back to the remanufacturing site. The previous research regarding the typical relationship with the customer, on the other hand, is limited to dispersed observations. The results presented in this dissertation shows that managing the relationship with the customer is a key aspect for the competitiveness of a remanufacturing company. By identifying the relationships and the characteristics of these relationships, the objective of the third research question is satisfied.

Up to this point, the discussion has been focused on the external processes. From this point forward, the discussion will be focused on the research questions that mainly consider the remanufacturing process within the factory walls. Starting with the fourth research question:
RQ 4: How is the organisation of the remanufacturing phases and the decisions taken linked to the remanufacturing process?

This question addresses the formulation and organisation of a general remanufacturing process. One of the main points with the formulation is also to describe the remanufacturing process so that it can be analysed in comparison with different remanufacturing cases. The advantage of a formulation of a general remanufacturing process is that it can be used as a general framework for further studies. Judging from the experiences gained from previous research and different remanufacturing cases, there are many different ways to organise a remanufacturing process (Sundin, 2004). In a dissertation by Sundin (2004), a generic remanufacturing process was developed; this general framework proposes that the order and organisation of the different remanufacturing “steps” is very case-dependent. In Paper IV, the analysis continues on the framework presented by Sundin (2004) with additional details. This study shows that are some general characteristics that appear to be valid in all situations – such as disassembly being conducted before reprocessing, and reprocessing being done before reassembly – and that the order of the operations in remanufacturing, such as inspection, testing, cleaning etc., are situation-dependent.

Based on the generic remanufacturing process (Sundin, 2004), remanufacturing can be divided into the following five phases (see Figure 50):

- Pre-disassembly phase
- Disassembly phase
- Reprocessing phase
- Reassembly phase
- Post-assembly phase

![Figure 50: An overview of the five remanufacturing phases (Paper IV).]
The specific order and purpose of the operations that define the process is dependent on a number of factors and decisions. In each phase, there can be one or many operations. In Figure 50, the specific set of operations will be illustrated in the same manner as the generic remanufacturing process described by Sundin (2004).

The formulation and the distinction of the five remanufacturing phases is a clear effect of the three major questions in the process. The decisions that are made in the decision points in the remanufacturing process are the following:

1. **Whether to remanufacture the core, cannibalize components, or recycle the core.**
2. **Whether to reuse, reprocess, or recycle the individual components.**
3. **Which components to reassemble into a remanufactured product.**

The timing of the different decision points in respect to the remanufacturing process can be seen in Figure 50. These decisions not only concern the organisation of the process, but also the management of the material flows. Concerning the decisions in the process, the second and third decisions have the highest influence on the material flow. This is because the components are separated from the core, thereby increasing the complexity as well as the planning needs. In the process, this is linked to the disassembly, reprocessing and reassembly phases.

The main contributions regarding research question four is a further detailed development of the general remanufacturing process as described by Sundin (2004) and Guide (2000). The identification of the important decision points in the remanufacturing process also have an major impact on the understanding of the remanufacturing process in general, and how this influences both the organisation of the remanufacturing process and the material flow in the remanufacturing process. By identifying these factors, the objective of the fourth research question is satisfied. The results from research question four and the view on the general remanufacturing process developed in Paper IV also provides a foundation for the forthcoming analysis to research questions five and six. Starting with research question five:

**RQ 5: How can lean principles for material planning and production planning be applied for remanufacturing?**

This research question addresses how material planning and production planning can be a solution for making the remanufacturing process more competitive, especially by using principles from lean manufacturing. The results show that applying lean principles in a remanufacturing environment can be difficult. One foundation for implementing lean principles in new production is the existence of standardised processes that are stable and predictable. In the remanufacturing process, the possibilities to realise such a predictable process are limited by the “normal” variations in quantity and quality of returned cores. The main conclusions that can be drawn from this study are that the inherent characteristics of variable processing times and uncertainty in materials recovered have the major negative impact for implementing
DISCUSSION AND CONCLUSIONS

lean production principles. Vice versa, given a predictable supply of incoming components for reassembly, all the principles of a lean material flow in normal manufacturing can be implemented in the phases of reassembly and testing.

Even though lean principles can be problematic to implement in the remanufacturing environment, this dissertation proposes a number of solutions that can be used to make the remanufacturing process more competitive from a material planning perspective:

- Improved reprocessing processes
- Component inspection as soon as possible to determine actual component recovery possibilities
- Cannibalization of components for missing components
- Reduction of sourcing lead-time for new components
- Reduction of minimal order quantities
- Expanding the freeze window

A similar list can also be created for process planning:

- Improved reprocessing processes
- Work in process buffers
- Solutions for a levelled workload  
  - Cannibalisation
  - Balancing reprocessing utilisation with new components
  - Quality categories
  - Work organisation

Just as e.g. the principle of reducing setup times is a key element in making ordinary manufacturing companies leaner, the proposed solutions can be a similar tool for making the general remanufacturing process leaner. Thus, the main contribution of answering research question five is the propositions on how the different solutions can be used to apply a leaner remanufacturing process, and as a result, make the process more competitive. Each of these solutions has different effects on different process phases and categories of components. By presenting these proposed solutions, the objective of the fifth research question is satisfied. Another important contribution from these results is the contribution to the lean remanufacturing area; the theoretical review for this paper shows that the literature in the area is limited. Only one case study was found where lean production principles were applied in a remanufacturing case (Amezquita et al. 1996), opposed to the numerous publications regarding lean production for manufacturing companies. The results presented here, therefore, are an important contribution for the theory regarding lean remanufacturing.

RQ 6: What principles for material handling can be suitable in the reassembly phase?

This final research question is closely linked to the fourth and fifth research questions. The previous research question (RQ 5) addresses the material planning of the remanufacturing process in general. With respect to RQ 5, the sixth research question...
addresses a more limited part of the remanufacturing process, that is, the material planning and handling in the reassembly phase. The empirical data for this research question is also limited to a single case. For this research question, the validated AC-model for manufacturing is developed further with the use of the results from Papers IV and V regarding remanufacturing characteristics. The result is a material handling framework for the reassembly phase of the remanufacturing process. This framework proposes that one way to organise the material flows in the reassembly phase is to divide the components into several material handling groups (see Figure 51). In this study, a framework for material handling was presented based on four different groups (see Figure 45). These groups were sorted into their respective groups by the use of four different quantitative criteria:

- Problem components – with a high value and a low demand (Criteria I)
- A–Components – with a high value of usage (Criteria II)
- C–Components – with a low annual demand (Criteria III)
- C–Components – with a high annual demand (Criteria IV)

Each of these groups has its own characteristics. These groups are then associated to different solutions for planning, movement, storage, and planning priorities according to the previously presented Table 13.

The main contribution of research question six is the development of a framework on how to handle different types of components in a reassembly situation in a remanufacturing process. The material handling for remanufacturing is different depending on the manufacturing situation, with for example slow-moving components. One main difference is the existence of planning Group I – that is the “problem components” with a low annual demand and generally long lead-times. The main contribution of this research question is the further development of the AC material-handling framework for a remanufacturing context.

Figure 51: The separation of components in material handling groups.


### DISCUSSION AND CONCLUSIONS

#### 10.1 Discussion of the Research Results

Companies in the remanufacturing industry are frequently compared to manufacturing companies and their practises. Both researchers and practitioners often characterise remanufacturing as a more complex industry with more variability in the processes. Still, remanufacturing is often treated with the same methods and solutions commonly used for manufacturing companies. The issue that should be further investigated is if these practices in manufacturing are suitable also for remanufacturing, and if not, how remanufacturing practice should be different. This dissertation has focused on shedding light on some of these issues, as well as highlighting new issues for further research.

The objective of this dissertation was to explore how remanufacturing companies can become more competitive through analysing and managing material flows and processes. Given the results of the research questions presented earlier, this dissertation has highlighted the importance of several areas in the remanufacturing system, as well as how these areas can contribute to the competitive advantage for remanufacturing companies. By exploring these research questions, the overall objective is also considered satisfied.

The results of this dissertation have different importance for different readers. Firstly, the industry actors that are already involved in remanufacturing have several potential gains from this dissertation, with the results from RQ 2, 3 and 5 as the most obvious. The discussion of these research questions is mainly explanatory in its nature, giving guidance for the management of the companies’ current processes. The second actor that has a potential gains is the industry actors that identify remanufacturing as a potential business opportunity, but are not currently involved in a remanufacturing operation. For these actors, the research questions one and four are the most important, due to the more descriptive nature of the results that provide support in a start-up phase of a remanufacturing operation. Thirdly, for the academic reader, the more theory-focused research results might be of interest.

To summarise, this dissertation’s main contribution to the reader is in providing increased insight how companies to become more competitive by analysing and managing the remanufacturing system.

#### 10.2 Future research

In this dissertation, the focus has been on the material flow and remanufacturing process, and how improvements in these areas can help companies to become more competitive. As concluded in the dissertation, these are important areas for the competitiveness of remanufacturing companies; still, there are many other areas that also have a big impact on the competitiveness of remanufacturing companies. During
this research, several other important issues regarding remanufacturing have been found.

The general trends of the previous research are focused on operations management with that aims in reducing the “costs” of remanufacturing, e.g. in some way balancing inventory carrying costs with production costs; this is often done with the use of rule-based management principles as e.g. economic order quantities. This type of mathematical modelling has had a major focus on the reduction of remanufacturing costs. One of the conclusions in this dissertation is that reduction of remanufacturing costs is one of the important factors for remanufacturing success; still, there are other business drivers for remanufacturing that require attention by researchers. One factor that deserve more attention is how remanufacturing can be a source for further collaboration with customers in a relationship perspective, especially for OEM remanufacturers. For example, the BT case indicates that remanufacturing can provide several advantages in driving new product sales and protecting the aftermarket. Regarding the profitability (= price - cost) of the remanufacturing process, previous research has focused on the cost for remanufacturing operations, not on the “price side” of the equation. Generally, the price for remanufactured products is lower than that of new products and still the status of the products can be “as good as new or better”; even so, customer behaviour drives the price for a remanufactured product down. If business solutions can be found that reflect on the quality of the remanufactured product, there is the potential for higher profit in remanufacturing operations. One potential source for this is when companies start to sell functions instead of products; in these cases, the customer pays for what is delivered from the product instead of the product itself. For example, an aircraft engine can be paid according to the amount of power the engine generates during one hour - “power by the hour”.

The second main point that also has a major impact on the possibility to create a profitable remanufacturing process is the design of the input product. The design of the product is a key issue regarding how effective the remanufacturing is going to be. Although the companies tend to design products for manufacturing, and this can be contradictorily to the design needs for competitive remanufacturing. One important issue here is to develop product development methods that consider both the design needs for manufacturing and remanufacturing.

There is also a need to further develop management control principles (methods of calculation, accounting, budgeting, etc.) that are adapted to remanufacturing environments.

Another important issue is how remanufacturing can be included in the service offering of a company. Examples of remanufacturing sold as mainly a service have been found in many cases. Here the different methods of selling the service of remanufacturing need to be mapped.
REFERENCES


APPENDIX A
INTERVIEW GUIDE FOR THE REKO STUDY

Basic company information
1. What annual turnover do you have for your remanufacturing business?
2. Do you also have some additional products that are manufactured?
3. How many employees do you have?
4. How many are linked to the remanufacturing operations?

External logistics

Supply chain characteristics
5. How is the cores supplied from the customer to the remanufacturing operations?
6. What are the lead-times for delivery in the supply chain?
7. Where are the cores stored in the supply chain?
8. What are the turnover rates in these inventories?
9. Who sends the cores to you? Specify in a percentage
   - Retailers?
   - The customer?
   - Independent party
   - Other:
10. Estimate the type of transportation used and the average distance.
11. How is your outbound logistics organized?
12. How is the material flow organized for products and components that cannot be remanufactured? And are recovered in other product recovery options?
13. How is the supply chain influenced by the type of customer that returns the product?
14. How is the logistics changed when the product have been on the market for a longer period of time?
15. What differences are there between the revered supply chain and the forward supply chain?
16. Can they be combined?
Collection of cores
17 How can you control when a core will be returning from a customer?
18 Is there any way that you can improve the control to get a more accurate return?
19 Describe how the costumer decides on how and when to return the core?
20 What different collection methods are there?
21 What percentages of the possible cores are generally collected?
22 How is the forecasting done for product returns?
23 Are there any business offers that are particularly advantageous for making products return, such as functional sales, rental, etc?

Transports
24 Is the products value in some way decreased over time during the product return process?
25 What are the most important aspect for you, lower cost for transportation or fast deliveries?
26 How dose the cost for transportation influencing the size of the possible target area for core take back?
27 What are the general costs for logistics activities?

Production process
28 What type of layout has you chosen and why?
29 Describe the material flow in the remanufacturing process by making a drawing
• What lead times do you anticipate
• Safety inventory
• Inventory turnover
• Work-in-process
• What are the operations
30 What are the drivers for the current layout and the material flow.
31 What advantages and disadvantages exist in the current layout
32 Are there any critical or product specific operations in the process that put limits on the material flow?
33 Are there any energy demanding operations in the process?

Advantages of scale
34 What advantages can be found when remanufacturing volumes increase in the current situation?
35 How is the relation between the fixed and variable costs associated with the plant and the remanufacturing operations.
APPENDIX A

Flexibility
Where is your customer decoupling point?
- MTO (Make to order)
- ATO (Assemble to order)
- MTS (Make to stock)
- Other:

36 What demands are put from the customer on the ordering lead time?
37 Are there any operations that have a major limitation on the lead time for the remanufacturing process?
38 Generally, what types of flexibility requirements are put on the equipment used in the remanufacturing process?

Remanufacturing characteristics

39 Generally, what is the most frequent reason/source for product returns? Specify in percentage:

- % Transportation damage discovered in the supply chain
- % Trade in
- % Warranty claims
- % Returns from functional sales, rentals, leasing, etc
- % Directly from retailer or similar (specify reason):
- % Technical upgrades
- % Buy back
- % Core dealers or similar
- % Quality defects from new production
- % Return of components for prolong life of a product
- % Other (specify):

40 Are the any particular characteristics for these returns?
What are your drivers for remanufacturing products? For example

_active_
- Cost savings, due to for example expensive raw material or difficult production operations
- Promoting an environmental image
- Defending the after sales market
- Creating a relationship with the customer?
- A more rapid way of delivering products to customer
- Other (specify)

_reactive_
- Environmental legislation
- Demands by customers
- Political
- Warranty claims
- Unprofitable for the current user – but not for other segments of customers

What criteria are used for the choice to take/back cores, for example:

- Legislation
- Economical
- Marketing reasons
- Other

How is the communication organized between the company and the actor that are actually retrieving the cores from customers?

How can this communication be improved?

If the cores are purchased, how is it valued?

Degree of remanufacturing

To what extent are the cores remanufactured? (Classify)

- The core are remanufactured as a unit to:
  - As “when newly produced” status
  - Upgraded to the latest specifications, similar to the currently new products
  - To a level specified by the customer
  - To a level specified by the company
- The core are cannibalized for components
  - To be used in remanufactured products
  - To be sold as spare parts
  - To be used in new products

Do you use a mix of the remanufacturing levels (described earlier), why is that and what determines the appropriate level?

In what situations do you choose to by components instead of reprocessing the component?
APPENDIX A

49 Who in the organizations sets these characteristics?
50 What type of information is needed to make the right answer?
51 How is this presented to operational personnel, for example in disassembly and
   inspection operations
52 Is this system working satisfying when the information changes over time?
53 How is the status of the core assessed before disassembly?
54 How and where is this information used?
55 Do you use some sort of quality categories for the status of the cores?
56 How are these used in the remanufacturing process?
57 What effects can be gained from quality categories in the remanufacturing process?
58 Is there any additional inspection needed further down in the process to assess what
to do with the core and the components?
59 Are there situation when remanufacturing isn’t appropriate? For example when:
   • Environmental reasons?
   • Legislation?
   • Competition with new products?
   • Economical?
   • Other?
60 Are there any possibilities to, at an early stage before the cores arrive at the
   remanufacturing plant, sort and decide what to do (and what needs to be done) with the
   core?
61 Do you use any system like this?
62 Internal material handling

Internal material handling
63 What characteristics are use to decide on how to handle the component in the factory?
   For example issues as:
   • The value of the components
   • Annual demand for a component
   • The physical space, in for example assembly lines
   • The since of the components
   • Other
64 Make a drawing on how the material is handled in the plant

Core inventory
65 For how long in general are a core situated in your core inventory
66 How is the core stored?
67 Are the cores sensitive to storage methods? E.g. storage outside
68 Dose the value of the core decrease during the time in inventory?
In the case when the supply of cores is greater than the demand of remanufactured products:

69 Under which conditions are a core recycled?
70 How is over stocking cores avoided
71 How do you now when to phase out a product from the product offerings?

In the case when the supply of cores is less than the demand of remanufactured products:

72 How is this situation dealt with?

Material handling in the material flow: (Disassembly)

73 How do you keep track of the components when they have been disassembled?
74 What types of material carriers are used?
75 What type of methods do you use to create an effective inventory management of disassembled components?
76 To what degree do you use specialized material carriers?

Material handling in the material flow: (Reprocessing)

77 How do you coordinate the need of components between disassembly, reprocessing and reassembly due to for example yield rates?
78 What degree of standardization of processes and material carriers are used in this phase?
79 What type of methods do you use to create an effective inventory management of reprocessed components?

Material handling in the material flow: (Reassembly)

80 Do you have some solution for innovative material carriers?
81 How do you store new and reprocessed/reused components?
82 What are the criteria for storing components at assembly stations vs. centralized storage?

Procurement

83 How are your possibilities for procurement of new components?
84 What are the differences between procuring a component that are also used in new products (e.g. cheaper, lower ordering lead times, etc) opposed to components produced as spare parts?
APPENDIX A

Obsolescence
85 How are obsolete new components managed in the inventory?
86 How are obsolete reprocessed components managed in the inventory?
87 On what criteria are the components classified as obsolete and what are done to these components?
88 Are there any options to send back unused components to the manufacturer?
89 When components are bought under high risk for obsolescence, how is it then priced internally?
90 How are the (high?) order quantities influencing the cost for new components in respect to risk (e.g. obsolescence)
91 Production planning

Production planning
92 What area has the greatest potential for improvements regarding your remanufacturing process?
93 Describe how the remanufacturing planning is conducted from order to delivery
94 Why is this approach applied in your case?

Planning
95 How are the disassembly orders set in respect to when and to what quantities?
96 How are the reprocessing orders set in respect to when and to what quantities?
97 How are the orders for new replacement component issued (when and to what quantities)?
98 How are the reassembly orders set in respect to when and to what quantities?
99 How do you coordinate disassembly, reprocessing and reassembly phases in respect to order quantities and timing?
100 What extent of planning and control are economically justified?
101 Are there any information technology software available to manage this issues?
102

Yield
103 Are there any calculation/forecasts on the material recovery rate in the different phases of the remanufacturing process?
   • If yes, how are these variables assessed?
   • If no, why not?
104 To what rate are the forecast of material recovery rate predictable?
105 To what extent are the forecasts for the material recovery rate used in the planning process?
106 Is the material recovery rate in any way measured during disassembly? If so, how is this information used, for example when ordering new components?
107
Reprocessed components

108 How do you assess the cost and time for reprocessing a component?
- Part of the cost of sourcing the product core?
- Energy?
- Machine hours?
- Labour?
- Material handling?

Capacity and flexibility

109 How is capacity planning performed in the process?
110 How dose the incoming quality of cores influence the capacity planning?

111 How do you se upon the need to be flexible in the remanufacturing process
   (compared to new production)?
112 Is it possible to increase the degree of reprocessing at times with high reprocessing
   capacity?
113 Do you use new components as a hedge for variations in reprocessing capacity?
114 How is the capacity managed between reprocessing job shops and the members of the
   operational staff?
115 How important is flexibility in the operational staff?

Bottlenecks

116 Do you have any specific bottlenecks in the remanufacturing process?
117 Does the position of the bottleneck in the material flow change frequently?

Lead-times

118 How are your anticipated lead-times in the remanufacturing process? (make drawing)
119 How is the amount of planning lead time influencing the efficiency of the
   remanufacturing process?
120 What operations are effecting the lead time the most?
121 Are ordering lead time an important aspect for customer orders?
122 Dose the lead time between order and delivery fluctuate, and why?
123 What effect dose fluctuating lead times generate?
124 Does the lead time effect the planning and cost for the reprocessing operations?
APPENDIX A

Remanufacturing Economics

125 Describe the general cost distribution of the remanufacturing system (draw)
126 Which of these costs can the company influence?
127 According to what principle are the pricing of the products performed?
128 If OEM, how is the internal pricing of new components conducted between the spare parts division and the remanufacturing division?
129 How is the correlation between the forecasted cost of remanufacturing and the actual outcome?
130 What variables regarding the performance of the remanufacturing system are measured upon? E.g.:
   • Financial data?
   • Customer satisfaction?
   • Personnel development
   • Internal data?
   • Other?
131 How are these factors measured?
132 How are the components valued during the remanufacturing process?
   • Core inventory
   • Disassembled components
   • Reprocessed components
   • Products ready for delivery

What effects does the values of the components have on material and production planning? (e.g. the choice to reprocess a component or not)

Logistical demands

133 What demands are set from customer regarding time to delivery?
134 What types of demands are set on the delivery accuracy?
135 How does the time between order and delivery of remanufactured products compare with new products time to delivery?

Additional questions

Are there any questions that you feel that should have been asked or some other aspects of remanufacturing that are important for the competitiveness of your company?
APPENDIX B

INFORMATION ON THE AUTHORS

EFFORTS IN RELATION TO THE PAPERS

This appendix will present a clarification to what extent the author of this dissertation has contributed to each of the Papers I-VII

For all the appended papers in this dissertation, I have been the main author, which means that I have been responsible for the process of writing them. As for my principal supervisor, Mats Björkman and my co supervisor Erik Sundin contributed constructive critique on all of them. Erik has also been a part in the gathering and co-authoring some of the appended papers. Concerning the research efforts in relation to each paper the following can be stated:

**Paper I**
I conducted the interviews at the companies; I also did the theoretical review as well as writing the paper. Approximately 95% of the work for this paper is done by the author.

**Paper II**
I conducted the interviews at the companies; I also did the theoretical review as well as writing the paper. Approximately 95% of the work for this paper is done by the author.

**Paper III**
I conducted the interviews at the companies; I also did the theoretical review. Erik Sundin contributed with a part of the methodology section as well as contributing to a 10% degree when writing the paper. Approximately 90% of the work for this paper is done by the author.

**Paper IV**
I conducted the interviews at the companies; I also did the theoretical review as well as writing the paper. Approximately 95% of the work for this paper is done by the author.

**Paper V**
The foundation for this paper is linked to a Master of Science in Business Administration thesis made jointly by myself and Maria Mähl. After this thesis has been written, I expanded the scope to also include the empirical data from the REKO-study. Approximately 80% of the work for this paper is done by the author.

**Paper VI**
The foundation for this paper is linked to a Master of Science thesis conducted by Helene Ekholm. My part for this paper was to identify the objective of the study and to initiate the project. All the empirical data was gathered by Helen, Approximately 40% of the work for this paper is done by the author.

**Paper VII**
The foundation for this paper is linked to a Master of Science in Mechanical Engineering thesis made jointly by myself and Rickard Svensson. Approximately 75% of the work for this paper is done by the author.
Abstract

In this paper the aim is to explore what drives companies to get involved in the remanufacturing operations. In the previous research there have been numerous case studies that partly have addresses the issue of why a company is getting involved in remanufacturing. A main conclusion from this study is that the motives for remanufacturing a product are very case-dependent e.g. in what industry sector the company have business in and what product type being remanufactured. In this study it is found that there are mainly three general business drivers for remanufacturing. These are: profit, company policy and the environmental drivers. For remanufacturing to be successful, these drivers are crucial, although it does not propose that all of these drivers have to be present for a successful remanufacturing system. When combining the profit, policy and environmental factors there is a great potential for a win-win-win situation, meaning that the customer gets a quality product at a lower price, the manufacturer reduces their manufacturing costs and the environment gains from a lower environmental impact.

Keywords:
Business Strategies, Business drivers, Product recovery

1 INTRODUCTION

The field of product recovery encompasses the recovery of all used and discarded products, components and materials. The product recovery consists of several activities such as: collecting products, determining the potential for the product reuse, disassembling the product and segregating valuable components; remanufacturing of the product; recycling materials; and disposing of waste. [1]

Product recovery has traditionally been viewed by customers as an economically and environmentally beneficial alternative to ordering new products. Product recovery is interpreted as a superior concept that involves concepts like reuse, remanufacturing and recycling. The aim with product recovery is to retrieve a product’s inherent value when the product no longer fulfills the user’s desired needs [2]. During the last century, the industrialized world has put limited focus on product recovery. Instead, the main focus has been on the production of products from virgin materials (i.e. non-recycled). For several different reasons, the focus has now shifted to an increase in product recovery. For example, society’s awareness of the environmental problems of the present use of material and products has grown [3]. As a result of the social perspective has resulted in increasing environmental legislative pressure from the European Union (EU), such as the launching of the WEEE and ELV directives. These directives has the potential in creating an environment where product recovery becomes profitable if not already profitable without a take-back law.

In this paper, the remanufacturing option of product recovery will be the area of interest. Remanufacturing is defined as an industrial process where worn-out/broken/used products referred to as cores are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and testing to ensure it meets the desired product standards. This could sometimes mean that the cores need to be upgraded and modernized according to the customer requirements (see e.g. [4], [5] and [6]).

1.1 The remanufacturing industry

The remanufacturing industry got a boost during the Second World War when many manufacturing facilities changed from ordinary production to military production, and therefore the products in use by civilians were largely remanufactured in order to keep society running. The concept of remanufacturing has spread during the latest decades to sectors such as those dealing with products like: automotive components, electrical apparatus, toner cartridges, home appliances, machinery, cellular phones and many others, see e.g. [6].

The remanufacturing industry, as an industry sector, is often referred to as a “hidden giant” as described by Lund [5]. The reason for describing it as hidden is that the majority of the remanufacturing performed in industry is done at companies that are not focused in pure remanufacturing operations and provides it mainly as an after market service. In comparison, the companies that are focused on pure remanufacturing are not at all as common. Therefore, it is hard to exactly estimate the turnover of the remanufacturing industry in a sector since the data is hidden in aggregated numbers. To give some examples of the importance of the remanufacturing industry, the size of the industry in the United States is estimated turnover $ 40.5 billion in 2003 [7]. In the United Kingdom, the size of the remanufacturing industry is estimated to £ 5 billion in 2004, which is about equal to the recycling industry [8]. However remanufacturing proposes a great business opportunity and the European market has an enormous growth potential; in the USA it is a major business and the automotive industry, sells approximately 60 million remanufactured automotive products compared to 15 million products in Europe, for an equivalent stock of vehicles [9].
In this paper the aim is to explore what drives companies to get involved in remanufacturing operations. In the previous research there have been numerous case studies that partly have addressed the issue of why a company is getting involved in remanufacturing. A main conclusion from these studies is that the motives for remanufacturing a product are very case-dependent (see for example [1], [2], [10], [11]).

1.2 Purpose
As the aim of this paper is to identify the possible generic drivers that make companies interested in performing remanufacturing. The formal purpose of this paper is to answer the following question:

What drivers can be identified for companies to remanufacture products?

Understanding what the drivers are for the remanufacturing system is a key issue for developing management methods and policies. The term management can be described as the “the actions taken to reach one’s intended goal” [10]. Using this analogy, the goal of the actions taken in the remanufacturing system would be to maximize the relevant drivers for remanufacturing. Hence, without knowing where we are going, we cannot deliver solutions to get there either. Therefore, the identification of remanufacturing drivers becomes an important issue not just for industry but also for the direction of management research in remanufacturing.

2 METHODOLOGY
The purpose of the design of a research methodology is to support the purpose and the research questions of a study [13]. The research made for this study is based on empirical data linked to several case studies of different remanufacturing companies as well as previous documented case study research results in the area of remanufacturing. In this paper new findings are presented integrated with the previous research to support the forthcoming analysis. Using case studies as a research method are particularly feasible in situations where the issues that are under investigation cannot be easily separated from their context or environment [13]. By using case studies, one can gain a complex and holistic view of a specific issue or problem. A case study can be described as “problem-focused, small-scale and entrepreneurial” [14]. Some specific abilities can be linked to case studies. According to Merriam [14], case studies can do several things. First, they can give guidance to the reader regarding what could be done, and what should not be done, in a similar situation; second, they help the reader to regard specific situations and still conclude to a general problem; and finally, they illustrate the complexity of a situation, e.g. the fact that not a single but a multiple of variables affect a given situation.

2.1 Empirical Investigations
The empirical data for this study is linked to an ongoing research project called “REKO” [15], which employs an explanatory multiple-case study concerning multiple types of products. The main source of data collection was semi-structured interviews. The questions formulated for this type of study are normally open and give the respondents a chance to go into detail regarding the answers, i.e. the questions were prepared without specific sequence or answering options [16]. Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions.

The case company selection was made from companies that were found in the study of the remanufacturing industry in Sweden [17]. In this study, a multitude of potential companies was found. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and remanufacturing process.

According to Eisenhardt [18] there is no ideal number of cases, though a number between 6 and 10 is good for theory building. Empirical data was gathered primarily from different Swedish remanufacturing companies. The companies selected for the case studies were:

<table>
<thead>
<tr>
<th>Case Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Industries</td>
<td>Forklift trucks</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Scandi-Toner</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Swepac International AB</td>
<td>Soil compactors</td>
<td>Medium</td>
<td>OEM</td>
</tr>
<tr>
<td>Tetra Pak</td>
<td>Filling machines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Volvo Parts</td>
<td>Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>UDB Production</td>
<td>Automotive components</td>
<td>Medium</td>
<td>Contracted and independent</td>
</tr>
</tbody>
</table>

3 BUSINESS DRIVERS FOR REMANUFACTURING
3.1 Profit as a driver for remanufacturing
One of the most frequent answers given when a company is asked why they are involved in remanufacturing is that remanufacturing is a profitable business for the company. The first driver for remanufacturing is based on the idea that resources that were used in the manufacturing of the product are reused, therefore the costs of producing remanufactured products has a potential to be lower than in new production and thereby making remanufacturing profitable (market price – costs for the remanufacturing process) [1]. The reused resources consist of the material in the product, energy, machine time, labor and other costs that have been accumulated in the new production process [2]. In the normal case, the price available for a remanufactured product is dependent on the price of an equal new product. Generally the price of the remanufactured product tends to be lower than the price of a new product [11].

General cost reductions
Remanufacturing as a solution for realizing a product that meets the customer requirements can provide substantial cost savings in comparison to the new product alternative. Remanufacturing can in advantageous situations provide cost reductions, both for customers and remanufacturers. This is done by taking advantage of the resources that were used in the manufacturing of the product, therefore the costs of producing remanufactured products has a potential to be lower than in new production and thereby realizing a cost reduction. This cost reduction is also the main criteria for making remanufacturing profitable. For example, Xerox Corporation saves hundreds of million of dollars a year by...
disassembling its end-of-life photocopyers and then cleaning, sorting, and reprocessing components and recycling residual materials [1]. Other examples of remanufacturing becoming profitable are when Volvo is using remanufactured engines in warranty claims instead of new engines.

New business strategies

How companies formulate their business strategy to meet customer demands can also create opportunities for profitable remanufacturing. A trend today is that many manufacturing companies are moving from a focus of selling products, to a perspective linked to creating a relationship with the customer during the product’s life cycle. By formulating a business strategy in a life cycle perspective, remanufacturing becomes a service in the product’s life cycle [19]. One example of this thinking is when the product is linked to a functional sales offer. In the functional sales offer (e.g. a rental contract), the business strategy of a company is to sell the function of a product instead of just the product. One result from this is that the product can remain in the ownership of the company and it can be remanufactured when returned from the customer [16]. In this case, remanufacturing can be a preferred product recovery option for products coming back after the lease or rental period [1]. One practical example of this is the rental agreements for forklift trucks offered by BT. Normally the forklifts are stationed at the customer for up to about five years. When the product is returned, it is remanufactured before it is sent to another customer or sold in the second-hand market.

New product sales and entry to new market segments

This category refers to the practice of trading in old products when the customers are buying a new product. When providing compensation in some form for the old product, a drive for new product sales is given. If the company is involved in, remanufacturing the effect can for example be; that the customer gets some discount on the new product, and the remanufacturer gets a core that can be remanufactured. For the OEM remanufacturer the result is a profit for the sale of the new products and a profit for the remanufactured product. One frequent cited reason for companies not to involve in remanufacturing is that it reduces the new product sales, although this dose not have to be the case since it is common that the new and the remanufactured products are not sold in the same marketing channel and targets different market segments. One example of this is remanufactured soil compactors from Swepac and the forklift trucks from BT that are targeted towards a different market segments. In both these cases, the products that are sold as remanufactured are targeted towards customer with a lower demand of innovation level and to customers that are price sensitive. Targeting new markets segments by offering remanufactured products is also one way for premium brands to address new customer groups that wouldn’t be able to by new premium products.

Provide Spare-Parts

For products that have been on the market for a long time the only option for the customer to replace a broken component, might be to remanufacture the component. The main reason for this is that there are no new or reused components available on the market [11]. Additionally, OEMs may be obliged to supply spare parts for products for a certain length of time after new production ceases. In many industry sector the long time frame can provide a problem, for example, in the automotive business it can be as long as 15 years, as for the case of Volvo and UBD. By using a business model which provides these spare parts as remanufactured products, OEMs are able to cease production of small numbers of new spare parts for old product lines. This means that remanufacturing can offer a further cost saving to the OEM.

Another interesting point is that remanufacturing also provides an alternative to new production of spare parts. Hence the dependency on sub suppliers for spare parts can to some extent also be reduced by offering the remanufacturing option [10]. This is especially true for components that have been on the market for a long time and the costs for producing new components are high due to the generally low production volumes.

3.2 Policy as a driver for remanufacturing

The drivers for remanufacturing can also be linked to non-direct economical issues. Policy issues, such as protecting a secondary market, promoting brand image, preventing legislation and other similar issues can motivate remanufacturing. The drivers that are presented here are drivers that have a positive economical impact on the company as a hole even if the profit from the remanufacturing operations can be negative.

Protecting aftermarket volumes

The aftermarket is defined “as the market for components and accessories to maintain or enhance a previous purchase” [1]. The aftermarket is often a very lucrative business area for the OEMs, therefore there are heavy invectives to keep independent competitors away form this market. By collecting components and products from customers, the “risk” of independent remanufacturers targeting this area is reduced. In a study at an engine remanufacturer Seitz has was given the following insight [10]:

“Officially a remanufactured engine can only bought if a core is returned. But if a customer offer us just the core, we tend to buy it anyway, because otherwise, the core would be “food” for our competitors. With regard to commercial vehicle engines, at one point, we even bought back used engines from scrap yards to avoid that competitors would get hold of them”

Another example of protecting the aftermarket is the company Lexmark that uses a “prebate” program giving a discount on a product if the customer agrees to the return the product after use; this program prohibits the customers from returning or selling their used products to other companies. [9]

Brand protection

The image of a company is one of the most critical factors for a successful business. It is also something that demands a lot of time and investment to build, and it can quickly be destroyed with for example negative publicity. For high profile OEMs that target premium customer segments, it is very important that the quality of remanufactured products is under control. To maintain control over the product during the lifetime the OEMs might want to restrict the supply of cores to the independent remanufacturing companies. In a sense the OEM, do not want independent companies “play around” with their products, resulting in a risk that the original brand that gets the negative impact if something goes wrong with the
In an environmental perspective, remanufacturing can, in some cases, offer superior material recovery due to additional reused resources [22]. From an environmental perspective, it is still important to consider the impact of prolonging the life of products with obsolete or polluting technologies. Remanufacturing products with less environmentally sound technology can have a negative impact, especially if the major environmental impact is concentrated in the use phase. Still, remanufacturing in the proper content can gain substantial environmental advantages. [2]

The environmentalness of remanufacturing has been debated since it e.g. could require more transports. However, previous research conducted by Lindahl et al. and Sundin shows that it is a partly preferable option. Lindahl et al. concludes that based on industrial cases and a literature review, remanufacturing is preferable from a material resource perspective when compared with manufacturing of new products. The second conclusion from this study is that remanufacturing is preferable from a more overarching perspective for some of the investigated cases, but it is not possible to draw any general conclusions since the companies studied are few and benefits from remanufacturing are highly context-related. [23] [6]

**Legislation**

The environmental considerations and corporate social responsibility are putting pressure on governments and other institutions to react. A result of this is that the environmental legislative pressure from institutions as the European Union (EU) is growing. Examples of this are the launching of the WEEE and ELV directives. These directives are currently being implemented in the EU member countries in either an “industry collective” or “company individual” manner. From a remanufacturing viewpoint, the effects of these directives can become a significant driver for the remanufacturing industry. How these directives are implemented will have a significant effect on the remanufacturing industry. According to Webster and Filta a collective implementation, the specific industry branch are collectively responsible, would make a structural change to the industry – creating an environment where remanufacturing becomes profitable if not already profitable without a take-back law. On the other hand if these directives are implemented company individually, i.e. each company will be responsible for their own products, the companies will get better control of their own remanufacturing business. [24]

One example of legislation as a driver for remanufacturing can be taken from the toner cartridges business. Toner cartridges are regulated under the WEEE directive; as a result, toner cartridges cannot be treated as ordinary office supplies. This creates a recycling problem for the customer. Scandi-Toner recognizes the embedded value in the discarded product that can be realized through remanufacturing. A recycling service is provided to the customer free-of-charge, and results in the access to used toner cartridges. The relationship is established by providing a take-back system that is realized with a return box that is (when full) sent to the company free-of-charge. The boxes are sent to the company randomly and can contain multiple cartridges. According to Scandi-Toner, the take-back system also motivates customers to remain customers, and provides a sales opportunity since a customer is more likely to

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4 Examples of legislative take-back laws are derived from different EU directives such as the waste electrical and electronic equipment directive (WEEE) (EU, 2002) and the end-of-life vehicles directive (ELV) (EU, 2000).
purchase remanufactured cartridges when they are supplying the used ones through the take-back system.

Moral and ethical considerations

When Kodak started to produce single use cameras, it was just “single use”. As a result the customers started to refer them as “throwaways” and “disposables” this, in combination of environmental groups addressing concerns of this wastefulness, resulted in a remanufacturing program that takes care of the single use cameras. This environmental driver was the start of one of the most successful remanufacturing programs in the world with millions of cameras being remanufactured each year. [1]

4 CONCLUSIONS

As described in this section there are mainly there general business drivers for remanufacturing. These are: profit, company policy and the environmental drivers. For remanufacturing to be successful, these drivers are crucial, although it does not propose that all of these drivers have to be present for a successful remanufacturing system. The main drivers for remanufacturing can be very different inbetween different industry as well as between individual companies. When combining the profit, policy and environmental factors there is a great potential for a win-win-win situation, see Figure 1

5 ACKNOWLEDGEMENTS

The authors wish to thank the companies that have contributed to this knowledge of this paper. Furthermore, the authors would like to give gratitude to the Swedish Governmental Agency for Innovation Systems (VINNOVA) as well as the Royal Swedish Academy of Science for partly sponsoring this research.

6 REFERENCES


PAPER II

Product Lifecycle Implications for Remanufacturing Strategies

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Abstract
For remanufacturing to be successful, there is a need to gain information on future market needs of remanufactured products and match this to the information on the magnitude of return flows. One of the major impacting issues of the possibilities to perform remanufacturing is in the difficulty of obtaining used products (cores) that are suitable for remanufacturing. The timing and quantity of return of a product is dependent on the type of the product. Factors such as the mean product lifetime, rate of technical innovation, and failure rate of components all influence the return rate of products from end-of-use and end-of-life. The balance between product returns and demand for remanufactured products is a function of many variables, were the rate of technological innovation and the expected life of a product are the major influencing characteristics. The main contribution of this paper is the support that is provides in different supply and demand situations. By using a product life cycle perspective, the supply and demand situations can be foreseen, and support is given on possible strategies in these situations.

Keywords: Remanufacturing, Component Cannibalisation, Product Lifecycle, Remanufacturing Strategies

1 Introduction
Remanufacturing is an industrial process whereby used/broken-down products (or components) - referred to as “cores” - are restored to useful life. Remanufacturing means that a product is reprocessed or upgraded in an industrial process. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, part reprocessing, reassembly, and testing to ensure it meets the desired product standards (Sundin et al., 2005). The business concept of remanufacturing is based on the idea that resources that were used in the manufacturing of the product are reused, thereby making remanufacturing advantageous. The reused resources consist of the material in the product, energy, machine time, labour and other costs that have been accumulated in the new production process (Bras et al., 1999). Remanufacturing can, in many cases, offer superior material recovery due to additional reused resources (Smith et al., 2004). From an environmental perspective, it is still important to consider the impact of prolonging the life of products with obsolete or polluting technologies. Remanufacturing products with less environmentally-sound technology can have a negative impact, especially if the major environmental impact is concentrated in the use phase (Bras et al., 1999).

The driving forces for using product remanufacturing in product recovery are many, just as are the barriers against remanufacturing. These motives and barriers can be both economic and technical. Several researchers have tried to characterise under which conditions remanufacturing is advantageous (see Seitz (2007) for an overview). A main conclusion from these studies is that the motives for remanufacturing a product are very case-dependent (Seitz, 2007). For remanufacturing to be successful, Thierry et al. (1995) highlight the need to gain information on future market needs of remanufactured products and match this to the information on the magnitude of return flows. Toffel (2004) also concludes that one of the major impacting issues of the possibilities to perform remanufacturing is in the difficulty of obtaining used products (cores) that are suitable for remanufacturing. The timing and quantity of return of a product is dependent on the type of the product. Factors such as the mean product lifetime, rate of technical innovation, and failure rate of components all influence the return rate of products from end-of-use and end-of-life (Umeda et al.
End-of-use returns refer to those situations where the user has a return opportunity at a certain life stage of the product. This refers to leasing cases and returnable containers like bottles, or returns to second-hand markets. Although end-of-use products are not new, they are often in a good or reasonable state. In respect to end-of-use returns, end-of-life returns refer to those returns where the products are at the end of their economic or physical life. They are either returned to the OEM because of legal product-take-back obligations or “returned” to another company for value-added recovery. Customers can be more or less active concerning the returns, as illustrated respectively by returning bottles to the supermarket or by sending back toner cartridges via mail (de Brito et al., 2002). The balance between product returns and demand for remanufactured products is clearly a function of many variables, were the rate of technological innovation and the expected life of a product are the major influencing characteristics (Guide, 2000). One conclusion that can clearly be drawn regarding this balance is that when a product is new on the market, the return of cores from end-of-use are generally lower than the potential demand for remanufactured products. Vice versa, after a point when the product has been on the market for a long time, the returns of end-of-use products are generally higher than the demand for remanufactured products (Umeda et al. 2006).

The purpose of this paper is to further investigate how companies can balance the demand for remanufacturing products with the rate of product returns. The aim is to develop strategies for companies that can aid them in balancing supply and demand as well as providing insights for possible remanufacturing strategies in different supply and demand situations. To analyse the problem of balancing the supply and demand, the theory of the product lifecycle (see definition in the forthcoming section) will be used as an analytical framework.

2 Previous research

The concept of the “product life cycle” has been discussed widely in research (see the overview by Kotler, 2003). In the theory, at least two conflicting definitions about the product lifecycle can be found. The first refers to the progress of a product from raw material, through production and use, to its final disposal. The second definition of the product lifecycle, that will be used in this paper, describes the evolution of a product, measured by its sales over time, as seen in Figure 1. Every product goes through a series of phases in the course of its life, referred to as the product lifecycle. The phases that a product goes through during its life are the introduction, growth, maturity and decline stages (Cox, 1967). The product life cycle can be analysed on different levels from the main product type (product class) down to different product models; this is illustrated in Figure 1 (Tibben-Lembke, 2002). The characteristics of the lifecycle and its effects on the reversed supply chain have been discussed by Tibben-Lembke (2002), although it lacks a discussion on its effects on remanufacturing operations.

![Figure 1: The product lifecycle for a VCR (Tibben-Lembke, 2002)](image)

When the historical sales data (product distribution) is known, this data can be used as a basis for forecasting when these products are likely to be returned (product disposal distributions). Umeda et al. (2006) present a model based on empirical data from return rates for remanufacturing of a single-
use camera and the remanufacturing of a photocopier. In this model, a simple normal distribution function has shown sufficient results in predicting returns when using average life as an indicator for timing of returns. In the study by Umeda et al., the distribution of disposed products \( S(t) \) is calculated as the historical sales data \( D(t) \) over a limited timeframe \( D(t) \Delta t \), distributed as a normal distribution function (NDist) with a standard derivation \( \sigma \) after an average usage time \( \mu \). This is illustrated in Figure 2 (Umeda et al., 2006):

Another source of items suitable for remanufacturing is the components of a product. Here, the end product (e.g. a car) is not at its end-of-use but requires the exchange of a component to continue working properly (e.g. remanufacturing of the brake caliper). This disposal distribution of components (CD) is therefore a function of how many products there are in the market (the installed base (IB)) and the failure rate of the individual components \( \lambda(t) \). This is shown in Equations 1 and 2 (Umeda et al., 2006):

\[
IB(t) = \int_0^t D(\tau) - S(\tau) d\tau \\
CD(t) = IB(t) \times \lambda(t)
\]

The relations between the different distributions are illustrated in Figure 3. In this figure, the upper line is the total amount of products on the market (the installed base). The installed base is the sum of the produced products to a given time subtracted by the sum of the disposed products during the given time (see Equation 2). Linked to the formulations of these distributions, Umeda et al. (2006) present a framework for product reuse based on three possible reuse scenarios: (1) product installation reuse, (2) spare part reuse from maintenance, and (3) spare part reuse from disposed products.

The disposal distributions in the Umeda et al. study are made in regard to end-of-use, end-of-life and reusable components, but there are also additional sources of cores that can be good sources for remanufacturing. Krikke et al. (2004) present commercial returns as another category, i.e. ones that are linked to the sales process. These products can be returns from customers that return products shortly
after purchase. Other reasons for the returns include problems with products under warranty or a product recall. Guide et al. (2000) also reports “seed stock” as a possible solution for core acquisition. Seed stock is composed of products that failed OEM specifications at the manufacturing plant. However, the possibility for independent remanufacturing companies to acquire seed stock is limited due to their frequent competition with OEMs (Hammond et al., 1998).

This previous research shows that the product lifecycle and the technical and economic issues linked to the lifecycle have a major impact on the ability to balance the returns and demand for remanufactured products. The characteristic of the lifecycle provides a theoretical foundation regarding the possibilities of acquiring used products suitable for remanufacturing. Different companies in different industries will apply different relations with the suppliers of the cores to get a sufficient number of cores for their remanufacturing operations. In a study, Östlin et al. (2007) presents seven different kinds of relationships with suppliers/end customers that have different characteristics for the ability to control the rate and timing of the returns of used products/components. These take-back relationships are ownership-based (e.g. leasing and rental), service-contracts, direct-order, deposit-based, credit-based, buy-back, and voluntary-based relationships (Östlin et al, 2007). Guide et al. (2000) present a number of management propositions on what to focus on when trying to balance the supply and demand for remanufacturing. Regarding core (used products or components) acquisition, one of the most important issues is to focus on identifying different sources of cores and rating them according to their characteristics. Forecasting core availability is critical in order to balance supply and demand. This reduces the need to purge the system of excess cores and reduces stock-outs of unavailable units. Managers should also try to synchronise return rates with demand rates, since doing so will lower the overall uncertainties in the system and lead to lower overall operating costs.

3 Methodology

The purpose of the design of a research methodology is to support the purpose and the research questions of a study (Yin, 1994). The research made for this study is based on empirical data linked to several case studies of different remanufacturing companies as well as previously documented research in the area of remanufacturing. The research has its foundation in empirical data, and links are made to the existing theoretical base. Case studies are particularly feasible in situations where the issues that are under investigation cannot be easily separated from their context or environment (Yin, 1994). By using case studies, one can gain a complex and holistic view of a specific issue or problem. A case study can be described as “problem-focused, small-scale and entrepreneurial” (Merriam, 1994). Some specific abilities can be linked to case studies. According to Merriam (1994), case studies can do several things. First, they can give guidance to the reader regarding what could be done, and what should not be done, in a similar situation; second, they help the reader to regard specific situations and still conclude to a general problem; and finally, they illustrate the complexity of a situation, e.g. the fact that not a single but a multiple of variables affect a given situation.

3.1 Empirical Investigations

The empirical data for this study is linked to an ongoing research project called “REKO” (2006) which employs an explanatory multiple-case study concerning multiple types of products. The main source of data collection was semi-structured interviews. The questions formulated for this type of study are normally open and give the respondents a chance to go into detail regarding the answers, i.e. the questions were prepared without specific sequence or answering options (Jacobsen, 1993). Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions. The formulation of the interview questions were reviewed and given feedback on by the research group linked to the REKO project. After the formulation of the questions, a pilot study was made to verify the validity of the questions. The main source of data for the case studies was interviews, all of which were recorded and varied in length from 1 to 4 hours, depending on how much information the respondents had to contribute. Typically, those interviewed

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1 The REKO project was sponsored by the Swedish Governmental Agency for Innovation Systems (VINNOVA) – see www.vinnova.se.
were facility managers, production managers, controllers and technicians. Other sources of data were direct observations made under the study visits to the companies, as well as documentation in the form of photographs, brochures and information from the Internet (independent as well as issued from the case companies). These sources were mainly used for data triangulation.

The case company selection was made from companies that were found in the study of the remanufacturing industry in Sweden (Sundin et al., 2005). In this study, a multitude of potential companies was found. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and remanufacturing process.

According to Eisenhardt (1989) there is no ideal number of cases, though a number between 6 and 10 is good for theory building. Empirical data was gathered primarily from different Swedish remanufacturing companies. The companies selected for the case studies were:

<table>
<thead>
<tr>
<th>Case Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Industries</td>
<td>Forklift trucks</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Scandi-Toner</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Swepec International AB</td>
<td>Soil compactors</td>
<td>Medium</td>
<td>OEM</td>
</tr>
<tr>
<td>Tetra Pak and Wahlquists Verkstäder</td>
<td>Filling machines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Volvo Parts</td>
<td>Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>UDB Production</td>
<td>Automotive components</td>
<td>Medium</td>
<td>Contracted and independent</td>
</tr>
</tbody>
</table>

To validate the findings of the case study, further (interview) studies were performed at the following companies:

<table>
<thead>
<tr>
<th>Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfa Laval</td>
<td>Heat exchangers</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Bättre Kontor</td>
<td>Office furniture</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Greenman Toners</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Inrego</td>
<td>Computers</td>
<td>Medium</td>
<td>OEM</td>
</tr>
<tr>
<td>Scania</td>
<td>Diesel Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Turbo Tech</td>
<td>Turbo chargers</td>
<td>Small</td>
<td>Independent</td>
</tr>
</tbody>
</table>

It was found that these case companies were sufficient for this study, since they provided good in-depth knowledge to fulfill the purpose of the study. It was determined that additional cases would take too much time to investigate; according to Voss et al., (2002) this is an important skill in theory building for case studies - to know when to stop.

4 Lifecycle Implications for the Remanufacturing System

In the remanufacturing environment, the lifecycle of a product and the disposal rate for both products and components has a great impact on the possibility to perform profitable remanufacturing. Previous research has shown that issues such as the age of the generation of the product, the expected life (reliability), the rate of technological development and the willingness to return products for remanufacturing will influence these distributions (Guide et al., 2000). This section will focus on shedding light on these issues, as well proposing strategies that possibly can make the overall remanufacturing system more efficient. In the following section, the stages of the lifecycle will be addressed according to three different remanufacturing scenarios (adapted from Umeda et al. (2006)).

- **Product remanufacturing** – Used products are remanufactured to “as new” or upgraded status; an example of this category is the remanufacturing and upgrading of Tetra Pak filling machines.

- **Component remanufacturing** – Used components are remanufactured to “as new” or upgraded status; an example of this category is the remanufacturing of automotive components (UBD case) and toner cartridges (Scandi-Toner case).
• **Component cannibalisation** – Used products are cannibalised for components, and the components are then remanufactured “to new” or upgraded status. An example of this category is the cannibalisation of components from heavy trucks (Scania) and forklift trucks (BT Industries). In these cases, the component cannibalisation option is mainly a supporting activity for the product and component remanufacturing scenarios.

### 4.1 Product Remanufacturing

#### 4.1.1 Demand for Remanufacturing

The shape of the product distribution of newly produced products has a major impact on the demand for remanufactured products. A theoretical illustration of the linkage between demand for new and remanufactured products can be seen in Figure 3.

![Figure 3: Linkage between new product sales and demand for manufactured products.](image)

Just as for new manufacturing, there is a possibility to affect the shape of the demand for remanufactured products by different remanufacturing offers; this is illustrated by the dotted lines in Figure 3. For example, if no marketing of the remanufacturing product is possible, then the demand of remanufactured products often tends to be lower, due to customers’ poor knowledge of the availability of remanufactured products. In addition, the pricing strategy of remanufactured products has a major effect on the shape of the demand for remanufactured products. For example, in traditional manufacturing a major reason for the drop in sales is that once new products with better performance are introduced, and that the price for the older version of the products cannot compete with the price of the newer product. In the case of remanufacturing, some products can still be attractive for a longer period of time due to the traditionally lower price for remanufactured products. This is especially true for products with low technological development, or within customer segments that are not sensitive to new technology. One factor that limits the demand for remanufactured products is other types of product recovery options; reuse is one example. In the secondary market, resale can be a more viable solution in the eye of the customer if the product at hand is in working order and the expected lifetime of the product is sufficient (the quality of the used product). In practice, this is largely a matter of the cost of the reuse and the remanufacturing options, as illustrated in Figure 4. For example, when the quality of a forklift truck is high, there is no motivation to remanufacture it because the value of the forklift on a secondary market is sufficient, and the cost for remanufacturing of this high quality product is greater than increase in the market price for the remanufactured product. Later, when the product is worn and has been on the market for a longer time, the cost for remanufacturing is less than the additional value of a product when it is remanufactured in respect to the resale price. For cores with low quality, the cost for remanufacturing can become so great that it cannot match the possible value on a secondary market; in this situation, it can be motivated to sell the used product to a segment with lower quality demands. Examples of these customers are those having very limited needs of “lifting capacity”; and who might want a forklift truck for use just for a couple times a week. For this customer, a reusable forklift of lower quality is “good enough” because the usage is so low that the remaining lifetime of the forklift will be sufficient. Hence, the competition from other recovery options limits the demand for remanufacturing volumes over the lifecycle.
Another interesting factor in respect to the demand for remanufactured products over time is that there is sometimes a local peak of remanufacturing sales after the product is no longer manufactured. This can be especially apparent for independent remanufacturers competing with OEMs that do not perform remanufacturing. One practical example of this can be taken from the furniture industry in Sweden, where Bättre Kontor (independent remanufacturer) remanufactures IKEA (furniture retailer) furniture that is no longer in production. In this case, the customer is normally interested in complementing a set of furniture with additional examples of the same furniture.

4.1.2 Supply for Remanufacturing

To match the demand for remanufactured products there is a need to forecast the future supply of cores suitable for remanufacturing. The potential supply of cores from end-of-use and end-of-life can be forecasted according to historical OEM production data as explained in the theoretical framework (Umeda et al, 2007). One problem with this is that the forecast is made for the total disposal distributions of all products, regardless of the quality level of the product. The disposed products are also subject to reuse/repair (if the quality level is high enough) and recycling/waste treatment (if the quality is too low), as illustrated in Figure 4. As a result and as seen in Figure 5, the supply of cores suitable for remanufacturing will always be lower than the disposal distribution. In addition, the supply of cores will fluctuate according to the quality level of the disposed products over time, due to the logic of the economically preferred product recovery option as a function of core quality as illustrated in Figure 4.

![Diagram](image-url)

**Figure 4:** Illustration of the economically preferred product recovery option as a function of core quality (from the forklift truck case).

**Figure 5:** Linkage between the disposal distribution and the distribution of products suitable for remanufacturing.
4.1.3 Lifecycle Aspects for Balancing Supply and Demand

The possible remanufacturing volumes for a product are dependent on the relation between the supply and demand curves. In the growth phase, the potential volumes are limited to the supply of cores suitable for remanufacturing. After the growth phase comes a maturity phase, where underlying supply and demand are more or less balanced. After a while, when supply increases and the demand starts to decrease, more cores are available than needed. In this decline phase, the limiting factor for remanufacturing volumes is the demand for remanufactured products. The case when remanufacturing is generated from end-of-use returns is illustrated in Figure 6. The shape of the potential remanufacturing volumes is dependent on the shape of supply and demand distributions. The exact shape of the distributions differ between different types of products, for example, and the potential remanufacturing volumes of single-use cameras are high due to the short average usage period that “pushes” the supply distribution to the left in Figure 6. An opposite example is the remanufacturing of filling machines to “as when produced status”; in this case, the machines are returned after a long period of time and the supply distribution is pushed to the right.

In product remanufacturing, there is one special case were this reasoning does not apply: when the supplier of the core is also the customer of the remanufactured product as in a direct-order customer relationship, as for example in remanufacturing as a service. In this case, the customer supplies the core directly according to a make-to-order principle, and there is potentially a perfect match between supply and demand. A practical example of this is the remanufacturing service provided for soil compactors (Swepec case), where the customer (often rental companies) supplies the compactor and gets it back within two weeks. The logic regarding this case is very similar to the make-to-order case of component remanufacturing; a discussion of this is referred to the forthcoming section.

In the case when remanufactured products are being upgraded to the latest specifications from cores based on a previous version (illustrated as A+1 in Figure 7), the situation can become advantageous from a potential remanufacturing volume perspective, as illustrated in Figure 7. Examples of this include filling machines that are upgraded to the newest development steps (Tetra Pak) or upgraded copying machines (Xerox). Upgrading products to the latest technical solution is a viable option when expanding the lifetime of a product. The possibilities to do so are limited according to the upgrading cost it generates, but also according to the level of technology of the core to be upgraded. If the fundamental technology of a product is changed completely in the new product (product class level), the possibilities to remanufacture are low. If instead the changes in technology are minor and concentrated only to specific modules/components (product model level) in the product, the potential for upgrading is greater. (For a detailed discussion about design solutions that can ease upgrading in a remanufacturing case, see e.g. Zwolinski et al., 2006, Bras, 1998 and Ishii, 1995.) In conclusion, upgrading products can be a very effective strategy for matching supply and demand and increasing remanufacturing volumes.
Potential remanufacturing volumes

Number of products

Figure 7: Potential remanufacturing volumes when upgrade to latest technology is a viable option.

4.1.4 The Introduction Phase

Before remanufacturing can be undertaken, there can be difficulty in identifying the potential products for which remanufacturing is profitable and technically feasible (Zwolinski et al., 2006). One important competitive mean for remanufacturing companies in this phase is to quickly develop and present remanufactured products to the market once a new type of product has been introduced (i.e. shorten the time-to-market for remanufactured products). To do this, it is important to quickly identify and secure the access of used products suitable for remanufacturing. One of the independent remanufacturers puts it like this “If we can work in different ways with the customer to identify products earlier, we can stand prepared when the need for a remanufactured product arises.” Closer cooperation between the remanufacturing stakeholders, new manufacturing and potential customers can result in these advantages:

• Better identification of potential remanufactured products can stimulate increased remanufacturing of products.
• A faster time-to-market for remanufactured products, gaining a first-movers’ advantage in respect of competitors.
• An earlier start of remanufacturing has the potential to better match underlying demand for remanufactured products, and hence increase remanufacturing volumes.
• Demands regarding quality and technical specifications of cores/components can be distributed from the OEMs to the remanufacturing industry.

In this phase, the possibility to identify potential products and shorten the time-to-market is largely dependent on the ability to act in a network of actors such as OEMs, component suppliers and customers. Hence, relationships between partners become important. Previous research reports that competition between OEM remanufacturers and independent remanufacturers can be a major limitation for collaboration, although this is not always the case (Hammond et al., 1998). In this study, there have been examples of fruitful collaboration between OEMs and independent/contracted remanufacturers. In the UBD case, the remanufacturer is contracted by the OEM, but it also competes with the OEMs as they also provide remanufactured products to the independent market. Additionally, if the products have been designed for remanufacturing in the first place, the possibilities to identify and motivate remanufacturing will be greater.

4.1.5 Growth phase

This is the phase when remanufacturing volumes emerge and increase over time. Here, the core returns from end-of-use are limited, and the potential demand for products is high. In this phase, the possibilities for generating good profit margins are high, mainly due to the high demand for remanufactured products with respect to the lower supply of products suitable for remanufacturing. The companies that have a better ability to acquire cores in this phase will have a major competitive advantage. As the end-of-use and end-of-life disposal rates are limited to failure rates and average usage periods, the possibility to manage the returns is low. In this phase, the greatest potential for acquiring cores is from other sources such as seed stock, commercial returns and other Secondary Channel Goods, as for example warranty claims and transportation damage. A practical example of
this is the remanufacturing of warranty claims and transport-damaged white goods at Electrolux. These sources of cores are especially fruitful because they appear early in the lifecycle. A source for competitive advantage is the ability to find new and creative ways to acquire cores needed for remanufacturing. One example is automotive companies (e.g. Scania), which are beginning to work closely with insurance companies, creating contracts for the supply of products being damaged linked to insurance activities (e.g. traffic accidents).

The growth phase also has a great impact on the inventory control of remanufacturing companies. The supply and demand situation makes it important to remanufacture the incoming cores and prepare them for delivery as soon as possible (see more about the importance in lead-time reduction in the component remanufacturing section). Hence, in order to decrease lead-times there is a need to minimise the number of products listed as work-in-process in the supply chain. An example of causes that can generate high work-in-process are infrequent transports between retailer and the remanufacturing facility, the need to batch products together, and a lack of new replacement components.

In this phase, there is a need to secure that the remanufacturing system is able to accept these new products. To secure the acceptance of these products, a justified degree of flexibility is needed at the same time as a stable process is being created. Flexibility in the remanufacturing process is an important factor in its efficiency due to the complexity and uncertainties in the process. In some cases, there is also a need for large investments in machining, test equipment and process equipment.

4.1.6 Maturity Phase

In this phase, the return rates from end-of-use increase more and more, to the extent that they start to meet and extend the demand for remanufactured products. As volumes increase and a more stable remanufacturing process is developed, efficiency and cost-consciousness become important issues. Important in this phase is to manage the inventory levels of returned products in relation to the demand for remanufactured products. Another important issue is how make the processes become even more efficient, e.g. through lean production principles.

As illustrated in Figure 6, there is a breakpoint between supply and demand. This breakpoint also has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on e.g. identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important, while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing. Another characteristic in the latter stages of this phase, as well as in the decline phase, is that the quality of the cores can become lower; this in turn can cause a demand for new types of reprocessing operations.

4.1.7 Decline Phase

In this phase, the need for remanufacturing decreases, and there is normally an abundance of cores available on the market. The main danger in this phase is having excessively high inventory levels of cores and remanufactured products when demand for remanufactured products decreases. This can result in high obsolescence costs, both for end products as well as for components that are kept in inventory as spare parts. This is especially important for complex, low-volume products with many product-specific components, as for example diesel engines (as in the Volvo case). Knowing when this drop is about to happen is critical in reducing the risk and cost of obsolescence.

4.2 Component remanufacturing

The cases of component remanufacturing and product remanufacturing are quite different. In the case of component remanufacturing, the demand for remanufacturing activities is primarily linked to the characteristics of the installed base and the failure rate of individual components. One example of this is that the need for break callipers remanufacturing is dependent on the number of installed cars (UBD case). Just as in the case of product remanufacturing, the component remanufacturing volumes are not directly correlated to the disposal distribution of components from a product.
Competition from other after-market options such as component replacement by new components (spare parts) influence the remanufacturing volumes. One additional problem in assessing the failure rate for components is that different components also have different characteristics, for example, mechanical components tend to fail in respect to how the product has been used, whereas electronic components display a more random failure pattern (Stinehilper, 1998).

Just as for product remanufacturing, component remanufacturing volumes are sensitive to new component pricing (spare parts pricing). As a result, automotive companies (Volvo case) report that when the end products still are in production, the prices for new replacement components generally tend to be lower, and increase when the end product goes out of new production. This logic is derived from that when end products stops being produced, the manufacturing volumes of components becomes limited to spare parts production and the produced volumes of new components decreases. As a result, the higher costs for new components (spare parts) can further stimulate remanufacturing volumes later when demand already has started to decrease. A reported negative impact on the remanufacturing companies is that some of the prices for replacement parts (sub-components) used in the remanufacturing process also have a tendency to increase according to the same logic. This increase in remanufacturing volumes late in the lifecycle is a result of component replacement options being reduced to buying a remanufactured or a reused one, as shown in Figure 8.

As a general conclusion, the competition arising from replacement volumes by new components is generally higher in the early lifecycle; vice versa, completion from component cannibalisation/reuse occurs later in the lifecycle (see reasoning in the forthcoming component cannibalisation section).

Figure 8: Potential remanufacturing volumes for component remanufacturing.

4.2.1 Balancing Supply and Demand

In a perspective of matching supply and demand, component remanufacturing is a lot different than product remanufacturing. In component remanufacturing, the supply of a core is linked to the demand for remanufacturing. Simply put, when a customer needs a replacement component they supply a component, and in return receive a remanufactured component. In this perspective, the need to balance supply and demand is not as prevalent as in the product remanufacturing case. Still, in the introduction phase there is a shortage of cores to be remanufactured as not every core is reusable. Another issue to consider is that the number of available cores from remanufacturing can also be decreased by losses of cores in the supply chain. One example of these losses can be the failure to collect used cores when selling a remanufactured product to a customer. Later in the lifecycle, when the rate of product disposal is increased, there is also an increase in available used components through component cannibalisation of disposed products. This is illustrated in Figure 8, along with the potential for remanufacturing volumes.

Figure 8 is typical for direct-order relationships (make-to-order). Here, the components are sent to the remanufacturer, remanufactured and returned to the customer. In this situation, there is direct link between supply of the core and demand for the remanufacturing service, just as in the case of solid compactor remanufacturing as a service to rental companies (Swepak case). The situation with a
deposit or a credit-based relationship (make-to-stock) is different due to that; it is a previously supplied (and remanufactured) component that is sold to the customer. In this situation, there is a lag between the supply of a component and the delivery of a remanufactured product, as illustrated in Figure 9. In this situation, the customer returns the used component and receives a different remanufactured component immediately. This system is common in the automotive industry, where the remanufacturer normally supplies a product to a sort of “middle man”; an automotive part retailer (as in the UBD example) is one such intermediary. The retailer pays a price and a deposit for the remanufactured product. When the retailers sell the product, they collect the used core from the customers; later, they return the core to the remanufacturer and their deposit is refunded, resulting in the one-for-one (1:1) take-back relationship shown in Figure 9.

Figure 9: Illustration of core/deposit flow in a deposit based relationship.

The problem with this system is the existence of a lead-time between the supplying of cores until the product is remanufactured and put in inventory, ready for sale. As seen in Figure 10, this lead-time will push the supply curve forward in time and reduce the possible remanufacturing volumes. A detailed discussion of the effects of lead-time is given in the following discussion about the lifecycle phases.

Figure 10: Potential remanufacturing volumes for component remanufacturing with additional lag in lead-time for the supply of cores.

4.2.2 Introduction and Growth Phases

Just as for product remanufacturing, there is a need to find potential components for remanufacturing; here, the same type of reasoning used for product remanufacturing is valid. Once new products have been introduced into the market, there is a specific problem for companies using deposit-based relationships (make-to-stock). Before being able to sell remanufactured products, there is a need to acquire cores; with no sale of remanufactured products, however, there is no incoming flow of used cores. In this phase, the producers will have to make an investment in cores before they can begin to sell remanufactured products. This need for investment can be quite large if e.g. a remanufacturer is to put an inventory of remanufactured products at each retailer (as for example in the UBD case). One way of minimizing the number of components to be used as an investment is to try to minimize the lead-times between when products are returned from the customer and when they are available for sales.

The possibilities to acquire cores suitable for remanufacturing are limited in the growth phase. Cannibalization of components from end-of-use and end-of-life is a potential source of cores, but it appears much later in the lifecycle (see discussion about component cannibalization). Cores coming
from seed stock and commercial returns can be a much more fruitful option. Just as in the case of product remanufacturing. In the automotive industry, auto repair shops are a major source for cores (UBD case). In the early lifecycle, the broken components are replaced with new components, while the used cores are sold to core dealers or directly to remanufacturers. Another frequent solution used in automotive practice is to supply new components instead of remanufactured products. Minimising lead-times from the supply of cores to the delivery of remanufactured products in the earlier phases of the lifecycle is an important issue, since the costs for acquiring cores are generally higher during the later phases of the lifecycle, when cores are more abundant. In the case of toner cartridges, the use of voluntary takeback is more widely used. This system is based on new components purchased early in the lifecycle, and used cores given back voluntarily to the remanufacturer. The drawback with this system is that there is no way of competing early in the lifecycle; it also entails the major risk that competition will gain a first-mover advantage.

4.2.3 Maturity Phase

In this phase, the product returns from end-of-use and end-of-life life start to increase. Acquiring component cores that have been cannibalised from end products begins to be a viable source. In the automotive industry, scrap yards are a frequent source of component cores for remanufacture.

4.2.4 Decline and cancellation

As previously discussed, in the case of component remanufacturing there can be a local peak of remanufacturing volumes in the latter phases of the lifecycle. This is a result of OEMs stopping manufacturing of new components (spare parts). Simply put, these components need to be replaced by remanufactured, or possibly reused products. Just as with product remanufacturing, the risks of obsolescence are great in this phase, especially for companies with make-to-stock polices. One solution to become less sensitive towards obsolescence is to apply a make-to-order policy on some parts of the offered products, thereby reducing the need to keep a finished product inventory. The disadvantage with the make-to-order policy is that the customer has to wait while the product is being remanufactured. As a result, this option is only viable when (1) the product can be sent off for a longer period of time, (2) when no cores are available, and (3) when the customers want the same product back as they sent in (e.g. customized products).

4.3 Component cannibalisation

This last category is based on the idea that products are cannibalised for components that are later remanufactured. Cannibalisation of components for reuse, in e.g. scrap yards, is a frequent activity in the automotive industry. Cannibalised components are also a source of components for both component remanufacturing and for product remanufacturing.

4.3.1 Balancing Supply and Demand

The supply of used products suitable for component cannibalisation is dependent on what other options are available. Figure 4 presented a framework regarding options about reuse and remanufacturing; a similar approach can be taken for the case of component cannibalisation. For cannibalisation to be economically motivated, the earnings must be higher than the earnings from other product recovery options such as remanufacturing, recycling, and reuse. The earnings from component cannibalisation can be calculated as Equation 4 (example taken from component cannibalisation of forklift trucks).

\[
Earnings = \sum_{x}^{x} p(x) + \sum_{y}^{y} r(y) - \sum_{z}^{z} ic(x) - DC - MP
\]

\(x = \text{number of components that can be reused}\)
\(y = \text{number of components that cannot be reused}\)
\(p = \text{market price of disassembled components}\)
\(r = \text{gain/cost for recycling/waste treatment of disassembled components}\)
ic = inventory carrying cost for cannibalised components
DC = total disassembly cost
MP = market price or cost for lost sales for the core in an "as is" status

There are two main variables that change according to the quality of the core and which
determine the outcome of Equation 4: the number of reusable components and the cost for acquiring
the core or cost for the lost sales. For cannibalisation to be a viable option, the market price of the core
should not be too great, and secondly the number and value of the reusable components should be
sufficient. As a result, cannibalisation has the greatest potential late in the lifecycle, when the supply
of cores is higher then the demand for remanufacturing and reuse of the product, resulting in a
generally lower market price for used products. Figure 10 illustrates the potential area for product
cannibalisation in respect to the remanufacturing option. The timeframe in which the possibilities to
cannibalise components can be quite limited, something which increases the risks of obsolescence in
reused components. A technical hindrance linked to cannibalisation is that components that are usually
demanded for remanufacturing operations are also in such bad shape in the object for cannibalisation
that they cannot be reused in remanufactured products. As a result, there might be a need to dissemble
several cores to find one component that can be remanufactured or reused in a satisfying manner. The
possibility to reuse and remanufacture cannibalised components is also a question of compatibility
between different versions of a product. If the components can be reused between the different
versions, the window in which cannibalisation is possible is expanded, and the chance that the
components will be reused is greater.

Figure 11: Potential component cannibalization volumes to be reused in product remanufacturing.

Component cannibalisation can also be motivated even though the potential earnings are low or
negative. For the OEMs, the option to recycle/cannibalise a product instead of selling the product to a
secondary market (e.g. an independent retailer) can be more advantageous. If the quality of the object
is too low, or if the product causes an accident, the product still carries the brand and can bring bad
will to the company. As far as brand image, there can be legitimate reasons for keeping the end-of-use
and end-of-life products off the market; in this case, cannibalisation can be a solution for restoring
some value. Other motivation factors for taking a product off the market are that the resale option is
competing with other, more profitable solutions, such as new sales and remanufacturing.

5 Discussion and Conclusions

This paper addresses the effects of balancing supply and demand in the remanufacturing
industry. This analysis is in its essence focused on how to provide remanufactured products in an
effective way during the product’s life cycle. The lifecycle theory can be effective when trying to
forecast the general trends of remanufacturing volumes. When going into further detail, the problem
becomes more difficult and addresses the problem of uncertainty in timing and quantity. The difficulty
in applying a lifecycle perspective in more detailed forecasting is that the variables used to calculate
future returns are insecure. The average use and life of a product/component can be forecasted in
beforehand, but this factor is also dependent on complex factors, for example, to what extent the
product has been used and in which environment (to mention some variables). Another factor is the
willingness to return old products for reuse. An example of this can be taken from the mobile phone
industry, where customers are reluctant to return their old mobile phones even after purchasing a new
one, rationalizing “my old phone can come in handy if my new one breaks”. In addition, the demand
for remanufactured products can be said to follow new production demands, but are also sensitive to
prices of substitute products as brand new products and reused second-hand products (if available). The rate of technical development also has a major impact on the demand for remanufactured products, in some cases resulting in a sudden drop of sales for remanufactured products. In all, these insecurities make it difficult to accurately forecast the supply and demand for calculating exact return quantities and timing.

The major advantage of using the lifecycle as a foundation for balancing supply and demand is the insights it brings on a general/strategic level. In this paper, a number of insights have been presented that can be used in the different phases of the lifecycle. At a general level, some additional conclusions can also be made. The OEMs are generally in a more favourable position to perform remanufacturing with respect to independent remanufacturers, especially in the earlier phases of the lifecycle when access to commercial returns and seed stock are a competitive advantage.

In the remanufacturing product life cycle there is a breakpoint where the supply of cores becomes greater than the demand for remanufactured products. This breakpoint has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on e.g. identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing. These conflicting ways of looking at cores may introduce difficulties for companies. Normally remanufacturers handle a vast amount of products that are in different life cycle phases, but they have to be coordinated in the same supply chain; the coordination and administration of different take-back systems is an important aspect in managing this. The mix of different marketing channels for product returns is also an important aspect for matching the different needs over the life cycle.

Upgrading products to the latest standard is one possible solution for increasing the potential remanufacturing volumes for the product remanufacturing case, using for example modular design strategies. For component cannibalization, this is not an as important issue; for this category to expand further, component remanufacturing has to become a more attractive option with respect to the new component alternative. Also, a more standardized and modularized use of components could increase the possibilities to cannibalize components for remanufacturing and reuse.

Furthermore, remanufacturers should focus on the development of methods that can make returns predictable. In remanufacturing, the source of cores is the current users of the desired cores. Each of these users is a potential supplier, but with a limited supply capacity and usually very long lead-times for core production. To identify and communicate continuously with all of these potential suppliers is simply perceived as impossible. The result of this lack of communication is that the user comes to the remanufacturer with the core only "when they think if it" (if they come back at all), thus displaying a stochastic return rate. The problem of sourcing cores becomes a question of which of these potential suppliers can supply a core at the right time, at the right quality and at the right price. To be able to find the right cores, different marketing channels and business concepts provide communication solutions with potential suppliers. For example, off-lease products have been rated more predictable than other types of returns due to the additional information that is available to the remanufacturing company (Thierry et al., 1995; Sundin et al., 2005). The off-lease product provides some degree of security that the product be returned at the right time and at a known price (and hopefully the right price). Using different contracts that result in the take-back of cores can be one solution for securing that products are returned at the right time and for the right price, although the quality of the returned product cannot be contracted that easily.

The problem of balancing supply and demand can also be limited or aided depending on the business solution. Remanufacturing of single-use cameras with fast exchange cycles are, for example, aided by the policy of returning the entire camera for development, resulting in faster returns. Coordination of leasing and rental contracts according to average usage age, as in the Xerox and Tetra Pak cases, can also aid a balance between supply and demand. As a result, the more thought about the business solution and how it can aid in balancing returns with demand, the greater the possibilities for successful remanufacturing.
6 References


PAPER III

Importance of Closed-Loop Supply Chain Relationships for Product Remanufacturing

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Abstract
Remanufacturing is an industrial process where worn-out/broken/used products referred to as cores are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and testing to ensure it meets the desired product standards. This could sometimes mean that the cores need to be upgraded and modernized according to the customer requirements [1], [2], [3].

During the Second World War the remanufacturing industry spawned, especially in the United States since many manufacturers were focusing on military production. Remanufacturing is still a rather large business in the United States [2], but also in Europe, where the industry has been growing lately due to its profitable business and environmental legislative pressure from the European Union (EU), such as the launching of the WEEE (Waste of Electric and Electronic Equipment) and ELV (End of Life Vehicle) directives. These directives are currently being implemented in the EU member countries in either an “industry collective” or “company individual” manner. From an institutional viewpoint, the effects of theses directives can become a significant driver for the remanufacturing industry. How these directives are implemented will have a significant effect on the remanufacturing industry. According to Webster and Mitra [4] a collective implementation, the specific industry branch are collectively responsible, would make a structural change to the industry – creating an environment where remanufacturing becomes profitable if not already profitable without a take-back law. On the other hand if these directives are implemented company individually, i.e. each company will be responsible for their own products, the companies will get better control of their own remanufacturing business.

Keywords: Product Recovery, Reverse Logistics, Relationship Marketing

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1 Introduction
Remanufacturing is an industrial process where worn-out/broken/used products referred to as cores are restored to useful life. During this process, the core passes through a number of remanufacturing operations, e.g. inspection, disassembly, component reprocessing, reassembly, and testing to ensure it meets the desired product standards. This could sometimes mean that the cores need to be upgraded and modernized according to the customer requirements [1], [2], [3].
There are various motives for product remanufacturing e.g. increased profitability, ethical responsibility, legislation, secured spare part supply, increased market share and brand protection [5]. Furthermore, remanufacturing has also been shown to be environmentally preferable in comparison with other end-of-life treatments, since the geometrical form of the product is retained and its associated economic and environmental values preserved [3],[6],[7].

Material flows are an important factor for the overall remanufacturing system [8]. A traditional view on these closed-loop supply chains is that they encompass two distinct material supply chains: the forward and the reverse. Generally, the forward chain concerns the flow of physical products from manufacturer to customer, while the reverse chain describes the flow of used physical products from customer, then acting as supplier, to the remanufacturer. These flows are then “closed” by, for example, the remanufacturing operation. One of the major differences between the “forward” and the “closed” supply chain is that the customer frequently acts both as a customer for remanufactured products and as a supplier of cores to the remanufacturing company [9].

Compared to manufacturing, remanufacturing has some general characteristics that complicate the supply chain. For example, a company retrieves used products (a.k.a. cores) from the suppliers of cores, these suppliers are normally the end customers but it can also be scrap yards, core brokers or incurrence companies. As for end customers there is a major difficulty to assess the number and the timing of the returns. Another complicating issue is that the quality of the used products is usually not known. [8],[10],[11],[12].

For the performance of the remanufacturing system, the question of acquiring cores is an important issue for the remanufacturer in order to be able to satisfy the demand for remanufactured products. “The challenge within the industry is not just how to manage irregular reverse flows, but how to obtain them in the first place” [5]. To illustrate the importance of a close relationship, Seitz et al gives an insight from a vehicle manufacturer:

*For vehicle manufacturers, a crucial issue is to maintain a relationship with customers so that when an engine fails, the customer returns to the retail network for a replacement. If the customer goes elsewhere, then the loop will not be closed and the manufacturer will not get access to the cores they need. Unfortunately, loyalty to OEM service schemes decreases noticeably over time.*

Here, the management of different types of relationships with the customer and suppliers is an important factor for the performance of the remanufacturing system. As Seitz and Peattie put it, “reverse logistics and remanufacturing are a customer relationship management challenge” [5]. A main conclusion form their study is that remanufacturing is typically discussed as a production and logistical challenge added on to a conventional system of consumption. To develop further, remanufacturing also needs to be considered in a customer perspective. For example, customers who demand remanufactured engines are typically car users who generate high mileage during short periods, such as those who drive taxis or vehicles for mail-order firms. These are customers who depend on their vehicles and are unlikely to accept delays in obtaining a replacement engine. These may also be longstanding and loyal customers.

### 1.1 Aim

The aim of this research is to identify what kind of relationships exist between remanufacturers and their customers/suppliers of cores, and how these relationships can be managed. Furthermore, in this paper we will explore how customer/supplier relationships perspective can support product take-back for remanufacturing with focus on the supply of cores. When considering the supply of cores to the remanufacturing process, the focus is on the relationships with the customers/suppliers of cores and how the supply of cores to the remanufacturer can be managed in the remanufacturers’ perspective.
This research also aims at contribute to previous research by theory building. This aim is pursued through case study research at remanufacturing companies; this is further elaborated on in the next paragraphs called “previous research” and “research methodology”.

2 Previous Research

Previous research has reported different systems and techniques for gathering cores for remanufacturing. A common observation is that off-lease and off-rent products are an important source of used products for remanufacturing. Thierry et al. have come to the conclusion that this type of return is more predictable than other types of returns due to the additional information that is available to the remanufacturing company [13]. In the automotive industry, there is widespread use of “exchange cycles” where products are only sold if a core is given back [5]. In this scenario you first have to act as a supplier of a core in order to become a customer of a remanufactured product. Other reported systems are voluntary systems where the supplier freely returns the used products/cores to a remanufacturer, or where the cores are bought from core brokers or end customers. The company Lexmark uses a “prebate” program giving a discount on a product if the customer agrees to the return the product after use; this program prohibits the customers from returning or selling their used products to other companies. Guide et al. present a number of management propositions on what to focus on when trying to balance the supply and demand for remanufacturing. Regarding core acquisition, one of the most important issues is to focus on identifying different sources of cores and rating them according to their characteristics. Forecasting core availability is critical in order to balance supply and demand. This reduces the need to purge the system of excess cores and reduces stock-outs of unavailable units. Managers should also try to synchronise return rates with demand rates, since doing so will lower the overall uncertainties in the system and lead to lower overall operating costs [11].

According to Geyer and Jackson, there are three crucial limitations that a remanufacturing firm needs to overcome: limited access of cores leaving the use phase, limited feasibility of product remanufacturing, and limited market demand for the secondary output from remanufacturing [12]. Furthermore, a challenge that remanufacturers need to tackle is the fact that market demands for remanufactured products and the disposal of used products does not always overlap. This is often referred to as, the problem of balancing supply of cores suitable for remanufacturing and the demand for remanufactured products. These issues have been further studied by Umeda et al. [14] (see Figure 1).

![Figure 1: An example of production and disposal distribution for same type of product [14]](image)

The reasons for returning used products are many. In theory, there are four basic types of returns: (1) End-of-Life Returns. These are returns that are taken back from the market to avoid environmental or commercial damage. These used products are often returned as a result of take-back laws. (2) End-of-Use Returns. These are used products or components that have been returned after customer use. These used products are normally traded on an aftermarket or being remanufactured. (3) Commercial Returns. These returns are linked to the sales process. Other reasons for the returns include problems with products under warranty, damage during transport or product recalls. (4) Re-Usable Components.
These returns are related to consumption, use, or distribution of the main product. The common characteristic is that they are not part of the product itself, but contain and/or carry the actual product; an example for this kind of return is remanufactured toner cartridges. [9]

The issue of forecasting for used product returns has proven to be a difficult challenge for the remanufacturing industry. The return of mainly mechanical products is dependent on factors such as age and use of the product, whereas electrical products tend to have a more random pattern of failure. van Nunen and Zuidwijk report that different IT-based systems are used for keeping control over the products during use; two examples of these technologies are remote monitoring devices that communicate usage data and RFID (Radio Frequency Identification) tracking systems used for keeping track of the installed base [10]. Rogers and Tibben-Lembke characterise good gate-keeping as “the first critical factor in making the entire reverse flow manageable and profitable” [15].

Another important characteristic in the closed-loop supply chain is the need for a well functioning reversed logistic network [8]. For example, reversed logistic networks for product recovery have been modelled by Kara [16], with the aim to calculate the total collecting costs in a predictable manner. Kim et al. also presents a closed-loop supply chain model for remanufacturing to minimize the total cost of remanufacturing [17]. To estimate the effects of return complexity for capacity in the remanufacturing operations, Vlachos et al. presents a dynamic model for capacity planning [18].

Furthermore, the reverse supply chain and remanufacturing processes are dependant on what type of relationship the remanufacturer has with the original equipment manufacturer (OEM) [19]. Remanufacturers are often categorized into three categories; original equipment remanufacturers (OER), contracted remanufacturers (CR) and independent remanufacturers (IR) [19],[20]. OEMs are in fact manufacturers that perform their own remanufacturing as a part of their company group, whereas CRs have a contract with OEMs to perform remanufacturing for them. In the last category, remanufacturers work independently from the manufacturers, and often as competitors in the same market. The type of remanufacturing category has a major impact on the supply of spare parts and cores [19].

The relationship perspective has the starting point that the important issue is the mutual exchange of value that occurs during an existing relationship between different parties. In a relationship perspective it is not the individual transactions that are considered the most important. Instead the important thing is the relations that are considered to aid and support the transactions [21]. These relationship and transactional perspectives are not mutually exclusive and there is no need for a conflict between them. However, one approach may be more suitable in some situations than in others. Transactional marketing can be considered most appropriate when marketing relatively low value consumer products, when switching costs are low, when the product is a commodity, when customer involvement in production is low and when the customer prefer single transactions to relationships. When the reverse of all the above is true, as in typical industrial and service markets, then relationship marketing can be more appropriate. [22]

In a relationship, many different characteristics or dimensions influence how successful a relationship can be. Studies have shown that there are up to as many as 45 characteristics that influences the overall relationship. Some of the most important characteristics for a successful relationship are: cooperation, commitment, trust, power, consistency, adoption and attraction. [23]

3 Methodology

The purpose of the design of a research methodology is to support the purpose and the research questions of a study [24]. The research made for this study is based on empirical data gathered linked to several case studies of different remanufacturing companies as well as previously documented research in the area of remanufacturing. The research has its foundation in empirical data and links are
made to the existing theoretical base. Hence, it follows an inductive reasoning. Inductive reasoning is based on a transition from specific observations to broader generalizations and ultimately theories. This is also called a bottom-up approach. In inductive reasoning, one begins with specific observations and measures, begin to detect patterns and regularities, formulate some tentative hypotheses that one can explore, and finally end up developing some general conclusions or theories. [25]

3.1 Case Study Methodology

Case studies are particularly feasible in situations where the issues that are under investigation cannot be easily separated from their context or environment [24]. By using case studies, one can gain a complex and holistic view of a specific issue or problem. A case study can be described as “problem-focused, small scale and entrepreneurial” [26]. Some specific abilities can be linked to case studies. According to Merriam, case studies can; give guidance to the reader in to what can be done, and what that should not be done, in a similar situation; regard specific situations and still conclude to a general problem; illustrate the complexity of a situation, e.g. the fact that not a single but a multiple of variables affects a given situation. [26]

As this research aims at building theory from case studies, some previous methodology research has been studied. Eisenhardt provide a suitable process of building theory from case studies according to Figure 2. The research for this paper has followed the process shown in Figure 2 in general [27]. No hypotheses have been stated for this study since this was not suitable for the task.

According to Eisenhardt theory building from case study research is particularly appropriate when little is known about a phenomenon because theory building from case studies does not rely on previous literature or prior empirical evidence. In the remanufacturing literature not much research about the importance of customer/supplier relationships has been found. Also, according to Voss et al. the theory building purposes with its unspoken research questions is facilitated by multi-site case studies [28]. Hence, case study methodology was chosen since it is suitable for qualitative research and theory building.

3.2 Empirical Investigations

The empirical data for this study are linked to an research project “REKO” [29] employing an explanatory multiple-case study concerning multiple types of products. The main source of data collection was semi-structured interviews with remanufacturing companies. The questions formulated for this type of study are normally open and give the respondents a chance to go in to detail regarding the answers, i.e. the questions were prepared without specific sequence or answering options [30].

Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions [31]. The formulation of the interview questions were reviewed and given feedback on by the research group linked to the REKO-project. After the formulation of the questions a pilot study was made to verify the validity of the questions. The main source of data for the case studies where interviews, these interviews were recording and the length of the interviews varied from 1 to 4 hours depending on how much information that the interviewees had to contribute with. Typically, the interviewees were facility managers, production managers, controllers and technicians. Other sources of data were direct observations made under the study visits to the companies, as well as documentation in the form of photographs, brochures and information from the
Internet (independent as well as issued from the case companies). These sources were mainly used for data triangulation.

The case company selection was made from companies that were found in the study of the remanufacturing industry in Sweden [32]. In this study, a multitude of potential companies was found. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and remanufacturing process.

According to Eisenhardt there is no ideal number of cases, though a number between 6 and 10 is good for theory building [27]. Empirical data was gathered primarily from different Swedish remanufacturing companies. The companies selected for the case studies were:

<table>
<thead>
<tr>
<th>Case Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Industries</td>
<td>Forklift trucks</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Scandi-Toner</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Swepac International AB</td>
<td>Soil compactors</td>
<td>Medium</td>
<td>OEM</td>
</tr>
<tr>
<td>Tetra Pak</td>
<td>Filling machines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Volvo Parts</td>
<td>Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>UDB Production</td>
<td>Automotive components</td>
<td>Medium</td>
<td>Contracted and independent</td>
</tr>
</tbody>
</table>

Other companies that can provide examples of the proposed relationships, on which no in-depth case studies were carried out.

<table>
<thead>
<tr>
<th>Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenman Toners</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Scania</td>
<td>Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Turbo Tech</td>
<td>Turbo chargers</td>
<td>Small</td>
<td>Independent</td>
</tr>
</tbody>
</table>

It was found that these case companies were enough for this study since it provided us with good in-depth knowledge to fulfill the purpose of the study. Further cases would take much time to investigate and this is according to Voss et al. an important skill in theory building from case studies to know when to stop [28].

4 Closed-loop Supply Chain Relationships for Remanufacturing

In the remanufacturing industry there are many different types of relationships with customers and core suppliers. Some relationships are very close, such as where the amount of trust, commitment and collaboration is high; in other relationships, the linkage is rather weak. Even in the latter case, the relationship still exists and constitutes an important issue for the remanufactures as well as the customers. In this study, seven different types of structural relationships have been identified. These relationships are:

- **Ownership-based.** This type of relationship is common when the product is owned by the manufacturer and operated by the customer, as for example in a rental, lease or product-service offer. Here, the control of the installed base is high and often regulated by contracts.
- **Service-contract.** This type of relationship is based on a service contract between a manufacturer and a customer that includes remanufacturing.
• **Direct-order.** The customer returns the used product to the remanufacturer, the product is remanufactured and the customer gets the same product back (if it is possible to perform a remanufacturing operation)

• **Deposit-based.** This type of relationship is common in the automotive industry. When the customers buy a remanufactured product, they are obligated to return a similar used product, thus also acting as a supplier to the remanufacturer.

• **Credit-based.** When the customers return a used product they receive a specific number of credits for the returned product. These credits are then used as a discount when buying a remanufactured product.

• **Buy-back.** The remanufacturer simply buys the wanted used products from a supplier that can be the end user, a scrap yard or similar, or a core dealer.

• **Voluntary-based.** The supplier gives the used products to the remanufacturer. The supplier can also be a customer but do not have to be.

Concerning these different types of relationships, some disadvantages and advantages can be identified. As will be shown, these relationship structures are not used individually but are rather integrated (Table 1). For example, the deposit-based relationship will have to be complemented with another alternative, due to the inevitable fact that not all cores can be remanufactured.

### Table 1: The use of supply chain relationships in relation to the companies studied for this research.

<table>
<thead>
<tr>
<th>Ownership-based</th>
<th>BT Industries</th>
<th>Tetra Pak</th>
<th>Swapac</th>
<th>UBD Production</th>
<th>Volvo Parts</th>
<th>Scandi-Toner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service contract</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct-order</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposit-based</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Credit-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buy-back</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Voluntary-based</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The following paragraphs describe the seven identified customer take-back relationships for remanufacturing companies.

### 4.1 Ownership-Based Relationships

An ownership-based relationship is often related to a leasing, rental or a product-service offering as in the forklift truck (BT-industries) case. The basis for the ownership-based relationship is that some sort of ownership is still present for the seller, and that the product is given back to the seller after the end of use; it is also in this point that the remanufacturing operation is undertaken. Frequently, the seller is also responsible for maintaining the operation of the product. The seller can also be the manufacturer of the product as in the BT case. BT is also a remanufacturer of the used products. Because the offer is based on a contract, different levels of control and involvement can be used. In this type of relationship, the linkage between the customer and seller is strong. The time range of this type of relationship makes commitment an important factor. A respondent puts it like this: “for a successful relationship the customer has to feel that our products and services are reliable”.

In a product-service offering, the seller is directly responsible for the product in use by the customer. Naturally, the management of the relationship becomes increasingly important. Issues like cooperation, trust, power and long-term commitment come into play. When a customer decides to enter in a relationship by signing the product-service offering contract, he becomes “locked in” by the seller and thus dependent on the same [33]. “Customer lock” is when a customer becomes dependent on a seller for after-sales support. A practical example of this comes from TetraPak, which used to give away its filling machines and profit from the packaging material. In an ownership-based relationship, there is normally a high level of interaction between the customer and the seller, due to a
high amount of after-sales service. For the relationship to be successful over a longer timeframe, the seller has to consider these issues.

The intensity can also vary dependent on the situation of the customer. In some cases, the product is rented to a customer for many years providing with regular servicing; other times, the products are rented for shorter periods, following for example seasonal demands. BT Industries, which provides many of its forklift trucks through rental programs, explains it to its customers as follows [34]:

“Think of the advantages. You avoid all the risks of ownership. You don’t consume capital – not even a deposit is required. We take care of the equipment and make sure it’s always reliable, and we work with you to manage your fluctuating need – we call it capacity management. Rental from BT means flexibility for the future and all of your costs are predictable.”

(BT Industries, 2004)

During the use phase, the seller is responsible for maintenance and repairs of the product; the maintenance technicians handle this commitment. By providing regular service and maintenance operations at the customer’s location, a relationship is established through the service/maintenance personnel. Maintaining the relationship is an important factor of the BT policy of basing its service technicians at its major customers.

Another effect of a close relationship such as found in the BT case is that the service/maintenance personnel gain detailed information as to whether or not there is a need for a future remanufacturing operation. This information can make the return flow of products easier to control and provide information on the forklift truck status to the remanufacturing process. A high degree of control can for example be gained by high control of the products that are in operation at the customer, also called the installed base. By using information gathered from the installed base, the supply chain can be effectively coordinated. This information can be gathered by, for example, service/maintenance personnel as in the BT case or by software solutions integrated in the product (used by for example Xerox in photocopiers).

The installed base of a rental/lease or functional provider is often called the “fleet”, and this term is also used at BT. The products in this fleet are either in operation at the customer (in use fleet) or waiting for a customer (buffer fleet) as shown in Figure 3. High use of the installed base leads to a low size of the buffer fleet; vice versa, a low degree of use will indicate a larger buffer fleet. If the use of the installed base is too high (i.e. a small-sized buffer fleet), the company tends to have problems in supplying the demanded products and only the unneeded products are available. If the use of the installed base is too low, there are too many products in the buffer fleet. This leads to inventory holding costs such as value loss over time, obsolescence, cost of tied-up assets, etc. It is, therefore, important to have an optimal size for the buffer fleet, making correct sizing of the buffer fleet a crucial issue for management. From a remanufacturing point of view the size of the buffer fleet also has a major impact on remanufacturing capacity. In some situations the buffer fleet can work as an inventory providing a hedge against sudden demand peaks.

![Figure 3: The product flows between customer and remanufacturer in an ownership-based relationship.](image-url)
As illustrated in Figure 3, the size of the buffer fleet is dependent on the inputs (the return of used products (cores) and new products) and the output (the need for products and the number of products that are sold or recycled/scrapped). Information about incoming products can enable more accurate fleet management. To balance the size of the buffer, has proven to be a difficult task due to the high number of variables that influence the need for the buffer. Some important variables are:

**Uncertainty in returns** – A close relationship between the customer and the seller can reduce this insecurity. Still, there are situations where the customer wants to prolong the contract; this, however, will delay the return of the products. Furthermore, sometimes the used products are not returned immediately after the contract has ended. This also increases the delay of returning cores (product take-back).

**Uncertain demand for products** – Accurately forecasting the needs for products is always a difficult task. This uncertainty can be reduced if the buffer fleets are coordinated in a wider perspective – for example on an international or national level as opposed to a regional level. By distributing products between regions and countries according to demand, the total buffer size required can be reduced. This is especially true for seasonal demands where a large number of specific products are needed for a limited period.

**A high number of customized products that target a specific segment of customers** – When dealing with leasing or product-service offerings, the physical product tend to remain at the customer for a long period. This first customer carries the major part of the finance for the product. For this reason, the sales department tends to be willing to customize the product, the result being that the product can become ill-suited for other applications. For example, a customer might want a specific reach height for their forklift truck. This makes the mast of the forklift truck taller than normal and unusable for other customers because it will not fit into their environment, limiting the forklift to a narrower range of customer. Here remanufacturing can provide a solution by changing the specifications of the forklift truck in the remanufacturing process, either to a standard or according to another customer’s specification. Having this in mind, a standardization and/or modularization of product types would facilitate the downstream remanufacturing processes. Remanufacturing provides an opportunity to modify the specifications according to the customer’s needs, given that the design of the product allows for modification.

Gaining control of the installed base provides more than just support for fleet management issues. By the information gathered from the customer provides detailed information about the life cycle of the products in use by the customer. In this way the company can plan its sales activities according to the needs of the customer.

To operate product-service offers, the product needs to be combined with services. The development of a service system, as in the BT case, demands a high investment. Many of these investments are needed because a producing company must transition from traditional manufacturing to also becoming a service provider, something which affects the entire structure of a company and increases requirements for administration. The transition from making products to services has been documented by e.g. Olivia and Kallenberg [35]. Also, when offering integrated, total or bundled solutions, the risk for maintaining the operations of the product is transferred from the customer to the seller. In this case, it is very important for the manufacturer to have a positive cost structure for the complete lifecycle of the product.

Furthermore, there are some challenges in product development that need to be tackled in a rigorous manner in order to achieve products that are adapted for integrated product and service offerings (see e.g. Sundin and Bras [36]). If this is conducted successfully, the risks for product obsolesce will be reduced and the potential for a successful product service operation will increase.
According to BT, remanufacturing volumes have been doubled during the last few years and they currently exceed the number of forklift trucks being newly produced in the ordinary manufacturing facility. This means that for companies like BT, the remanufacturing business has recently become a very important part of their overall business.

4.2 Service Contract Relationships

This type of relationship has a high degree of similarity with the ownership-based relationship. The main difference is that the ownership goes over to the customer, thereby reducing the level of control over the products. This type of relationship is based on the formulation of a contract for aftermarket service. In the Swepac case, this contract contained clauses for repairs and maintenance as well as remanufacturing after a set period of time. The main difference between a service contract relationship and an ownership-based relationship is the ownership of the product; a major similarity between the cases is that the offers are still regulated by a contract that has the major influence on the relationship. Given these similarities, the characteristics of the ownership-based relationships is still valid, although the lack of ownership and the characteristics of a service contract add some difficulties for the producers.

For Swepac, coordinating returns for remanufacturing has proven to be a difficult task, mainly because of the unwillingness to return products at a specified date. This problem is rooted in the reduction in the customer’s capacity when a product is being remanufactured. When a product is sent for remanufacturing, it is unusable by the customer; consequently, this leads to unwillingness to return the product for remanufacturing at a specific time. As a result, the timing of the returns becomes unpredictable.

In this type of relationship, it is important to manage the remanufacturing activity. If the remanufacturer pushes the remanufacturing operation according to a contract, this can result in a negative response from the customer, dependent on if the customer needs the product at that time. This can result in a negative perception of the relationship in a customer perspective. One way to reduce this risk is to plan remanufacturing at a time when the utilisation of the product or the fleet of products is low. For example, Swepac performs its remanufacturing operations during the winter, when demand for compactors is less due to the ground frost. This is fundamentally the same problem as the companies that have a direct-order relationship, which is further described in the following section.

4.3 Direct-Order Relationships

In this situation, the customer gives an order for the remanufacture of a used product, as in the Turbo Tech case. Generally in the eyes of the customer, there is a problem in determining if there is a technical possibility to remanufacture the used product (core). Another uncertainty is what the price of the remanufacturing will be. The cost of the remanufacturing is dependent on the quality of the core and how much new material and labour will be needed in the process, and this is difficult to determine before the remanufacturing is undertaken. Regarding the pricing of the remanufacturing operation, there are different practices from company to company, and pricing can be variable to fixed. If fixed prices are used for remanufacturing, these risks of sending the used product to remanufacturing will be transferred to the remanufacturer.

In a case where the customer orders the remanufacturing, there is not normally a need to keep an inventory of cores; this is because the cores are supplied directly by the customer. Using a make-to-order system also reduces the need for a finished goods inventory. In some cases, remanufacturing to a direct order is the only alternative due to for example a lack of spare parts (normally due to the age, and consequently the low volumes of the product).

In the situation of a direct-order, the cores from a customer have to be sent away for remanufacturing. Say, for example, that the core for remanufacturing is a component of a product; the result will be that the product will be non-usable for the time when the component is being remanufactured. This is not
preferable for many situations; for example, a truck that needs to replace its turbo charger would have to stand still for a significant time while the turbo is being remanufactured. Most surely, the expenses for not using the truck are greater than the gains for the (potential) lower cost for remanufacturing. Still, this does not have to be the situation for someone that can wait for the remanufactured component while it is being remanufactured. Similar situations emerge when whole product is remanufactured. For example, if a filling machine such as those described in the TetraPak case were to be sent to remanufacturing, the result could be that e.g. the complete process in a dairy would become inactive. In these types of cases other relationships can be more effective.

4.4 Deposit-Based Relationships

In this situation, the customer is obligated to return the core when buying a remanufactured product, thus becoming the supplier of cores. This system is common in the automotive industry, where the remanufacturer normally supplies a product to a sort of “middle man”, for example, an automotive part retailer as in the UBD example. The retailer pays a price and a deposit for the remanufactured product. When the retailers sell the product, they collect the used core from the customers; later, they return the core to the remanufacturer and their deposit is refunded, resulting in a one-for-one (1:1) take-back relationship, see Figure 4.

This system creates a theoretical match between the supply of cores and the demand for remanufactured products due to the one-for-one link. An example of this is in the case of the brake calipers in a car (UBD case). In this case, the customer returns a number of brake calipers that directly correspond to the remanufactured products needed by the same customer according to the 1:1 principle. This system also creates a win-win situation for both the customer and the remanufacturer: the customer gets a low cost option by supplying, from their perspective, a low-value core, while the remanufacturer gets a supply of cores. However, in practice UBD reports that the 1:1 link is not valid. In reality, some of the cores are still not being demanded due to many random actions, for example sales clerks failing to demand the take-back of the core. Another factor that reduces the theoretical 1:1 relationship is that a percentage of the cores that are returned cannot economically be remanufactured due to extensive damage that would require extensive reprocessing. The result of this mismatch is that the company must use alternative systems to gather the lacking cores. A common solution used by UBD is to buy back cores from different kinds of scrap yards and core dealers.

In relation to the direct-order relationship, the deposit based relationship enables the customer to get a remanufactured product back at the same time as the used product is given back. This has proven to be a strategically important ability, especially for business-to-business relations where maintaining functionality is a critical factor. Another important issue not to be neglected is that this type of relationship is common when dealing with warranty claims. To be able to provide a remanufactured product immediately once a product breaks down during warranty can help to create a positive relationship with a potentially unsatisfied customer.
Even though a perfect correlation can exist between supply and demand, there is always a lead-time for a single product to be remanufactured. For UBD, this means that the market introduction of a remanufactured product demands an investment in cores. These cores have to be gathered in another way. Due to the lack of cores in the market introduction, the system frequently has to invest in newly-produced products.

Another issue and strategic question is the level of the deposit; if the price of the deposit is too low, the cores tend to disappear and a supply problem arises. A practical example can be taken from an auto repair shop were the repair staff throws away the core and charges the customer for the deposit, or the core is sold to someone who pays a higher price. Vice versa if a higher price is paid for the deposit the greater the chance that the core will be returned. At the same time, the retailer is forced to tie up capital in deposits. This type of problem can be solved with, for example, an extended credit note.

With a deposit-based system, no consideration is taken about the quality of the core that is supplied to the remanufacturer. The result may be that the perceived cost of remanufacturing, according to the customer, becomes too high if a high-quality core is supplied. Vice versa, the value of remanufacturing for a customer supplying a low-quality core becomes higher.

### 4.5 Credit-Based Relationships

This type of relationship is similar to the deposit-based relationship, but provides a higher level of sophistication (Volvo Parts case). Instead of a deposit fee, the customers receive credits for what they supply to the company. The number of credits the customers gain from the supplied cores is dependent on the state of the core. The credit they have acquired gives them a discount when ordering a new remanufactured product, see Figure 5. This credit system, however, does not have the same 1:1 relationship as the deposit-based system. This enables the customers to return as many cores as they wish.

![Figure 5: Illustration of core/credit flow in a deposit based relationship](image)

In the deposit-based system, no considerations are taken to the quality level of the returned core; it also does not motivate the customer to return more cores than the one-for-one principle. With a credit-based system, these considerations are taken in account. Credits are given according to two factors: 1) the quality level of the core, and if any of the specific components in the core are missing. 2) the amount of credits given is also variable between different types of products; highly demanded cores are given a higher credit; vice-versa a low credit is given for unwanted cores. In this way, the remanufacturer gets a high variety of cores and can practice some level of control by the credit system, while the customer can return cores for credits. This type of system enables the remanufacturer to some extent control the balance between supply and demand. The credit system can also function as a method for assessing the incoming quality level of the cores according to the amount of credits given for returned cores.

This credit system can be proven ineffective as well. This type of system provides the customer with a high degree of flexibility to return cores, but the control and predictability will be more complex then with the deposit-based system. The system can also be taken advantage of by the customer, for example if the credits given are unbalanced. Respondents have reported cases when customers have...
given back twenty cores of low value (e.g. a water pump) and used the credits to order a high value item (e.g. a remanufactured engine) that results in a major loss for the remanufacturer. In this situation, there is a lack of long-term commitment and cooperation that is needed for this system. One major disadvantage with this system is also that it creates a higher administrative cost for the remanufacturer. The customers will also be given an uncertainty in the number of credits they will receive for a specific core; this can result in a situation where price-sensitive customers hesitate to remanufacture, due to the uncertainty in price.

### 4.6 Buy-Back Relationships

Buy-back is as simple as it sounds; the remanufacturer simply pays out money for the cores. The sellers of a core, or multiples of cores, can be core brokers/dealers that specialize in the trading of cores, scrap yards, or end customers. This type of relationship is present in most cases of remanufacturing, and it is used as a compliment to some other type of relationship. It is common that the cores that are difficult to find are acquired in this way.

In many cases, buy-back is considered to be the last resolution if no other alternatives are present. For example, buying a product on a spot market is one way of buying cores; other more advanced systems are also used. One way is through core brokers, who have a close relation with their suppliers, often scrap yards. They are specialized in what they do and they have their own channels for acquiring cores. Maintaining a relationship with the suppliers is a strategically important issue. These core brokers are relatively frequent in the toner and automotive industries; the disadvantage can be the higher price paid (UBD and Greenman Toners).

Scrap yards can also be a good source for cores. Different levels of sophistication exist in scrap yards; in the UBD example, the company frequently visited a number of scrap yards to inspect their inventories and buy cores. Some scrap yards have sophisticated database systems, and online ordering is possible. In some situations, the OEMs have their own facilities for cannibalisation of components. The company Scania has a facility that buys Trucks that are in some way damaged, and cannibalise them for valuable components for reuse and remanufacturing. The main source of trucks in this case is those that have been damaged and are supplied by insurance companies.

When communicating with the customers in a buy-back relationship, UBD supplies its demands for cores to the customers, which in turn respond to the need of UBD. The suppliers of cores frequently also communicate concerning the types of cores available. In other situations, as in the Greenman Toner case, the cores are simply sent back to the remanufacturer, and the customer receives a refund according to a specified list.

Buy-back of products mainly results in customers getting money for their cores, although other systems do exist. Toffel reports a case where Lexmark uses a “prebate” program giving a discount on a product if the customer agrees to the return the product after use [37]. This program prohibits the customers to return or sell products to other companies. According to Lexmark, this program has boosted their return, although no reports about the efficiency of the program are given. The ability to gather “hard-to-get” cores is especially important when there are many independent remanufacturers that want to retrieve cores for their business.

### 4.7 Voluntary-Based Relationships

This sort of system is common in the recycling of different types of material such as newspapers. It also exists in the closed-loop supply chain with remanufacturing (Scandi-Toner case). As for recycling, this system is based on the idea that the customer will voluntarily give back the core. This system can also be forced on the customer and the original equipment manufacturer. This is done for
example through take-back laws stimulated by EU directives like the waste electrical and electronic equipment directive (WEEE) [38] and the end-of-life vehicles directive [39].

One example of this is the toner business that is regulated under the WEEE directive; as a result, toner cartridges cannot be treated as ordinary office supplies since they have been previously used. This creates a recycling problem for the customer. Scandi-Toner recognizes the embedded value in the discarded product that can be realized through remanufacturing. A recycling service is provided to the customer free-of-charge, and results in the access to used toner cartridges. The relationship is established by providing a take-back system that is realized with a return box that is (when full) sent to the company free-of-charge. The boxes are sent to the company randomly and can contain multiple cartridges. According to Scandi-Toner, the take-back system also motivates customers to remain customers, and provides a sales opportunity since a customer is more likely to purchase remanufactured cartridges when they are supplying the used ones through the take-back system.

The cores are supplied for free; the cost for the company is the transportation and material handling costs. According to Scandi-Toner, a key issue for profitability is to acquire the cores to a low cost. The environmental advantages of remanufacturing are strongly promoted as a motivational factor due to the lack of financial stimuli. This is done both to acquire cores and for use in motivating sales. Of course, the environmental issues count as a sales motivation in the other types of relationships as well, and not just in the Scandi-Toner case, but it is here where this issue is most actively marketed to the customer. A strong relationship with the customer is important; if possible, the integration with the customer should be as high as possible. An example of this is the free-of-charge return box used by Scandi-Toner.

The voluntary takeback relationships can generate a high supply of cores that in many situations have low demands for remanufacturing; this can lead to high levels of obsolete cores in inventory. A key issue is to keep this tendency at a minimum, continuously reviewing core inventory according to long-term forecasted needs. This type of relationship can also lack the ability to motivate the return of valuable cores that have a high demand for remanufacturing. The cores that are the most valuable do have a value and are subject for buy-back from competitors. A challenge here is to make the customer long-term committed to the company.

5 Discussion

Previous research has highlighted that there are some major differences between the “normal – forward” supply chains and the closed-loop supply chain with remanufacturing [40]. In previous research the characteristic of the closed-loop supply chain are explained and the implications of these characteristics have been modelled. Although in a management perspective it is important to go one step further, not only to realise that it is a problem to be handled but also on how to reduce the source of the problem. By applying a relationship perspective to the area of remanufacturing and the closed-loop supply chain, important insights can be gained. The importance of managing relationships has also been proven a prosperous and important issue in the supply chain management literature. Christopher adapt the following definition of supply chain management [41]:

“The management of upstream and downstream relationships with supplier and customers to deliver superior customer value at less cost to the supply chain as a whole”

In a closed-loop supply chain the management of relationships becomes even more important as the supplier of cores and the customer often are the same person or company.

In this paper, seven different customer/supplier relationships have been identified in the closed-loop supply chain. Each company has different resources and abilities that limit them to some specific relationships. For example, the ownership-based and the service-based relationships are mainly linked
to original equipment manufacturers, and are less common among the independent remanufacturers. As a result, none of these relationships is suited for every company. Another important issue is that these relationship structures are not used individually; in reality some of these relationships are used simultaneously to compliment each other. One general observation from this study is that buy-back relationships are generally present in all companies that are involved in remanufacturing. Although buy-back is normally not the major source of cores, and it is used only for the “hard-to-get” cores. The buy-back of cores also serves other strategic issues. For example, the buy-back of a product can both provide a sales opportunity as well as protect sales in the aftermarket [36]. The ability to adapt a specific type of relationship is dependent on multiple factors. Issues such as the type of product and the interest from the customer to have a relationship will influence the success of a specific type of relationship. A summary of these different findings is given in Table 2.

Table 2. A summary of the relationship characteristics in a remanufacturer perspective

<table>
<thead>
<tr>
<th>Relationship</th>
<th>Core control</th>
<th>Relationship focus</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ownership</td>
<td>High, returns are often regulated by contracts</td>
<td>High, long term relationships, focus on integrating products and services</td>
<td>Used by OEM with a high degree of interactions with customers that focus on the function (e.g. reliability) of products</td>
</tr>
<tr>
<td>Service contract</td>
<td>Medium high, return probability are dependent on different contracts</td>
<td>High, long term relationships, focus on adding services to the products</td>
<td>Used by OEM with a high degree of interactions with customers that want to own the products</td>
</tr>
<tr>
<td>Direct-order</td>
<td>High, cores are supplied to an order</td>
<td>Low to medium according to importance of the product in respect to customer operations</td>
<td>Suitable in situations when: the product can be sent off for a longer period of time - no new parts are available - the price of remanufacturing is an important issue - the customers want the same product back as sent in. Can provide a remanufactured product immediately once a product breaks down, e.g. during warranty.</td>
</tr>
<tr>
<td>Deposit-based</td>
<td>Medium, a theoretical 1:1 relation exists</td>
<td>Low, transactional focus</td>
<td>No considerations about the quality of the core is needed</td>
</tr>
<tr>
<td>Credit-based</td>
<td>Medium, enables some control opportunity, no strict 1:1 relation</td>
<td>Medium to high, based on long term cooperation</td>
<td>Considers and compensates for different quality levels of the core</td>
</tr>
<tr>
<td>Buyback</td>
<td>Medium, one can control what you want to buy or not</td>
<td>Low to high, ranges from buying cores at spot price to long time collaboration with e.g. insurance companies</td>
<td>Used manly as compliment to some other type of relationship. Used especially for acquiring hard to get cores</td>
</tr>
<tr>
<td>Voluntary</td>
<td>Low, the company gets what the customer is willing to give</td>
<td>Low to high, focus on providing the customer with a positive environmental profile</td>
<td>Minimising the cost for acquiring cores</td>
</tr>
</tbody>
</table>

Regarding the different types of relationships, the ownership and the service-based relationships have the highest control over the installed base, and have a favourable position in gaining information about the installed base. The higher degree of control gained by the detailed information can decrease uncertainty in the quality level of the incoming product (core). This information, combined with detailed contracts about the duration of the contracts and the point of return, makes the remanufacturer able to predict the timing and quantity of the returns and ease the need to balance returns with demand. In an earlier study, Thierry et al. comes to the same conclusion when they write that “companies that lease their products are generally in a more favourable position than companies that only sell products. Lease companies usually have more information on the quality and return of used products” [13].
With the information about the status of the installed base gained from the customer, the seller can be one step ahead, realising the needs of the customer before the customer themselves. In a sense, a seller can control timing of different activities according to its ability to perform at its best. For example, sale advantages can be gained when the products that are close to their end-of-use are to be replaced. This information can then initiate a proactive sales activity. Another example is when an innovation pushes the product’s usage out of its economic lifetime. According to Holmlund, the actions in these sequences have great influence on the perception of the relationship [42]. Without the information about the customers installed base, this advantage would not be possible. As a compliment, the information about the customer also gives an information advantage over the competitors.

In the ownership and service-contract types of relationships, there is an increased focus on delivering a function. With the increased focus on functions, the downside is that the perceived risks of the customer can increase. During the time that the product is remanufactured, the customer loses the functionality of the product, which can cause a negative sequence in the relationship. By minimising the loss of functionality, the perceived costs of the relationship can also be reduced. The company Swepac solves this challenge by performing remanufacturing when utilisation of its products is low. Other solutions can be to compensate the loss of function with another product; this is a strategy frequently used by, for example, auto repair shops.

In direct-order relationships, the risk of loss of function becomes especially apparent. From the perspective of the customer, this system generates a high risk, as well as lack of functionality when the product is away for remanufacturing. In addition, the way the pricing of the remanufacturing service is undertaken is a source of risk. Pricing of a remanufacturing service can be variable or fixed resulting in different levels of perceived risk in the eyes of the customer. These disadvantages make this type of relationship only suited for a limited range of situations, mainly when:

- The product can be sent off for a longer period of time
- When no other type of spare parts are available
- When the price of remanufacturing is an important issue
- When the customers want the same product back as they sent in (e.g. customized products with high value).

A deposit or credit-based system would be more appropriate in situations where it is critical for the customer to maintain functionality of a product. This is due to the importance of being able to provide a remanufactured product/component as soon as possible. The advantage with these relationships is that they can provide a replacement right away. One important aspect of this system is that it demands an initial investment in cores when a new product type is starting to be remanufactured. The main implications are that this system is preferable for rather standardised products with a high volume, e.g. toner cartridges.

Regarding deposit and credit-based relationships, the major difference is the level of sophistication. The credit-based system has an additional function of stimulating the customer to return specific cores. From a customer-relationships perspective, this system will be most fair. This system also stimulates cooperation between the parties. The accumulation of credits also stimulates a long-term commitment to the remanufacturer. Overall, the credit-based system relies on commitment, trust and the win-win situation, compared to the more transaction-based and deposit-based relationships. In this type of relationship, the gate-keeping function is very important. Gate-keeping in this context means the screening of the cores that are coming back to the entry point of the reversed logistic network. The foremost important issue of the gate-keeping function is inspecting cores and giving the appropriate number of credits.

Voluntary-based relationships are based on the idea that the customers will voluntarily give back the core. This relationship system can also be forced on the customer and the OEM with take-back laws. To stimulate customers to give back their used products, relationship management becomes important. Some negative effects of this system are that it can generate a high supply of cores that in many
situations have a low demand for remanufacturing. It can also lack the ability to motivate the return of valuable cores that have a high demand for remanufacturing. The environmental advantages of remanufacturing are strongly promoted as a motivational factor due to the lack of financial stimuli.

5.1 Result Validation

Building theory from case studies attempts to reconcile evidence across cases, types of data, and different investigators, and between cases and literature increase the likelihood of creating reframing into a new theoretical vision [27]. The triangulation by using other data collection methods rather than only interviews and comparisons with other companies made the results of this study more valid.

A drawback of theory building from case studies is that the intensive use of empirical data can yield theory which is overly complex [27]. Hence, the result can be theory which is very rich in detail, but lacks the simplicity of overall perspective. Having this in mind – the different closed-loop supply chain relationships presented in this paper should only be seen as important factors in the management of reverse supply chain management.

Strong theory-building research should result in new insights. Theory building which simply replicates past theory is, at best, a modest contribution [27]. Furthermore, replication is appropriate in theory-testing research, but in theory-building research, the goal is new theory, as in this research study.

6 Conclusions

This research has been building theory based on case study research. By identifying the closed-loop supply chain relationships, a higher understanding can be gained about the structure of the remanufacturing industry and the characteristics of the relationships. The identified relationships are ownership-based, service-contract, direct-order, deposit-based, credit-based, buy-back, and voluntary-based relationships. These individual relationships have different characteristics and are suitable in different situations as described in the previous section. The more general conclusions about how the relationships can be managed are:

Firstly, one should understand that these relationship structures are not used individually; in reality, some of these relationships are used simultaneously to complement each other.

Secondly, a proposition is that the more important a product is for the customers operations, the higher is the will to have a closer relationship as in an ownership or service contract relationship. Also, the perceived risk of the remanufacturing operation has a strong influence on the willingness to become involved in a closer relationship. Issues like cooperation, trust, and long-term commitment are important in these types of relationships. When managing these types of relationships, the focus should be on reducing risk and the perceived relationship costs.

Thirdly, a higher degree of control over the installed base can enable the OEM remanufacturers to control the timing of activities in the relationship (as in an ownership or service contract relationship). The information can enable a seller to be one step ahead, realising the needs of the customer before the customer themselves. In a sense, a seller can control timing of different activities according to its ability to perform at its best.

Fourthly, remanufacturing can be a source of negative responses in the relationship. This is especially apparent when the remanufacturing operation results in a loss of functionality in the customer’s value-adding process. One way of reducing the risk of a bad response is to plan remanufacturing at a time when the utilisation of the product or the fleet of products is low and thus reduce the perceived cost of the relationship.
Fifthly, one proposition is that remanufacturing becomes more effective when there is a clear win-win situation for both the customer and the remanufacturer. In the sense that the customer enables the low cost option of remanufacturing by supplying, from their perspective, a low-value core, in the same time as the remanufacturer gets a supply of cores.

Sixthly, take-back systems can be taken advantage of by both customers and suppliers, for a long-term successful relationship there is a need to have mutual commitment and trust.

To conclude this paper, the success of a remanufacturing business is very dependent on the relationship between the remanufacturer and the customer, since the customer can both act as a supplier and a customer to the remanufacturing company. Since the retrieval of used products is crucial for the remanufacturer, the management of these supplier/customer relations are very important. The companies studied in this paper all recognise that the management of the relationship with their suppliers/customers has contributed to their business success.

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8 References


Material and Process Complexity – Implications for Remanufacturing

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Abstract
Remanufacturing is a complex business. Many different factors and decisions affect the performance of a remanufacturing process. In this paper, four different remanufacturing cases are analyzed in how they manage these complexities.

Based on the generic remanufacturing process, remanufacturing can be divided into the five phases of pre-disassembly, disassembly, reprocessing, reassembly and post-assembly. In each of these phases, a discussion is made regarding the specific factors and decisions that influence the order and purpose of the individual operations.

Keywords: Decisions, Disassembly, Reassembly, Remanufacturing, Reprocessing.

1. Background
Remanufacturing is “an industrial process whereby products referred to as cores are restored to useful life. During this process the core passes through a number of remanufacturing steps, e.g. inspection, disassembly, cleaning, part replacement/refurbishment, reassembly, and testing to ensure it meets the desired product standards” [1].

Compared to ordinary manufacturing, the process of remanufacturing is affected by a number of additional complexities. Some of these presented by Guide [2] are: (1) the uncertain timing and quantity of returns, (2) the need to balance returns with demand, (3) the disassembly of returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

In the remanufacturing process, there can be major differences in material handling and the remanufacturing process from case to case [1]. In the research reflected in this paper, some of the complexities that influence the remanufacturing process have been addressed, and done so from a generic remanufacturing process perspective.

2. Aim
In this paper, the complexity of material handling and process control in remanufacturing is described. This complexity is based on a number of factors and decisions. A discussion is presented on how different factors and decisions affect the process, and how they are managed in four different industrial cases. Comparisons to existing theory and empirical investigations are also made.

3. Methodology
The research conducted for this paper is a part of a larger research project called the REKO-project: “Sustainable Systems and Products for Remanufacturing and Refurbishment”. Today, the project encompasses three Swedish case companies (BT-Industries, Scandi-Toner and UBD Production). In each case, eight semi-structured interviews, ranging from 30 minutes to four hours, were performed. The interview respondents consisted of management staff (e.g. manufacturing and logistics managers) as well as operational staff. During the course of the research, one master’s thesis was completed that analyzed material handling at Volvo Parts [3]. A workshop has also been conducted in collaboration with the Linköping Re-Group research group, Volvo Parts and UBD Production. In total, four Swedish companies were investigated.

4. Theoretical framework
In the literature, there are a number of different models for the different processes in remanufacturing. Some are
specific for different cases (see e.g. [4]), while others are more generic. Sundin [1] is one researcher who presents a generic model of processes in remanufacturing (see Figure 1). This generic model encompasses seven generic processes that can be a part of a remanufacturing process. These are: inspection, cleaning, disassembly, reprocessing, reassembly, testing and storage, although all of these processes do not have to be included to make a remanufactured product.

Regarding the production planning in remanufacturing environments, the focus has been on quantitative models for disassembly and calculating optimal inventory levels, order quantities, etc. For an overview, see Guide [2] and Inderfurth et al. [5]. Inderfurth et al. present a report on production planning in the closed-loop supply chain focusing on disassembly and possible disassembly strategies, determining the best strategy (through a net profit analysis), and disassembly scheduling. Regarding material planning, the same authors present a model for material requirement planning (MRP) in a remanufacturing environment. For the operations in the disassembly system, Bröte [6] presents a generic disassembly model, with more than 20 different operations.

When considering complexity in remanufacturing, the relationship with the customer also needs to be considered in the closed-loop supply chain. Different types of relations provide different characteristics for the remanufacturing process, such as ownership-based relations, deposit-based relations, credit-based relations, buy-back relations and take-back relations [7].

5. Four different remanufacturing processes

The analysis from this paper is based on empirical data from four different case companies: toner cartridges at Scandi-Toner (independent from Original Equipment Manufacturer (OEM)); forklift trucks at BT-Industries (OEM); engines at Volvo Parts (OEM); and automotive parts at UBD Production (Independent/Contracted). Each of these cases will be briefly described in the following sections.

5.1. Scandi-Toner

The remanufacturing process at Scandi-Toner is as follows. The toner cartridges are sent randomly to the company in boxes from the customer. Each box can hold multiple cartridges. When the box arrives, it is unpacked and undergoes a combined manual operation where the product is simultaneously identified, inspected and sorted. The cartridges are sorted according to a preset standard based on whether they have been used only one time (virgin) or have been remanufactured before (non-virgin). They are also sorted after the status of the core; an example here would be if the cartridge was damaged in some way.

The sorting is also done because of an over-supply of cores, and the best (i.e. virgin) are designated for remanufacture, while the remaining are placed in reserve. Another reason is for capacity management: when there is a demand peak, it is only the virgin cores that can be used, enabling more rapid remanufacturing and thereby a higher remanufacturing volume. Non-virgin cartridges are used in situations of over-capacity, due to the increased time it takes to remanufacture the cartridges.

After the sorting operation, the cores are stored in inventory while waiting for a remanufacturing order. When the order arrives, the cores are sent to a disassembly operation.

From this point, some of the parts are sent to a cleaning operation, while others are sent to machining operations to be reprocessed and, in some cases, cleaned. Some of the parts are also sent to recycling/landfills, and new
components are used to replace the discarded. The reason for the discarding is either that the components are broken, or due to a policy at the company to always replace the components.

After all parts have gone through reprocessing operations, they are reassembled with the new components. After reassembly, they are tested and packed before they are placed in the finished goods inventory.

For the production planning, a make-to-stock re-order point system is used. Order quantities are set to the re-manufacturing of a specific number of cores. In the process, a percentage of the cores are found non-usable (about 10%, but this figure varies from product to product), and the number of remanufactured products gained from the process varies. One of the problems in the process is the availability of the cores to be remanufactured. The availability can be uncertain due to the characteristics of the take-back system. In the toner cartridge remanufacturing business, the availability of products is a key success factor, and therefore the out-of-stock costs can be seen as high. In this environment, the company’s main focus is on the remanufacturing lead-time.

5.2. UBD Production

This company remanufactures car components. The main product is brake calipers, but it also remanufactures products such as steering racks, steering pumps, master cylinders, etc. UBD uses a deposit-based supply chain system. This creates a theoretical match between the supply of cores and the demand for remanufactured products. Although this is not the case, and spare cores have to be acquired by other means. UBD has two different facilities, one in Poland and one in Sweden. The incoming cores arrive at the plant in Sweden where they are inspected and sorted into “UBD numbers” – a company-specific code system that is car manufacturer-independent. No consideration is taken for the quality level of the core; only those that are clearly non-remanufacturable are sorted out from the system. After sorting, the products are held in stock awaiting a remanufacturing order. When an order is taken, the products are sent to Poland for disassembly. As in the Scandi-Toner case, the components are sent to different reprocessing operations: repairing, cleaning, blasting and painting. When the components from a batch are reprocessed, they are sent to Sweden for reassembly with complementary new parts that have been discarded.

In this case, the remanufacturing is conducted according to a make-to-stock policy for the independent market, and a make-to-order one for the contracted orders. In the make-to-stock policy, the order release is made by re-order points. The focus in the remanufacturing process is on operational and transportation costs.

5.3. Volvo Parts

This case presents a remanufacturing process for heavy diesel engines. The company uses a credit-based supply chain where the customers receive credits for what they supply to Volvo. The credits are then used for obtaining discounts when ordering a remanufactured product. This makes the balance between supply and demand relatively even. When the cores arrive at the facility, some of the external components from the core are disassembled and sent, for example, to remanufacturing. The cores are thereafter placed in an inventory until a remanufacturing order is received. The core is then disassembled. It is in this operation that the components are also visually inspected. After this, the components from the original core are kept together as they move between the reprocessing operations in a sequential manner, in contrast to the flow in the Scandi-Toner and UBD cases. However, some of the components are separated from the core to be sent away for reprocessing. The reason for this is that they require higher batch numbers due to, for example, higher set-up costs. The engine is reassembled with reprocessed components from the original core, new components and reprocessed/ cannibalized components from inventory\(^1\). Following reassembly, the remanufactured product is tested and then (if it passes the test) painted. There is also a difference in the level of reprocessing in the process: the processes may be the same, but the level of replacement of components and the level of reprocessing of the components are different. The purpose of this is to provide different solutions for different customer needs.

The engines are produced in a make-to-stock environment with delivery to a central inventory. The orders are based on MRP, but re-order point systems are also used for some low-value components (See [5] for details). Overall, there is a 1:1 relation of a core to a remanufactured engine in the process, although there are times when spare cores are disassembled to be cannibalized for parts.

5.4. BT-Industries

In the forklift truck cases, the cores are controlled by a take-back system that is ownership-based. In the BT case, the forklift trucks are linked to a functional sales contract, which gives the company a high degree of control regarding the closed-loop supply chain. When the remanufactured products arrive, they are inspected and sorted into different levels. When a need arrives, they are sent to a remanufacturing shop for disassembly. The forklift always has a fixed position during the

\(^1\) Further details of the reassembly operation can be found in the study by Svensson et al. [3] or Östlin et al. [8].
remanufacturing process, and this is also when components are replaced. Some simpler reprocessing of components is also performed, but the components are for the most part replaced with new ones. After functionality testing, the product is painted.

In this case, the remanufacturing is done in a make-to-order environment. As in the Volvo Case, there is a 1:1 relationship been the core and remanufactured product in the process. The components are replaced when needed, and to a certain degree according to the different functional sales solution.

6. The Five Remanufacturing Phases – Decisions and Factors that Effect the Process

Judging from the experiences gained in the previously described remanufacturing process, there are many different ways to organize one.

Even though there are some general characteristics that appear to be valid in all cases – such as disassembly being conducted before reprocessing, and reprocessing being done before reassembly - the order of the other operations in remanufacturing, such as inspection, testing, cleaning etc., are case dependent.

The specific order and purpose of the operations that define the process is dependent on a number of factors and decisions, which will be described in the following sections.

Based on the generic remanufacturing process, remanufacturing can be divided into the following five phases:

- Pre-disassembly phase
- Disassembly phase
- Reprocessing phase
- Reassembly phase
- Post-assembly phase

A general overview of the relationships between the phases is shown in Figure 2. In the following paragraphs, each of these remanufacturing phases will be described in detail.

6.1. Pre-disassembly phase

This phase can be described as a preparatory phase – before the remanufacturing process begins.

When a core is returned from a customer, the state of the core must be considered. This is important in order to decide whether to remanufacture, cannibalize components or recycle the core (see Figure 3).

In the UBD case, there is no need to rank the quality level of the core; there, only the type of core is identified due to the fact that there is a higher demand of products than the supply of cores, and thus all of the cores are used.

In the Scandi-Toner case, in contrast, the cores are inspected to maintain better control of the process.

In the BT case, the inspection is important to make a correct valuation of the market value of the core and to obtain an estimate of the costs for remanufacturing. This is then considered in regard to the market value of a remanufactured product. In the BT case, some of the information regarding the state of the product is known in advance, due to a specified service record.

Figure 2: An Overview of the Five Remanufacturing Phases
In this phase, inspection and testing are made to identify the product, the quality level of a product or the market value. Sorting is performed to be able to control the process in later phases, for example by using high quality cores when free capacity is low, as in the Scandi-Toner Case. Sorting is also done in order to determine what economic potential a core has for remanufacture.

When information about the core is retrieved, there is a decision point concerning what to do with the core. The alternatives are to remanufacture, cannibalize components, recycle the core or keep it in inventory for future needs. The decision about what to do with the core is based on a number of different factors.

To be able to motivate remanufacturing, for example, the resources that are put into the remanufacturing of a core should be less than then the market value. Here, the information about the cores can be of great use when deciding to remanufacture the core or not. In this situation, there are many different contributing economic factors that influence the choice to remanufacture a core, such as:

- Costs for acquiring the cores
- Potential costs for disassembly, reprocessing and reassembly as well as the cost for new components
- Inventory levels and values of components (new, used and reprocessed components) in the disassembly and reassembly phases
- Minimal order quantities in relation to future needs
- Cost for logistical and marketing activities

All of these factors add to the complexity of the process. By gaining information about the core, the decision can be simplified. Therefore, making it easy to retrieve this information can aid in making a correct decision.

Another important factor is that the design of the product to be remanufactured also influences the processes (for further details of this factors see e.g. [1]).

For the decision to cannibalize the core for components, the inventory levels and the need for individual components later in the disassembly and the reassembly process need to be put in relation to the costs associated with disassembly. Another important factor when cannibalizing for specific components and keeping the core in an inventory is that one needs to “remember” what parts that are taken from what core; if not, this can create problems in the future.

Deciding whether to recycle the core is a question of, for example, whether it can be useful in the future. This depends on if there are other cores available to be remanufactured/cannibalized, as well as the status of these cores in respect of the present core.

Figure 3: The Process in the Pre-Disassembly Phase

- Core to be Remanufactured
- Core to be Cannibalized

Figure 4: The Process in the Disassembly Phase

- Disassembly
- Separating, Inspecting, Sorting, Testing, Cleaning, Valuation
- Status of the Components: reusable, reprocessable, not reprocessable
- Decision Point 2
- Inventory
- Decide to Reuse the Component or Recycle the Component

Figure 4: The Process in the Disassembly Phase

- Extended Core Information: Core Identification, Quality Level, Core Value, Fault Diagnosis, etc.
- Decision Point 1
- Inventory
- Recycle the Core
- Cannibalization of Components
- Remanufacturing of the Core

Information from:
Customers, Service Records, etc.

Core to be Remanufactured

Core to be Cannibalized

Inspection, Sorting, Testing, Cleaning, Valuation

Figure 3: The Process in the Pre-Disassembly Phase

- Core Identification
- Quality Level
- Core Value
- Fault Diagnosis
- etc.
6.2. Disassembly phase

When the decision is made to remanufacture a core or cannibalize a core for components, the cores are sent to disassembly. After the component has been disassembled from the core, another important decision must be made regarding the state of the components: if they are reusable, reprocessable, or not reprocessable for a reasonable cost. Depending on the state of the component, there is an option to reuse it as is, to reprocess it or to discard it (See Figure 4).

The disassembly can possibly involve a number of different activities where different separating operations are the most prevalent. In the Volvo Parts case, the complete core is disassembled. In the disassembly operation, the components are inspected to determine if they are reusable or reprocessable; if not, they are sent to recycling. Some of the components may be reusable or reprocessable, but are still recycled. For example, all of the case companies have policies in place to always exchange certain components. These policies can be driven by reliability or security reasons, for example.

Some of the components, however, might be out of date when a product is being upgraded to a higher innovation level, as in the Volvo case. In the BT case, the forklift truck is disassembled according to the need of replacement/reprocessing of individual components. This implies to that the entire core does not have to be disassembled; the level of disassembly also depends on the status of the individual components.

If it has been determined that some components are to be reused after disassembly, no reprocessing is done. Depending on the material handling solution, the components can be stored in an inventory before reassembly (as in the Scandi-Toner case) or be kept in a “reassmbly kit” with the components that are to be reprocessed (as in the Volvo Case).

Regarding the decision of what to do with the components, the same type of reasoning as with the core is applied, although some of the insecurities have disappeared due to the earlier decision in the pre-disassembly phase. In this case, the status of the component is important; for example, a component might be reusable, but not appropriate. Take, for example, a battery from a forklift truck in the BT case. Here, the battery is in working condition, although it has only 30% of its normal capacity. Installing this battery in a remanufactured product will mean that the customer must change it in a short period of time, potentially creating a warranty claim or badwill. Alternatively, the battery could go through a reprocessing activity that, for example, would change out a cell of the battery and return the battery’s work capacity to 60%, or the battery could be recycled. Some customers might demand the highest standard; in that case, a new battery would be the only option. As for the core, this question depends on many different aspects, such as:

- Potential costs for reprocessing as well as the cost for new components
- Inventory levels and values of components in the reassembly phases (new, used and reprocessed components)
- Lead-time to reprocess or to purchase new components
- Minimal order quantities in relation to future needs and the risk for obsolescence
- Quality level needed by the customer
- Availability of an upgraded version of the component

6.3. Reprocessing phase

The components that are planned to be reprocessed can undergo a variety of different operations that aims to repair or raise the quality of a component. Although in some cases, the component might be found non reprocessable, and it is recycled. An example of this is a hidden crack in the housing of a brake caliper.

In some cases, the reprocessing activities might make changes in the component that makes it incompatible with
its former core or a component. An example would be when a cylinder in an engine is damaged and can be reprocessed by expanding the diameter, with the result that another diameter for a piston has to be used. When doing so, the complexity of the process increases since the bill of material (BOM) is changed (due to the difference in piston diameter). The changes made demands some sort of documentation and administration. For this reason, UBD chooses not to remanufacture a product if it changes its BOM, as this creates excessive administration. This is not the case for all cases. Volvo uses “over dimensions” as in the cylinder example. The difference between Volvo and UBD is that an engine has a higher value than a brake caliper, and thereby the additional cost is compensated for.

The extent of component reprocessing varies significantly between the different cases. The trend is that the more value in each component, the more feasible it is to reprocess; this depends, however, on the desired level of quality demanded by customers.

6.4. Reassembly phase

In the reassembly operation, the individual components that have been separated from the core need to be reassembled. This can be done in four ways: with a reprocessed component, with the replenishment of a new component, with a reused component or with a component taken from a cannibalized product by ordering a disassembly operation. The new component can be an exact copy of the original component or an upgraded one, depending on the customer needs.

In the UBD case, all the components that are to be reused and have been reprocessed are stored together. Here, the challenge is to have the right number of each component. The missing components are replaced with mostly new components, but in some cases with used ones. Another alternative used by Volvo is that new, used and reprocessed components are stored together, and the specific amount is gathered from this common inventory. The advantage of the UBD scenario is that some material handling is avoided. In the Volvo case, the gathering process is easier.

Regarding the decision of what components to use in the reassembly of the remanufactured product, the used components should be used in first hand, because, ideally, they should have the lowest cost (if not, they should have been recycled in earlier phases). Even so, some of the components might need to be replaced with a new component due to differences in customer needs (as, for example, in the battery case presented earlier). The gaps in the product that lack components need to be filled with other components; here, the first priority are the reprocessed components, if they are available. It is possible that the lead-time for reprocessing may be too long, meaning that components might not be available in time. Some components can also be cannibalized from cores if the new component cost is too high.

One of the major obstacles in controlling the remanufacturing is that it is not possible to know how many components can be used again or reprocessed. Purchasing and storing new components can solve this problem; if the need arises, they are accessible and can be used directly. This solution, however, is not ideal for all components, because it demands inventories, and herby capital, and it could create obsolescence problems. To order all the new components in the reassembly phase means that the lead-time would be very long if a component takes a long time to arrive. One solution made by Volvo is to “forecast” the “material recovery rate” of each component; this is set by experience. Based on this, a percentage of the components are ordered for a specific order. An example of this can be when 12 engines are to be remanufactured and 40% of the 12 camshafts are predicted to be recycled; in this case, the company would order 5 new ones. This, of course, depends on the volume, the value of the product and the lead-time for an order of new components (for a detailed discussion, see [8]).

6.5. Post-assembly phase

When the core is reassembled, it is ready to become a finished remanufactured product. In this phase, the products are put into working order. For example, software might be upgraded to the latest standard (as in the Volvo case). The functionality might also be tested. Other operations can include painting and preparations to send the remanufactured product to the customer.

6.6. Decisions in the Process

From the different phases described earlier, three clear decision points exist:

1. Whether to remanufacture, cannibalize components or recycle the core
2. Whether to reuse, reprocess, or recycle the individual components
3. Which components are to be reassembled into a product

For the planning of the process, however, there is another important decision to make:

4. Whether to plan according to the need for products or the availability of cores

From a planning perspective, this can be approached in two different ways: from the reassembly point of view...
(plan according to the need of products) and from the disassembly point of view (plan according the availability of cores).

In the Volvo and BT cases, planning was done according to the need for products, whereas UBD and Scandi-Toner used a reorder-point system. The planning according to the need for products, the focus was on the number of remanufactured products to be produced. In the planning according to availability, the number of cores that would enter the remanufacturing was the focus.

6.7. Planning for the need of products

In the Volvo and BT cases, each product had a low volume and a high value. The supply and demand of cores and remanufactured products was also quite even, due to the supply chain characteristics.

The planning focus is on the number of remanufactured products to be produced; this means that the number of cores to enter the process is variable. However, in both the Volvo and BT cases, there was more or less a 1:1 relation between cores entering and products exiting the process. In both of these cases, a MRP environment was used where the cores were sent for remanufacturing and the components that were sent back were either new components or cannibalized ones. These components were then taken from an inventory or ordered depending on the situation. Some of the components were also reprocessed, but that depended on if there was capacity in the reprocessing operation. In all, this can prove to be an expensive process, especially if the core to be remanufactured requires a great number of new components. Here, cannibalization can prove to be an attractive solution to decrease the cost for components, especially when considering the cost of cannibalization.

6.8. Planning according to availability of cores

UBD and Scandi-Toner both had high volume and low value, which was the opposite of the Volvo and BT cases. Both UBD and Scandi-Toner use a reorder-point system for initiating remanufacturing orders. The order is dependent on the number of cores that are available in inventory when the order arrives. These are then sent through the process, and the number of remanufactured products that exit the process are variable, but this variability is not that important from a control perspective since the use of this reorder point system is connected to a make-to-stock policy. However, if the demand for remanufactured products is high, it is important to get as many cores out from the supply as possible; if the supply is stronger, then the opposite is true.

7. Conclusions

Remanufacturing is a complex business. When controlling a remanufacturing process, there are many factors and decisions that must be considered. This paper has presented solutions and ideas that can aid in the management of the remanufacturing process.

8. Acknowledgement

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References

Lean Remanufacturing – a Study Regarding Material Flow

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1 Introduction

Sustainability is an important issue in most of today’s economies, as product take-back and product recovery laws have been implemented in many nations (Pyke et al., 2002). Together with these legislative demands from governments¹ and a growing interest for a “green” image and environmental care, there are many economic incentives for companies to take interest in product recovery and the after-market. Remanufacturing, the focus of this paper, has evolved as a great business opportunity, especially given the European market’s enormous growth potential. In the USA, the remanufacturing industry is a major business sector. The automotive industry in the US sells approximately 60 million remanufactured automotive products, compared to 15 million products in Europe for an equivalent stock of vehicles (Seitz et al., 2004). However, volumes and revenues for remanufacturing are characterised by high variability and are difficult to forecast, since the demand could be described as low-volume with immense fluctuations (Ashenbaum, 2006; Guide, 2000; Dowlatshahi, 2005; Steinhilper, 1998).

In remanufacturing, worn-out, discarded or broken product/components, referred to as “cores”, are being restored to a condition with the same performance as a new product, but produced at a lower cost (Amezquita et al., 1995). Compared to manufacturing, the remanufacturing batch sizes are normally smaller, the degree of automation is lower and the amount of manual labour is higher compared to that in a manufacturing plant (Steinhilper 1998). Remanufacturing is a complex business due to the high degree of uncertainty in the production process (Guide, 2000; Seitz et al., 2004), which is primarily caused by two factors: the quantity and quality of returned products, i.e. cores (Atasu et al., 2005; Umeda et al., 2005). This uncertainty also creates variations regarding capacity requirements as well as the yield of the process. Guide (2000) defines these factors in greater detail and presents altogether seven characteristics of remanufacturing that are found in the current research literature and which increase complexity. These characteristics are: the uncertain timing and quantity of returns; the need to balance returns with demand; the disassembly of returned products; the uncertainty in materials recovered from returned items; the requirement for a reverse logistics network; the complication of material matching restrictions; and the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

Just as for manufacturing companies, the remanufacturing industry is also subject to increased competition in markets and pressure from customers and suppliers. World-leading manufacturing companies are in a state of change towards a different view of manufacturing. The pressure on a company can be observed from its customers, who demand customized, cost-reduced and quality-enhanced products enabled within short lead-times, and from its suppliers, who demand reduced inventory levels and increased demand variability (Mentzer et al., 2001). To respond to these demands, Lean Production, which is said to increase productivity, decrease lead-time and costs and enhance quality, is widely adopted (Sanchez et al., 2001). The concept of Lean Production, developed by Toyota, is in its most basic form the systematic elimination of waste - overproduction, waiting, transportation, inventory, motion, over-processing, defective units - and the implementation of the concepts of continuous flow and customer pull (Womack et al., 1996). In a study made by Sundin

¹ Examples of legislative take-back laws are derived from different EG directives such as the Waste Electrical and Electronic Equipment Directive (WEEE), Directive 2002/96/EC, and the End-of-life Vehicles Directive (ELV), Directive 2000/53/EC.
(2004) using a Rapid Plant Assessment (RPA) ranking methodology investigating how lean remanufacturing companies are compared to classic manufacturing companies, it was found that the additional complexities regarding material flows in remanufacturing may be a limiting factor for remanufacturing companies in the application of Lean production principles. Seitz and Peattie (2004) concluded the same results in a study where differences in comparison to manufacturing were observed. Further research is desired by both academy and industry. (See e.g. Dowlatshahi 2005)

The previously presented research clearly shows that remanufacturing companies generally perform poorly in material flow and material handling issues. One reason identified for this was that the remanufacturing process is subject to uncertainties in many different forms. The objective of this paper is to identify how lean principles for material planning and production planning can be applied for remanufacturing?

2 Previous Research

2.1 Previous research of Lean Production in Remanufacturing

The previous research in applying lean production principles in remanufacturing is scarce. The only known previously reported study in this area is a case study by Amezquita et al. (1998) that focuses on the remanufacturing of an automotive clutch. The main results from this case study were the development of techniques for lean automation and different methods for reduction of setup times. Another conclusion from this study is that different reprocessing technologies – e.g. additive technologies – need to be developed to be able to apply several lean principles, e.g. a one-piece flow.

Remanufacturing research is relatively young; one of its pioneers was Robert Lund, who conducted one of the first studies in 1978 in the USA. In 1994, Brennan et al. observed that the technical literature was scarce and existing articles only dealt with those topics on a general level. Guide & Srivastava (1997) recognized a growing demand for extended research in the remanufacturing production planning and control area. Recent findings by Seitz & Peattie (2004) and Dowlatshahi (2005) state that research is still conducted on a general level. Although said to have a promising future, studies by for example Nasr (1998) show that the remanufacturing industry’s growth possibility is threatened and limited by the few techniques and technologies specially developed for remanufacturing.

2.2 The Remanufacturing Process

The process within which the used product is remanufactured is called the remanufacturing process. It is an industrial process where the core (defined here as a used/broken product suitable for remanufacturing) is returned to the remanufacturer, where it passes through the typical steps of the remanufacturing process - inspection, disassembly, component reprocessing, reassembly and testing - to ensure it meets desired product standards (Sundin, 2004). Alternatively, Steinhilper (1998) arranges the process in the order of disassembly, cleaning, inspection, reconditioning, reassembly and testing. Disassembly and cleaning of used products/components can be viewed as new technologies on the industrial level, where industry itself has a pioneering role in setting new standards and creating new solutions. In disassembly, the product is disassembled to the single component level. The components are first identified and inspected, and the decision is made whether the individual components are reprocessable, can be reused in their current state or if they should be scrapped or recycled. Oil, dirt and rust can complicate disassembly operations and call for new solutions to be developed.

Automation is rare, even though some experiments with robots have taken place in recent years. In the disassembly processes, the cores can also be cannibalized for components. Component cannibalization is when components are separated from the core and used to repair or rebuild another unit of the same product (Rogers et al., 1998). Thereafter, during inspection, it is decided if and how the components should be reprocessed. The uncertainty of the quality of a core, i.e. how many of its components can be recovered, is measured using the metric Material Recovery Rate (MRR) Equation (1) below (Guide 2000).
According to (Steinhilper, 1998), the cleaning operation is the most time consuming, and entails much more than just removing dirt; it also means de-greasing, de-oiling, de-rusting and freeing components from paint. For this complex task, several methods have been developed for both subsequent and concurrent execution, including sand blasting, steel brushing, baking ovens, cleaning petrol, chemical and hot water baths, etc. Following the cleaning operation, reprocessing has the aim of repairing or increasing the quality of core. Geometrical change of the components through metal cutting like grinding will change the dimensions. Sometimes after reprocessing, for example, a highly worn-out product will not match the standard tolerance, such as the diameter of a crankshaft, and must be scrapped. In the reassembly operation, the separated components are assembled. Reassembly can be done with components that are either reused, reprocessed, taken from previous cores (i.e. cannibalised components) or new components. The reassembly of components is often done with power tools and assembly equipment as in new product assembly. Thereafter, the final testing of the product is executed. During the reprocessing and operations, the component’s quality is continuously assured through applied measurements. (Steinhilper, 1998)

Bras and Hammond (Sundin 2004) use an aggregated categorization of cleaning, damage correction, quality assurance (inspection and testing) and component interfacing (disassembly and reassembly). Arranging the steps in a standardized order, however, could be misguided, since every remanufacturing process is unique. For example, inspection should be performed before disassembly and cleaning in order to prevent cores with too many fatal errors to enter the production flow; conversely, inspection could be performed with greater detail after the core has been cleaned (Sundin, 2004). Östlin (2006) divides the remanufacturing process into the five phases of pre-disassembly, disassembly, reprocessing, reassembly and post-reassembly. Within these generic phases, there can be multiple operations where the order and the active operations in the process are dependent on the characteristics of the individual product. For example, inspection is an operation that can take place in the pre-disassembly, disassembly and reprocessing phases.

2.3 Lean Production

Taiichi Ohno is often regarded as the founder of the Toyota Production System (TPS). TPS evolved out of need, as the marketplace in post-war Japan required small quantities of cars to be produced in many varieties, and this created a new type of production system at Toyota Motor Company. It was essentially the further development of the Ford principle of mass-producing the same automobiles in large production runs. Womack et al. (1990) coined the phrase Lean Production to describe TPS when they printed the results of a five-year study in the automotive industry in the book “The Machine That Changed the World”. Lean is in its essence an approach that eliminates waste by reducing costs in the overall production process, in operations within that process, and in the utilization of production labour. The focus is on making the entire process flow, not the improvement of one or more individual operations. According to these authors, “waste” can be categorized as anything that the customer is not willing to pay for (Womack et al., 1996).

2.4 Material Flow in Lean Production

The principle of Lean Production is to target these wastes in different ways with the aim of reducing them. Figure 3 illustrates an implementation plan of different Lean Production methods covering a vast number of issues in a manufacturing business. As the focus of this paper is not targeted towards Lean Production in general, but rather specifically towards material flow, the forthcoming analysis will address only the relevant aspects of Lean Production that have the greatest impact on the material flow. These methods can be grouped in the following generic groups: (1) production to customer orders (customer pull); (2) create a levelled workload; (3) one-piece flow; (4) reduced setup times (costs for order preparation); (5) takt time; (6) just-in-time deliveries; and (7) stable production processes.

\[
MRR = \frac{\text{Number of reusable components}}{\text{Number of total components}}
\]
3 Methodology

3.1 Empirical Investigations

The empirical data for this study is linked to an ongoing research project, “REKO2” (2006), which is an explanatory multiple-case study concerning various types of products. The research conducted for this paper has two distinct phases: the first is a larger scale qualitative study; the second, a more detailed, quantitative study. The main source of data collection for the first phase was semi-structured interviews. Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions (Östlin, 2006). The questions formulated for this study were semi-structured, and the respondents were given a chance to go in to detail regarding the answers, i.e. the questions were prepared without specific sequence or answering options (Jacobsen, 1993). After the formulation of the questions, a pilot study was made to verify the validity of the questions. The main source of data for the case studies was interviews, each of which was recorded, and the length of which varied from 1 to 4 hours depending on how much information the respondents had to contribute with. Typically, the interviewees were facility managers, production managers, controllers and technicians. Other sources of data were direct observations made during the study visits to the companies, as well as documentation in the form of photographs, brochures and other information (independent as well as issued from the case companies). These sources were mainly used for data triangulation.

The case company selection was made from companies that were found in the study of the remanufacturing industry in Sweden by Sundin et al. (2005). In this study, a number of potential

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2 The REKO project was sponsored by VINNOVA, the Swedish Governmental Agency for Innovation Systems. (See www.vinnova.se for additional information.)
companies were found. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and remanufacturing process.

According to Eisenhardt (1989) there is no ideal number of cases, though a number between 6 and 10 is good for theory building. Empirical data was gathered primarily from different Swedish remanufacturing companies. The companies selected for the case studies were:

<table>
<thead>
<tr>
<th>Case Company</th>
<th>Remanufactured Products</th>
<th>Company Size</th>
<th>Relation to original equipment manufacturer (OEM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT Industries</td>
<td>Forklift trucks</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Scandi-Toner</td>
<td>Toner cartridges</td>
<td>Small</td>
<td>Independent</td>
</tr>
<tr>
<td>Swepac International AB</td>
<td>Soil compactors</td>
<td>Medium</td>
<td>OEM</td>
</tr>
<tr>
<td>Tetra Pak and Wahlquists Verkstäder</td>
<td>Filling machines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>Volvo Parts</td>
<td>Diesel Engines</td>
<td>Large</td>
<td>OEM</td>
</tr>
<tr>
<td>UDB Production</td>
<td>Automotive components</td>
<td>Medium</td>
<td>Contracted and independent</td>
</tr>
</tbody>
</table>

It was found that this selection of case companies was suitable, since it provided good in-depth knowledge to fulfil the purpose of the study. It was determined that additional cases would take too much time to investigate; this is, according to Voss et al. (2002), an important skill in theory building from case studies – knowing when to stop.

The second phase of the study was an in-depth quantitative study of a car engine remanufacturer. To assess material flow, five major components in a car engine were assessed. For the collection of data, a validated Value Stream Mapping (VSM) methodology has been used (Rother & Shook, 2002). Supplementary interviews, both semi-structured as well as unstructured, were carried out with operators, production planners and management. The analysis of the remanufacturing process was based on the analytical framework developed by Östlin (2005). The analysis of the collected data explored what characteristics of remanufacturing resulted in waste in the phases of pre-disassembly, disassembly, cleaning, reprocessing, reassembly and testing, as well as what hindered the implementation of any lean principle in each of the phases.

4 Lean Remanufacturing Implementation

The analysis in this study regarding the material flow is focused on two categories: material and production planning. In this study, material planning is referred to as the coordination of incoming material, both cores and new replacement components, with the customer demand of output. Production planning is defined as the coordination of the different processing phases (pre-disassembly, disassembly, cleaning, reprocessing, reassembly and post-assembly).

4.1 Material Planning on a Aggregated Product Level

In the remanufacturing environment, one of the characteristics is that the demand for remanufactured products (output) and the returns of cores (input) do not always correlate. The rate of product returns is dependent on the characteristics of the product life cycle. The balance between product returns and demands for products is a function of many variables, where the rate of technological innovation and the expected life of a product are the major influencing properties. For further details regarding the research about balancing supply and demand, see Guide) 2000 and Umeda et al. (2006).

There are principally two ways to plan material flows: (a) planning for the demand of products and (b) planning according to availability of cores. This is illustrated in Figure 2.
Planning for remanufactured product demand

In the Volvo, Tetra Pak, Swepak and BT cases the planning focus was on the number of remanufactured products to be produced; this means that the number of cores that exit the process are fixed and the number of products that enter the process are variable. For example, the production planning might demand four products to be remanufactured, but six cores enter the process. Hence, the extra two cores that enter the process are cannibalized for components instead of being remanufactured. However, in the observed cases there was more or less a one-in and one-out (1:1) relation between cores entering and products leaving the process. This was especially true when the products were new on the market; that is, when the supply of cores suitable for cannibalization was low. Later in the lifecycle, when cores were easier to find and less expensive, the companies used cannibalization as a planning option.

Planning according to availability of cores

Both UBD and Scandi-Toner used a reorder-point system for initiating remanufacturing orders. The planned remanufacturing orders were dependent on the number of cores that were available in inventory when the order arrived. These were then sent through the process, and the numbers of remanufactured products that exited the process were dependent on the number of products that could be remanufactured economically. This variability was not that critical from a material control perspective, since they were used to fill up an inventory (although variation in capacity usage does influence production planning, as discussed in the next section). Hence, a proposition is that material planning according to availability of cores can be preferred in make-to-stock situations, or when cannibalization of components from a core is a viable solution for component sourcing.

4.2 Material Planning on Component Level

On the aggregated level, the material planning problems were focused on balancing demand for remanufactured products and the supply of cores. On the component level, the problems addressed the uncertainty in the number of components recovered from the returned items. The components that were broken or faulty needed to be reprocessed or exchanged by a new component.

From the material planning perspective, the components can be separated into different planning categories. These categories are: (1) components that are always replaced; (2) components that can be reused or reprocessed; (3) components that are found unusable, but can be ordered before the
reassembly due-date; and (4) components that are found unusable, but have to be ordered according to forecasts (see Figure 3).

**Components that are always replaced**

Some components in a remanufactured product are always replaced with a new component. Normally these components are wear-and-tear components, for example, pistons and roller bearings in an engine. The components in a remanufactured product can also be upgraded to the latest standards; one example are the electronic control units in the filling machine (Tetra Pak) case that are replaced by components of the latest standard. When components are always replaced, there is no need to consider the specific characteristics of remanufacturing, as for example variations in the material recovery rate (MRR), since no components in this category are reused. As a result, all of these components can be sourced independently of what happens in the forthcoming remanufacturing process. Material planning of this category of components is the most predictable. When the customer orders for remanufactured products are issued, the exact demand for components can be calculated without any need for disassembly or inspection, just as in a manufacturing situation. Still, some complicating factors might cause planning problems. One practical example of this is that ordering lead-times for new components can be longer then the time between confirmation of a remanufacturing order and the reassembly start date. In these situations, the components have to be ordered according to forecast and placed in inventory. Minimal order quantities accepted by vendors can also pose disadvantages when being higher than the confirmed demand for components (confirmed demand of products refers to the orders from customers opposed to orders generated by forecasts); as a result, some of the components are ordered according to forecasted demands. The different planning horizons for each of the component categories are illustrated in Figure 4.

![Figure 4: Planning horizons for the different component categories](image)

**Components that can be reused or reprocessed**

These are the components that in some situations can be reused or reprocessed; this decision is dependent on the quality of the single component. An example of these components is broken housings for the brake callipers (UBD case) that can be reprocessed in some situations. The ratio between reusable and non-reusable components is described as the material recovery rate (MRR), as shown in Equation 1. For these components, the confirmed demands are not known until the components have been inspected and approved for reuse/reprocessing. For some types of components, the status of the component can be assessed before disassembly is undertaken (pre-disassembly phase). For other components, the components might need to be disassembled from the core before inspection/testing can be done (disassembly phase). From the planning perspective, the result is a shorter planning horizon for the components inspected in the disassembly phase. For the components that are being reprocessed, the reprocessing operation has to be done within the timeframe between
disassembly/inspection/testing and the reassembly is undertaken; this can be referred to as the reprocessing window. If the components can be reprocessed before reassembly is undertaken, they can be reused in the same core; otherwise these components need to be sourced in a different manner, e.g. from a reprocessed component inventory or as new components. Therefore, performing inspection as soon as possible can increase the timeframe for both ordering new components and the time available for reprocessing.

An example of the impact of the reprocessing window is taken from the remanufacturing of engines at Volvo Parts, as illustrated in Figure 5. In this case, the engines are remanufactured according to customer orders. The lead-time for customer delivery is three weeks. Hence, all customer orders within a timeframe of three weeks before the remanufacturing due date are confirmed. This three-week timeframe with confirmed customer orders is referred to as the “freeze window” in the lean literature. Customers also provide demand forecasts that consider future demands outside of the freeze window. The needed cores are delivered to the facility before the 3 weeks of freeze window, according to customer forecasts. Reassembly of one weeks’ production (deliveries to customers are performed once a week) are then planned to start about 1.5 weeks before the delivery due date. The disassembly of cores is planned to begin three weeks before the remanufacturing due date. As a result, the reprocessing window becomes less than 1.5 weeks, depending on how soon the disassembly operation can be performed. In the Volvo study, a value stream mapping investigation showed that some of the components could not be reprocessed within the reprocessing window, mainly due to high amounts of work-in-process. The main reasons for the high amount of work-in-process were unmotivated high batch sizes in combination with sequential operations with long throughput times, for example cleaning and drying operations (see the forthcoming section about production planning for additional details.)

Figure 5: An example of the remanufacturing lead-time and the effect on the reprocessing window

Components that can be ordered within the lead-time for reassembly
This category of components is the components that have been inspected/tested and found faulty, and which are not economically viable to reprocess. In this situation, the preferable situation is to order the lacking components and have them delivered before the reassembly due date. If the inspection can be performed as early as possible, the chance to order according to confirmed need of components is higher. The information about confirmed component demands can be used to create a customer pull for this category of components.

Components that cannot be ordered within the lead-time for reassembly
The components in this category are the most difficult components to plan. The lead-time of these components is longer than the time available before reassembly. The components in this category can also be divided in to two sub-groups. The first group is the components that that are ordered according to the forecast of remanufacturing orders. In the Volvo example, this would be components that have to be ordered three weeks before the due date (outside of the freeze window). The second group is the components that can be ordered as a result of confirmed remanufacturing orders (within the freeze window); in the Volvo example, these are the components that can be ordered three weeks before the remanufacturing due-date and delivered before the reassembly is undertaken. Ordering components according to demand forecast for remanufactured products is, in comparison, a less favourable option.
since this group of components is sensitive to both uncertainties in future demand for remanufactured products as well as uncertainties in the number of recovered components (those subject to MRR). When ordering according to confirmed demand of remanufactured products, the uncertainties in future demand are reduced. From a lean perspective, ordering components without confirmed customer demand can result in unwanted waste.

4.3 **Lean Implementation Solutions for Material Planning**

In the previous section, four different component categories were presented, each of which had different characteristics that complicate material planning. From a lean perspective, it is important to actively adapt to these characteristics and to develop lean principles that are specific to the remanufacturing characteristics. Among the categories of components, the one with the worst implications for lean practice are the components that cannot be ordered within reassembly lead-time and have to be placed in inventory according to forecasts. One solution to make the remanufacturing process leaner is to try to transfer these components into the other “better” planning categories. A company can for example invest in reprocessing technologies and reprocess the component instead of manufacturing or purchasing it. The result of a reprocessing activity is that components can be moved to the reprocessable component planning category. The alternatives for adapting lean principles to the remanufacturing environment found in this study include:

- Reprocessing technologies
- Component inspection as soon as possible
- Cannibalization of components
- Reduction of sourcing lead-time for new components
- Reduction of minimal order quantities
- Expanding the freeze window

| Table 2: Proposed solution for material planning and the effects on different component categories |
|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Components that are always replaced          | Components that can be reused                    | Components that can be ordered within the lead-time | Components that are ordered according to forecasts |
| Reprocessing technologies                    | More components can be reused                    | Can increase MRR resulting in lower purchasing costs | Can lower the need for placing components in inventory |
| Inspection as soon as possible                | Is a source for reusable components.             | More components can be ordered according to confirmed demands | Can lower the need for new component inventory       |
| Cannibalization                               | Viable for components with high MRR.            | Decreases the need for purchasing of new components. | Can lower the need for new component inventory.     |
| Reduction of ordering lead-time and minimal order quantities | More components can be ordered according to confirmed demands | More components can be ordered according to confirmed demands | Can lower the need for new component inventory       |
| Expanding the freeze window                   | More components can be ordered according to confirmed demands | The reprocessing window is increased. | Can lower the need for new component inventory       |
| Inventories                                  | Have to be used for components with high minimal ordering quantities | Have to be used for components that cannot be reprocessed within the reprocessing window | Have to be used for products that cannot be ordered within ordering lead-time |
In Table 2 a summary is given regarding these different ways of implementing a more lean material flow and the effects on the individual component categories.

**Reprocessing technologies**
Reprocessing aims to process broken or worn components back to original specifications or better. By doing so, the costs for new components can be reduced. Reprocessing is generally an advantageous strategy for components with high purchasing/manufacturing prices, long purchasing lead-times and when there is low annual demand for new components to be kept in inventory. One disadvantage with this solution is that the possibilities for using reprocessing technologies are limited to some specific areas. Most of the reprocessing technologies that have been observed are additive technologies that add new material to broken or worn-out materials; these components are then machined to original specifications. The use of additive technologies is frequent in, for example, the automotive industry, with many mechanical components (as seen for example in the UBD and Volvo cases).

**Inspection as soon as possible**
One of the major sources for instability in material planning is the effect of insecure material recovery rates (MRR). Planning according to a preset MRR is a frequent practice at remanufacturing companies, but from a lean perspective, preset MRR should be avoided. The main reason for using preset MRR is that components cannot be inspected before replacement components have to be ordered (due to e.g. long sourcing lead times). Therefore they have to be ordered in beforehand according to a preset MRR. If components can be inspected earlier, the time gap between inspection and reassembly can be extended. The earlier inspection can be undertaken, the more components can be ordered according to confirmed demands on a component level. The result of this is a higher opportunity to generate a customer pull. One major obstacle in many cases is that the status of the individual components cannot be inspected until disassembly is undertaken. Different techniques, such as on-line monitoring and other monitoring devices, can be used to communicate faulty components and therefore ease the material planning.

Even though the inspection operation gives information that is useful for the forthcoming material and production planning (see the following section), the studies at the companies show that this information is not collected and used as wildly in practice (e.g. as in the Volvo case). The main reason for this is that there are no efficient ways of gathering and analyzing the information, and that the cost for administration is perceived as greater than the gains. One reason for this is that the use of MRR calculations for future new component demand shows a “good enough” result. Another important insight is that even if inspection can be performed earlier, the sourcing lead-times will still be too long. Another limiting factor is the minimal ordering quantities that force the remanufacturer to order batches of components that also cover forecasted demands. As a result, the category of components that can gain the most planning advantages from inspection operations are components with low sourcing lead-times and low minimal order quantities, which instead of being kept in inventory can be ordered just-in-time.

**Cannibalization**
Cannibalization of components from a core is a debated subject. The principle of cannibalization is based on the two scenarios. In the first scenario, a demand for some components arises and all of the components from a core are disassembled. If the entire core is disassembled it generates a lot of components with no demand that have to be put in inventory for future demands or scraped. In the second scenario, the cores are kept in inventory and when the demand for component arises a specific component is disassembled from the core. After the disassembly of the component, the core is placed in the core inventory again. When specific components are taken from a core it generates an administrative problem of keeping track of what components that have been taken from what core.

For cannibalization to be an option, it must first be an economically viable solution for product recovery, meaning that the cost savings of cannibalizing a core for components is higher than the gain from other product recovery options. These options can e.g. be remanufacturing the core or selling the core on the second-hand market. In practice, this means that for cannibalization to be a viable option
there has to be an excess of cores on the market compared to the demand of remanufactured or reusable products. This situation is mostly common when the product has been on the market for a while and the product is in the later phases of its life cycle. However, under specific characteristics cannibalization is a viable solution. This is especially true for components with a high chance of retrieving a reusable component from a core (high MRR). In the case of components with a low MRR the opposite is true; in many cases, several cores have to be cannibalized before a reusable component can be found. For components with a high MRR, the general demand for new components is generally low – simply because the component seldom breaks. The low demand for new components will also generally have a negative impact on the ability to purchase new components at a competitive price and lead time for sourcing.

Reduction of ordering lead-time and minimal ordering quantities for new components
The long purchasing lead-times for new components are a hinder for employing a just-in-time principle. If the sourcing lead-times can be lowered, the possibilities for ordering more according to confirmed demands will increase. Guide et al. (2000) report that the main reasons for long lead-times are that: 1) components no longer are in production; 2) the component has a sole supplier; and 3) the purchase orders are small (resulting in unresponsive vendors). Another issue for many components is that the minimal order quantities force the remanufacturer to order batches of products that are greater than the actual demands. A result of the minimal ordering quantities is that a part of the order will be made according to forecast. To be able to reduce ordering lead-time and minimal ordering quantities, remanufacturing companies have to work together and develop relations with their suppliers.

Expanding the freeze window
To compensate for long ordering lead-times and long reprocessing throughput times, one solution is to expand the freeze window. The result is that more components can be ordered according to confirmed demands. There is also a greater chance that reusable components can be reprocessed within the reprocessing window and be used in the same core as from which it was disassembled. Negative impacts are that the ordering lead-time in a make-to-order case will be extended. In a make-to-stock environment, the amount of safety stock will have to be increased due to an increase in remanufacturing lead-time.

Inventories
Some components simply have to be put in inventory. Generally, components with long ordering lead-times have to be ordered and put in inventory according to forecasts. A negative impact on lean practice is that components are pushed forward instead of being pulled according to confirmed customer orders. The result is a need for keeping components in inventory, something that also results in additional costs. Components with long lead-times are normally components that no longer are in production and with generally low annual demands; as a result, these components become sensitive to obsolescence. Another reason for storing new components in inventories concerns minimal order quantities, where orders have to account for future forecasted demands. Still, keeping components in inventory is a key cost driver in many remanufacturing companies (Guide et al., 2000). In the research there has been a strong focus on adapting different rule-based optimization models (e.g. heuristics for determining economic ordering quantities) for inventory management; for an overview, see e.g. van der Laan (2006).

4.4 Production Planning
To analyse the remanufacturing process from a lean perspective, an analytical framework has been used that divides the process into five phases: pre-disassembly, disassembly, reprocessing, reassembly and post-assembly (Östlin, 2006).

4.4.1 Pre-Disassembly Phase
This phase can be described as a preparatory phase before the disassembly process begins. Normal activities in this phase include inspection, testing and sorting of the cores. The major purpose of this phase is to receive information about incoming cores in order to control the forthcoming process. One
important aspect of this information is decision support in order to decide whether to remanufacture, cannibalize components or recycle the individual cores.

By inspecting cores and sorting them into quality categories, a capacity control mechanism can be created. Through the use of different quality categories, “hard” or time-consuming cores are remanufactured when the capacity utilisation is low; when capacity utilisation is high, “easy” cores are remanufactured. By sorting cores into different quality categories, a solution for levelling the workload is created. These quality categories can be used to control the effects of the uncertainty in MRR as well as the stochastic routings and variable processing times in the forthcoming phases. The variability cannot be reduced per se, but the information helps to balance the remanufacturing capacity on an aggregated level.

4.4.2 Disassembly Phase

After the decision is made to remanufacture a core or cannibalize a core for components, the cores are sent to disassembly. The disassembly phase can involve a number of different operations where separating is the most prevalent. Other operations in this phase are e.g. inspection and sorting. This phase is highly exposed to stochastic processing times due to different quality levels of the incoming cores. Broken, dirty, and rusty cores can be very hard to disassemble, and as a result, the cycle times for disassembly operations can be highly variable. This variation in cycle time strongly limits the possibility to introduce lean principles of a fixed takt time and a levelled workload, and it limits a stable production process. The main reason for not being able to employ a takt time is mainly due to the waiting time that is generated due to variations in cycle times, resulting in major risk for balancing losses. Still, the possibilities for a levelled workload are not excluded due to the possibility of sorting cores into quality categories.

During disassembly, the majority of components can be inspected and the defective components are scrapped or sent to recycling. The remaining components are then reused or reprocessed. Information concerning the recovered components can potentially aid in both material and production planning. In material planning, this will confirm demands of replacement components, as discussed in the previous section. For production planning, information regarding confirmed reprocessing demands can be used to balance capacity in forthcoming process phases. Still, just as for material planning, the use of MRR calculations for capacity planning can be sufficiently shown. One reason for this is the short planning horizon between inspection and the reprocessing operations that limit the planning possibilities (see Figure 5 regarding planning horizons in the Volvo Parts case).

4.4.3 Reprocessing Phase

After that the components have been disassembled they are reprocessed (or reused) if the quality level of the components is sufficient. The reprocessing phase aims to raise the quality of a component. The components can undergo a variety of different operations in this phase, such as testing, cleaning, different machining operations, painting, etc., all depending on the type of component.

From a planning perspective, the ideal situation is that the reprocessing operations of each component should be performed within the reprocessing window (time between disassembly and reassembly). If components cannot be delivered to reassembly before reprocessing has been initiated, a component from the inventory must be used (if available). Taking a lean perspective, this will constrain the use of a customer pull; thus, it is important to design the reprocessing phase so that the highest degree of components possible can be reused in the same core.

The reprocessing of components can be organised in two principal ways: either in parallel or in sequence. In the parallel situation, the components from a core are separated and reprocessed independently of each other. In the sequential situation, all of the components from a core are kept together and operations are undertaken one at a time. In the observed cases, none of the companies used purely sequential or parallel strategies; normally, they applied a mix of both. The choice of
reprocessing organisation has a substantial impact on important variables such as lead-time and material-handling efficiency, as illustrated in Figure 6.

![Diagram of Disassembly and Reassembly](image)

**Figure 6:** Differences in accumulated lead-time in the reprocessing phase with a parallel and sequential flow.

**Parallel reprocessing**

When applying a parallel reprocessing organisation, the minimal theoretical reprocessing lead-time of the operations becomes equal to the throughput time of the longest component, as shown in Figure 6. From a material flow perspective, parallel reprocessing has the potential for a low throughput time and low levels of work-in-process (WIP). The negative aspects are that when separating components from a core it can create non-value adding activities in the form of extensive administration and complex material handling. Normally, when the individual components are separated from the core they are placed in material holders that often are specialised according to the type of components. The components are then transferred to different reprocessing workshops. The possibility to apply a one-piece flow in a parallel material flow can be limited by material handling. The major limiting factor to employ a one-piece flow in the Volvo Parts case was the transportation costs between disassembly cells and the specific reprocessing workshops. The transportation between the workshops generated material handling costs, which in turn generated a need to batch components from multiple cores together to reduce the material handling costs. Other material handling activities that result in "ordering costs" can be the need to switch between specialised material carriers in between product categories. The reduction of material handling between disassembly and reprocessing workshops is therefore important to work against a one-piece flow; this is the same logic as when reducing setup times in machining operations. In practise, high material handling cost can result in material carriers that contain several days of production before transferred to reprocessing operations. In fact, cases have been observed with even higher levels, accounting for several weeks of production. Overall, this has a major impact of the lead-time of the system. The parallel material flow can also generate a lot of non-value adding activities. When separating the components, the natural link to the bill of materials (BOM) of the original core is lost and several inspections might have to be done during the reprocessing operations just to keep track of the components. One solution to avoid multiple inspection requirements is to attach different types of labels that ease identification, although the labelling itself becomes a non-value adding activity. Another difficulty with inspection is that cores with material matching restrictions, meaning that the components from a core need to be used in the same remanufactured product, will demand additional administration.

**Sequential reprocessing**

Instead of separating the components, a second solution is to have components from the same core stored together on a material carrier that is transported through reprocessing in a sequential manner. The employment of such a strategy poses a number of advantages with respect to the parallel organisation. Firstly, it reduces the need for identification, sorting and handling in the disassembly operation. Secondly, it enables a one-piece flow. Thirdly, it reduces setup times in the disassembly operation because of a reduction in the material carriers needed. Fourthly, it solves the problems with material matching restrictions. A disadvantage of keeping components together in a material carrier proceeding sequentially between different reprocessing cells for different components is that the theoretical throughput time becomes the sum of the throughput times of all components.

For some components, the only opportunity from a lean perspective is to use a sequential material flow, especially when applying takt time. To apply a takt time, the demand for remanufactured
products is broken down into needs for component reprocessing, allowing takt time to be calculated. This is then compared with the average reprocessing operation times, and the number of workstations needed is given. The problem arises when the total reprocessing time of a component is lower or higher than the takt time, as seen in Figure 7. If the reprocessing time of a component is low it will have to be grouped together and reprocessed sequentially with other components in one workstation. If a component requires longer reprocessing, the reprocessing will have to be shared among several workstations if possible. When applying a takt time, one major prerequisite according to lean practice is to have a stable production process. If not, the risks for balancing losses are high.

![Figure 7: Reprocessing of four components and the resulting design of workstations according to a fixed takt time.](image)

Variation in processing times and effect of the material recovery rate (MRR)

The quality level of the incoming cores has a major impact on the reprocessing phase of the remanufacturing process, resulting in variances in processing times for example in the cleaning and machining operations. The variances in quality levels also have an impact on the material recovery rate. An example of this can be taken from the reprocessing of crankshafts at Volvo. To make the crankshafts reusable there is a need to smoothen specific surfaces which is done by grinding the surface material. Depending on the amount of surface unevenness, there will be different processing times according to the amount of material that has to be removed. In the case of crankshafts, there is also a limitation of how much material that can be removed. For instance, if the unevenness of the surface is too high, the component cannot be reused.

![Figure 8: Simulation of a operation time outcome of 8 cores in a one-piece flow.](image)

In a situation applying a one-piece flow through the reprocessing operations, the impact of the variations in processing times and the MRR can be illustrated as in Figure 8. This figure illustrates the case of a component from eight cores entering one workstation in a one-piece flow. The figure
illustrates the unevenness in processing times for the individual objects as well as the effect when the object has previously been rejected (e.g. in the disassembly phase). From a lean perspective, these characteristics have a negative impact on the possibilities of implementing principles like a stable production processes and a levelled workload. The MRR will create a waiting time when the component from the (scrapped) fourth and the sixth cores are supposed to be reprocessed; this will then demand WIP buffers. When applying a takt time, the takt is calculated according to the maximum processing times, resulting in balancing losses when components requiring shorter processing times are processed. From a lean perspective, the possibilities of implementing principles of a one-piece flow and takt time are constrained.

Lean implementation solutions for reprocessing operations

In the reprocessing phase, highly variable processing times and stochastic routings imply limitations of the flow. The effects of the characteristic uncertainty in materials recovered add additional complexity. These two characteristics can be derived from the quality of the core and have to be considered, although division of cores into quality categories can partly mitigate the effects of uncertainties in MRR. From a lean perspective, it becomes important to try to reduce the effects of the MRR and the variations in cycle time. Some solutions that can be used to reduce the effects are:

- Reprocessing technologies
- Work-In-Process buffers
- Solutions for a levelled workload
  - Cannibalisation
  - Compensating low capacity with new components
  - Quality categories
  - Work organisation

Reprocessing technologies

The use of reprocessing technologies can possibly increase the MRR – reducing balancing losses in a one-piece flow. Taking a one-piece flow perspective, the use of reprocessing technologies can also result in some negative effects. For example, the use of additive technologies will demand additional operations where material is added on to the component before machining can be undertaken. These additional operations are not used on every reprocessed component, thus adding variations in processing time and the introduction of stochastic routings. Still, the reprocessing activity addresses the wastes of scraping reusable components and is a value-adding process.

Work-In-Process buffers

Using a one-piece flow with a takt time can create a large amount of waiting time in workstations due to balancing losses. If the use of a takt time is discarded and buffers of work-in-process can be placed between workstations, then the buffers can work as a hedge against both variations in processing times as well as MRR. The negative effects with adding WIP is that it prolongs the throughput of the components and ads inventory carrying costs. The use of batches in production can be positive for the components with high variations in MRR or processing times due to the balancing losses that otherwise can occur.

Cannibalisation

Using cannibalised components as a replacement for scraped components can reduce the effects of variations in MRR. This will enable the use of a takt time in this respect. It would also provide a solution for maintaining a levelled workload, at least in the sense that capacity is utilised. The disadvantage with this solution is that it does not reduce the variations in processing times.

Compensating low reprocessing capacity with new components

When the reprocessing capacity becomes scarce, as for example at remanufacturing volume peaks or when incoming quality is low (resulting in additional reprocessing demands), there is always the possibility to source new components or to use cannibalised components that have been previously reprocessed and put into inventory. The existing inventory of components ready for reassembly (new
or cannibalised components) can then serve as security against fluctuations in capacity requirements. The components that cannot be processed due to lack of reprocessing capacity are then rescheduled to periods with lower capacity utilisation. The negative effects of this practise are that components are placed in inventory. Hence, one important question is to decide which components are to be rescheduled. This is mainly a question of balancing costs for carrying inventory and the costs for capacity utilisation. Components that are well-adapted for rescheduling can, for example, be low-value components, with a low risk of obsolescence, high turnover and that also has a high strain on reprocessing capacity.

Quality categories
The effects of the MRR and variable processing times could partly be suppressed by inspection and quality categorization, making the capacity demands predictable. Sorting of cores enables a capacity control, i.e. when there is available production capacity, remanufacturing “hard” or time-consuming cores, and when capacity utilisation is high, remanufacturing “easy” cores. The negative impact when applying this principle is that there has to be an inventory of cores available. Therefore, this option is only suitable in situations where the supply chain characteristics results in a core inventory.

Work organisation
In situations where capacity demands can be increased by increased man hours, a possible solution is to rearrange operators in the flow according to actual demands. Another solution is to reorganise the work content so that operators can perform value-adding tasks when waiting time arises, e.g. perform setups when switching between orders. This can reduce balancing losses and therefore also reduce the effects of an uneven workload.

4.4.4 Reassembly and Post-Assembly
In the reassembly phase, the components are assembled. The components to be assembled can be taken from four sources: reused components, reprocessed components, new components or cannibalized components. In this phase, processing (assembly) times are not variable as in the disassembly and the reprocessing phases. When all components are available for reassembly, the remanufactured products can be reassembled in a procedure similar to manufacturing. Hence, the foundations for applying lean principles are equal to manufacturing environments, given that all components are available for reassembly. Although a general difference is that many more (different) products and versions are to be handled in the flow, this especially true for the independent remanufacturers which remanufacture many different brands of products.

Complications in previous phases can result in not all of the required components being available for reassembly, which in turn will negatively influence stability in this phase. When demands for a new component are calculated using MRR, problems can occur if the estimated MRR is false. The result in a false MRR is either component shortage or excess inventories of new components. Therefore, a correct estimation of the MRR will have a great impact on the inventory management.

The possibility to create a customer pull for new components is also limited, mainly due to long purchasing lead-times and high minimal order quantities from suppliers. If a purchase lead-time extends the freeze window for orders, the products must be ordered according to forecasts or kept stocked, thereby hindering a just-in-time material flow. If just-in-time deliveries and contracts could be used the principle of customer pull could be realized, although, according to management, the negotiation position for remanufacturing companies is not high when forming purchase contracts with suppliers.

5 Discussion and Conclusions
In this paper, the focus has been on the material flow and how different solutions specific to remanufacturing can make the process and the material flow leaner. In the previous section, the material and production planning are addressed independently, but the linkage between the two is strong. For example, one factor that has a major impact on the material flow is the setup of customer
order to delivery process, and especially the time between fixed order deliveries for the remanufactured product. This puts major limitations on the organisation and planning of the remanufacturing process in general, and sequentially also on the material planning horizons.

Applying lean principles in a remanufacturing environment can be difficult. One foundation for implementing lean principles is the existence of standardised processes that are stable and predictable. In the remanufacturing process, the possibilities to realise such a predictable process is limited by the “normal” variations in quantity and quality of returned cores. The main conclusions that can be drawn from this study are that the inherent characteristics of variable processing times and uncertainty in materials recovered have the major negative impact for implementing a lean production process. Vice-versa, given an accurate supply of cores for reassembly, all the principles of a lean material flow in normal manufacturing can be implemented in the phases of reassembly and testing.

The analysis section of this paper presents different solutions that can be used to reduce the hindering characteristics of remanufacturing. Each of these solutions has different effects to different process phases and categories of components. To summarise, the proposed solutions for making the material flow lean can be a source of inspiration to the lean practitioners in their daily task of reducing different types of waste.

References


Lean Production Principles in Remanufacturing –
A Case Study at a Toner Cartridge Remanufacturer

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Abstract— Scandi-Toner AB works with remanufacturing of
toner cartridges; both color cartridges and black cartridges. The
company Scandi-Toner and the remanufacturing industry in
general do, compared to ordinary manufacturing, have some
specific characteristics that might limit the possibilities to apply
lean production principles, due to the high degree of uncertainty
in the production process. These uncertainties are mainly caused
by two factors: the quantity and quality of returned cores.
Overall, these characteristics make the remanufacturing material
flow harder to control. Hence the purpose of this paper is to
analyze if lean production principles for material flow can be
applied in a remanufacturing environment, and especially at the
Swedish remanufacturer Scandi-Toner AB.

The analysis shows that lean production principles can be applied
in remanufacturing environments, with some constraints. For the
case company the study showed that for example the workshop
layout could be improved significantly according to lean
production principles.

The one major conclusion that can be drawn from this analysis
is that the inherent characteristics of variable processing times
and uncertainty in materials recovered have the major negative
impact for implementing a lean production process. Vice versa,
given an accurate supply of parts for reassembly, all the
appropriate principles of a lean production material flow can be
implemented in the phases of reassembly and testing.

Keywords: Lean Production, Value stream mapping, Rapid Plant
Assessment, Remanufacturing

I. INTRODUCTION

Remanufacturing is an industrial process whereby products
referred to as cores are restored to useful life. During this
process, the core passes through a number of remanufacturing
operations, e.g. inspection, disassembly, component
reprocessing, reassembly, and testing to ensure it meets the
desired product standards. [1]

The business concept of remanufacturing is based on the
idea that resources that were used in the new production of
the product are reused and can therefore be profitable. [4] The
reused resources consist of the material in the product, energy,
machine time, labor and other costs that have been
accumulated in the new production process. Remanufacturing
is in many cases superior to material recovery due to additional
reused resources.

Scandi-Toner AB works with remanufacturing of toner
cartridges; both color cartridges and black cartridges, and they
are one of the leading companies in Scandinavia today. The
company Scandi-Toner and the remanufacturing industry in
general do, compared to ordinary manufacturing, have some
specific characteristics that might limit the possibilities to apply
lean production principles. One example of this can be limited
possibilities for just-in-time deliveries of spare parts [2].
Working in a remanufacturing environment do also leads a
high degree of uncertainty in the production process, mainly
caused by two factors: the quantity and quality of returned
cores, which is a reflection of the uncertainties in a products
use and length of life. This uncertainty also creates variations
regarding how long the process will demand and the products
these factors in greater detail and present altogether seven
characteristics of remanufacturing that are found in the current
research literature that increases the complexity in the
remanufacturing process. These characteristics are the
uncertain timing and quantity of returns, the need to balance
returns with demand, the disassembly of returned products,
the uncertainty in materials recovered from returned items, the
requirement for a reverse logistics network, the complication of
material matching restrictions, and the problems of stochastic
routings for materials for remanufacturing operations and
highly variable processing times. The rate of returns and when
is influenced by many factors such as the life-cycle-stage of a
product and the rate of technological change. Overall,
compared to manufacturing, remanufacturing batch sizes are
smaller, the degree of automation is lower and the amount of
manual labor is higher compared to a manufacturing plant [5].
One reason for this is the vast variation of different products
and versions that tend to accumulate over time. The number of
different kinds of toner cartridges on the market has increased
quickly because of technical innovations. To keep track with
the trends in the market Scandi-Toner AB needs a more
flexible and high-speed production to be able to stay on the
Scandinavian market as one of the leading companies. This has
lead to a request for a more flexible, well-planned
remanufacturing at the company.

In a study made by Sundin [1] investigating how lean
remanufacturing companies are compared to classic
manufacturing companies, using mainly a Rapid Plant
Assessments (RPA) ranking methodology (see Figure 1). One
main conclusion is that remanufacturing companies are
performing below average regarding the material flow issues of
lean production. This indicates that the additional complexes
regarding material flows in remanufacturing may be a limiting
factor for remanufacturing companies to apply lean production
principles.
The principle of Lean production is to target these wastes in different ways with the aim to reduce them. Lean production methods - covering a vast number of issues in a manufacturing business. As the focus of this paper is not targeted on Lean production in general, but specifically on material flow, the theoretical framework will address only the relevant aspects of Lean production that have the greatest impact upon the material flow.

To make Lean production generate an effective material flow there are some specific methods and goals that especially targets the material flows. These methods can be grouped in the following generic groups: (1) production to customer orders (customer pull), (2) create a levelled workload, (3) one-piece flow, (4) reduced setup times, (5) takt-time, (6) just-in-time deliveries and (7) a stable production process. [8]

Case studies of implementing Lean in a remanufacturing environment have been performed (see [1] and [12]).

III. METHODOLOGY

The research methodology for this paper is a case study methodology limited to one individual company – Scandi-Toner an independent remanufacturer. Scandi-Toner has a product mix of about 50 different toner cartridges that are remanufactured today. Remanufacturing of a toner cartridge follows some general steps but a certain number of operations are different between cartridges, depending on which type is being produced. In an analysis of these cartridges the result is that 75 % of the toner cartridges can be categorized in to three groups (A, B and C) according to similarity in design, operation times and the remanufacturing process. These groups form the basis for the forthcoming analysis. After sorting out these groups there has been an analysis of the current state in the remanufacturing process using a “value stream mapping” methodology.

The results of the value stream mapping regarding the current situation was then analyzed to identify possible actions that could make the remanufacturing process “leaner”. In a remanufacturing environment there might be some characteristics that will make these principles harder to implement. According to Guide (2000) the complicating factors in remanufacturing are: (1) the uncertain timing and quantity of returns, (2) the need to balance returns with demand, (3) the disassembly of returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times. The effects of these characteristics has been analysed according to the impact on the possible implementation of the seven lean production methods presented earlier.

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1 Independent in regard to the Original Equipment Manufacturer (OEM)
IV. ANALYSIS

In the current process for category A and B cartridges there
are ten different individual operations undertaken in the
remanufacturing process, see Figure 2. The remanufacturing
process at Scandi-Toner follows a classical remanufacturing
process that starts with disassembly of the cartridge in to two
parts, the Hopper Section (HS) and the Waste Bin Section
(WBS). After separation the two parts are sent to different
parallel workgroups where the HS and the WBS are cleaned,
reprocessed and reassembled. In the remanufacturing process
there are mostly manual stations, but some machining is
undertaken in the process. These operations have the following
setup and operation times considering a batch of 20 toner
cartridges, see the Gantt chart in Figure 3.

![Figure 2. Overview of the remanufacturing process operations in the current situation](image)

A. Implications of the remanufacturing characteristics

The remanufacturing process has been divided in to six
different steps for analysis. These steps are: inspection,
disassembly, cleaning and reprocessing, reassembly and
testing. Each of these steps is analyzed in the forthcoming
sections.

1) Inspection

The major purpose of the inspection step should be to receive information about incoming cores to control the forthcoming process. By inspecting cartridges and sorting the cartridges in categories is done to suppress the effects of the uncertainty in materials recovered as well as the variable processing times in later phases. The variability cannot be reduced per se, but the information helps to balance production on aggregated level. This realized by the division of used cartridges into different categories based on its quality. The inspection and the sorting of cores enables a capacity control, when there is available production capacity, remanufacture “hard” or time-consuming cores, and when capacity is scarce, remanufacture “easy” cores.

Detailed inspection and sorting of cores in to different quality categories can mitigate the effects of the characteristic of stochastic routings and highly variable processing times in the forthcoming phases of the remanufacturing process and enable implementation for a (more) levelled workload.

2) Disassembly

Depending on the quality of the cartridge; dirt etc, the cycle time for disassembly step can be highly variable. This limits the possibility to introduce the lean principles of a takt time, a levelled workload and it limits a stable production process. The main reason for not being able to employ a takt time and a one-piece flow is mainly due to the waiting time that is generated when the cycle times of the operations is variable resulting in a major risk for balancing losses. Although, the possibilities for a levelled workload is not excluded due to the possibility of sorting cores in to quality categories.

During disassembly, defective components are scrapped or sent to recycling. The effects of the uncertainty in materials recovered have an impact on the profit for the remanufacturing of the individual cartridges because of the need to replace components. Although this characteristic has no additional impact when applying lean principles in this particular step, it will strongly influence the forthcoming process.

The operation of disassembling cartridges require a sorting of the different separated component into different material holders, this is done mainly to keep track of all the components. This practice might limit the possibility of a one-piece flow due to the need of batching components together for storage and transportation.

![Figure 3. Gantt chart illustration of current setup and operation times in the current remanufacturing process](image)
3) Cleaning and reprocessing

Depending on the type and the quality of the core, the cleaning operations as well as reprocessing operations will result in different cycle times of the operations. Generally there are two characteristics of remanufacturing that has a major effect on these steps of the process. These are variation in processing lead-times and variations in materials recovered. An illustration of a visual simulation of these effects in a one-piece flow using a takt-time is illustrated in Figure 4. When applying a one-piece flow the variations in the process yields a major risk for balancing losses. This limits the possibilities of implementing principles like a stable production process, levelled workload and takt-time. The risk of balancing losses is today managed by using batch sizes up to about 100 cartridges that on an aggregated level makes the production more stable and less sensitive.

The effects of the inherent characteristic of uncertainty in materials recovered and stochastic routings and variable processing times could partly be suppressed by inspection and quality categorization, enhancing the possibilities of a levelled workload and a stable production. The operation with the largest cycle time will set the pace for the flow, thereby causing waiting. Re-arranging operators in the flow could balance this waste but the possibility to introduce takt time is still constrained. However, the main impact for the processes is variations in the material recovery rate that results in loss of components to be reprocessed, which creates instability and reduces the possibilities for a levelled workload and takt time. If the one-piece flow is to be efficient operators have to be flexible and able to perform other tasks when waiting time arise, e.g. perform setups when switching between orders. Another alternative is to reprocess cannibalized components left over from previous cartridges or as a last resolution, build up buffers between operations so that if a component is lacking from a cartridge the operator can continue straight away with one from the buffer of cartridges.

4) Reassembly and testing

After being cleaned and reprocessed the components are reassembled as a mix of purchased and reprocessed components. In this phase the setup times as well as the cycle times, are not as variable and fluctuating as in the reprocessing and the cleaning phase. Some variations exist in between product families depending variations in design of the cartridge. Since these variations in between different cartridges are known with certainty – they are not stochastic – this is not per se a hindrance for an implementation of Lean principles.

When demands for cartridges are known, the material recovery rate (MRR) is used to estimate the need for purchased components. If the estimated MRR is false, component shortage or excess inventories of new components might occur in this phase, with in turn can cause waiting. Another result can be that a stable production process cannot be reached due to this uncertainty. The possibility to create a customer pull from this phase is also variable, mainly due to different contracts with suppliers for purchases of new components. If a purchase lead-time extends the freeze window for orders the products has to be ordered according to forecasts or kept stocked and thereby hinder a Just-in-Time material flow. If just-in-time deliveries and contracts could be used, the principle of customer pull could be realized. Although, according to management, the importance of the remanufacturing companies needs are not high on the agenda when forming the purchase contracts with suppliers. When all parts are available for reassembly, the remanufactured engine can be reassembled in a procedure similar to manufacturing. The difference is that a lot more different products and versions are to be handled in the flow. Besides the effects of the non-eradicable characteristic uncertainty in recovered materials no additional constraint of implementing all the methods of a lean production material flow has been identified in this step.

5) Balancing demand with returns

As mentioned there can be a problem in linking demand of a specific cartridge with an appropriate used cartridge. The return of cartridges is dependent of the amount and types of cartridges returned from customers. Scandi-Toner bases its system on voluntary take-back. The cartridges are collected in boxes (see Figure 5) that are distributed to the customers. These boxes are based on a standard transporting format, enabling cost-effective transportation. According to the facility manager, the cost of acquiring the cores is an important strategic question. The environmental advantages provided by the remanufacturing are strongly promoted as a motivational factor for the take-back system, as seen for example in the recycling logo on the return box in Figure 5.
Scandi-Toner collects cartridges in the Scandinavian region, specifically Sweden, Norway, and Finland. Each of these countries has a central point where the boxes are collected and sent together in large volumes to the remanufacturing plant in Sweden. Within the Scandi-Toner group, there is collaboration with three manufacturing plants in Sweden, England, and Italy, where used cartridges are sent between the facilities depending on the local needs and inventory levels. By coordinating demands of different markets can be one way of decreasing inventory levels, although the possibility for a Just-In-Time delivery is especially hard to realize for the delivery of used cores, due to the dependency on customers to return products.

6) Economic order quantities and layout considerations
As described in the theoretical framework the existence of a one-piece flow and reduction of inventories are highly dependent on using small batches of products. To identify the possibilities to use low batch sizes in the current remanufacturing process, the current EOQ has been calculated. The EOQ for the different cartridges ranges between 20 to 140.

One main critic by the lean practice when using economic order quantities to calculate batch sizes is that the cost for order preparation (setup costs, etc.) is considered fixed. The analysis on the reasons for the order costs are not found linked to the setup of machines as commonly found is traditionally manufacturing. The main difference between the two is the low automation level of the remanufacturing process at Scandi-Toner. Instead the main reasons for the existence of order costs are the costs for material handling, as for example bringing cannibalized and spare parts from storage to the assembly lines. In a transportation perspective the layout is not optimal. Generally the components are moved back and forward between workstations, this makes the transportation time long and it is more difficult to control where different products are located inside the plant. Another waste is the time it takes to collect different tools needed for an operation in a workstation. Tools are used in several workstations and materials are stored in different places in the plant. The reasons for the unnecessary material handling are mainly an issue of the layout of the facility and the limitations that constrains the process layout. By rearranging the layout of the process these waste has been targeted. The new layout of the facility after an analysis of the costs for order preparation and transportation is illustrated in Figure 6.

The workshop layout has been rearranged so that there is space for storage with material next to workstations and also have the tools needed for every station near by (see point “G” in Figure 6). As for the placement of workstations it has also been rearranged in to and placed in a straighter route. This aims to bring down the transportation time and it also enables better quick overview of the production.

<table>
<thead>
<tr>
<th>A</th>
<th>Disassembling and Cleaning Cartridges</th>
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<tr>
<td>B</td>
<td>Milling</td>
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<tr>
<td>C</td>
<td>Disassembling HS and WBS</td>
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<td>D</td>
<td>Place for wagons and cases</td>
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<td>E</td>
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<td>Testing</td>
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<td>K</td>
<td>Printers for testing storage</td>
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Figure 6. The previous layout of the remanufacturing process is presented in the right figure and the new layout in the left figure.
V. RESULTS AND CONCLUSIONS

The study also shows that some of the lean production principles are harder to implement in the remanufacturing system. Some of the main hindering issues can be summarized to; a lack of systems for just-in-time deliveries in both used products suitable for remanufacturing and for spare parts, uncertainties in the material recovery rate and a variable processing time. In a normal manufacturing environment the processes are relatively stable but in remanufacturing there is characteristics that limits the possibilities for a lean material flow that can result in unstable operating times, resulting in build-up of work-in-process as well as balancing losses, etc.

The main conclusions that can be drawn from this analysis are that the inherent characteristics of variable processing times and uncertainty in materials recovered have the major negative impact for implementing a lean production process. Vice versa, given an accurate supply of parts for reassembly, all the appropriate principles of a lean production material flow can be implemented in the phases of reassembly and testing.

The analysis shows that lean production principles also can be applied in remanufacturing environments, with some constraints. For the case company the study showed that for example the workshop layout could be improved significantly according to lean production principles. The work-stations did not have a straight flow, which means they where not logically order according to the factory layout. Another point of issue was that most of the tools and material where not placed in close proximity to the workstations. Recommendation was to organize the workshop to a straight flow and place material storages nearby resulting in decreased set-up-times as well as lowering batch sizes. This would shorten the lead time and the production would be easier to keep an eye on as well as making the remanufacturing process more flexible.

ACKNOWLEDGEMENT

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VI. REFERENCES


Material handling in the remanufacturing industry: a case study of a diesel engine remanufacturing process

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Abstract

In this paper a remanufacturing plant for diesel engines is evaluated mainly from a material handling point of view. The analysis is concentrated to the reassembly of the engines. A framework for material handling is developed using replenishment strategies of spare parts, movement and storage options. An ABC analysis is used to create a base for differentiated material control. Different material control principles are proposed, like Material Requirement Planning (MRP), reorder point (ROP), and visual systems as the two-bin system. After that are material movement and storage methods proposed, either using line storage solutions or material kits.

Keywords: Remanufacturing, material handling, material control, replenishment

1 INTRODUCTION

The field of product recovery management encompasses the management of all used and discarded products, components and materials [1]. The product recovery consists of several sequential activities: collecting products; determining the potential for the products reuse, disassembling the product, and segregating valuable components; remanufacturing components; recycling materials; and disposing of waste [2].

In product recovery management some general driving forces can be identified as: economics (indirect and direct), legislative and corporate citizenship [1],[2],[3]. In this paper the main concern is addressed to direct economical gains. Some direct economic gains associated to product recovery are [3]: input materials, cost reductions and value added recovery.

Some indirect gains can also be identified [3]: anticipating/impending legislation, market protection, green image and improved customer/supplier relations.

In this case, the product recovery option of remanufacturing is analysed with the focus on material handling and how it economically affects the remanufacturing facility. According to the Material Handling Industry of America [4] "material handling and logistics is the movement, protection, storage and control of materials and products throughout the process of their manufacture and distribution, consumption and disposal."

The process of remanufacturing is the rebuilding of a product. "During this process the product is disassembled, defective components are replaced and the product is reassembled, tested and inspected to ensure it meets newly manufactured product standards". [5]

Earlier studies of remanufacturing companies have shown that the cost of material handling and holding inventory is one of the largest cost drivers in the remanufacturing process [6]. The reason for high cost levels can be associated to low inventory turnover, which creates high inventory levels. The low inventory turnover can also increase the risk of obsolescence for items [7],[8].

In this case there is a focus on the reassembly activity and how it affects: material control and replenishment strategies for spare parts, material movement and storage for both spare and reprocessed parts.

The purpose of this project was to improve the material handling in the case company and develop a framework for material handling, focusing on the reassembly operation.

Similar frameworks have been developed for manufacturing environments. What this framework aims to do is to adapt a new framework to the remanufacturing environment.

The focus on the reassembly operation is made due to the increasing complexity when dealing with a complete remanufacturing process, although the complete remanufacturing process must be kept in mind when developing the framework.

2 CASE COMPANY

The case company is a major original equipment manufacturer (OEM), which produces diesel engines. The remanufacturing process is located within the OEMs service and spare parts division, and treated as its own unit. The company produces about 1500 remanufactured engines annually, which mostly are sold to the service company, to later be distributed to the customer. The remanufacturing unit also procures spare parts from the service organisation. In the company’s responsibility there are about ten different groups of engines, divided by cubic capacity. Within each group there can be as many as 15 different versions, due to the 15 year service policy for engines set by the OEM for marketing issues. After the remanufacturing process the engines are shipped to a central inventory held by the service division. The remanufacturing unit has responsibility for the replenishment of the inventory and forecasts the demand for each engine.

2.1 Management Issues

Low volumes combined with a vast number of engine versions complicate the material handling. The material control, movement and storage are especially complicated. The results from insufficient material handling can create insufficient service levels and unwanted expenses that can lead to lost revenues. There is a need for simple and effective solutions due to the limited control recourses in the organisation.
3 METHODOLOGY
In this case study the data collection was based on both qualitative and quantitative material. Regarding the qualitative information, semi-structured interviews were held with people working in different workshops as well as in the management. The interviews with management were concentrated to people working in the manufacturing, logistics and economics departments. For the quantitative study a questionnaire was used to estimate the time spent on material handling activities. Data regarding characteristics of the different items in the product as: demand pattern, value and price were also gathered.

4 THEORETICAL FOUNDATIONS
For the following analysis of the case company, some experiences from both manufacturing and remanufacturing aid the understanding of the problems at hand. Existing theoretical models regarding remanufacturing issues and applicable models used in manufacturing environments are presented.

To gain a general understanding for remanufacturing a simple remanufacturing process is presented, and a discussion of the problems regarding the remanufacturing environment. The problem to coordinate replacement material is also presented as well as the decision regarding product recovery options. Then relevant material control issues in remanufacturing and manufacturing are presented. The basics of the ABC analysis are then presented as well as the specialised AC analysis for material control. Issues in spare part management and obsolescence are also taken into account.

4.1 Remanufacturing Process
The case factory uses a typical job-shop layout with three distinct sub-systems: disassembly, reprocessing and reassembly, as illustrated in Figure 1.

Compared to ordinary manufacturing, production planning and control for remanufacturing are influenced by some additional complicating factors. These factors are: (1) the uncertain timing and quantity of returns, (2) the need to balance returns with demand, (3) the disassembly of returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times. [9]

4.2 Replacement Material
Another complicating factor to the production planning is the coordination of replacement material that can come from both remanufactured and manufactured parts. In the case when parts can not be remanufactured they have to be purchased. This leads to some problems, due to reasons like: (1) long lead times for purchased products, (2) single supplier for parts or components, (3) poor visibility of requirements, (4) small purchase quantities lead to unresponsive vendors, (5) parts no longer in production, (6) vendors' minimal purchase requirements. Even though purchase of material can be complicated, some protection can be gained against variability in material recovery as well as more predictable remanufacturing schedules. [10]

4.3 Product Recovery Options
The product recovery options are important issues in remanufacturing and have strong influence on the profitability. The major recovery decisions are generally connected to disassembly and inspection of the product and its assemblies. Some parts are always recycled or shredded, some are always remanufactured if possible, and others demand inspection or further disassembly to find the best option. Optimal disassembly models have been developed (see e.g. [11]). Due to the complexity of the operation a heuristic approach can be more feasible, especially if the product consists of a large number of sub-assemblies and parts [12].

4.4 Material Planning in Manufacturing
In the field of material planning the focus in this study is replenishment policies. Today, there are some general ideas and methods how to handle these issues and the most common are: reorder point, order-up-to-S, Kanban and Material Requirement Planning. For an overview see e.g. [13].

Reorder Point (ROP)
As mentioned before, ROP policies are one of the most common principles, and one reason for its popularity can be its simplicity. The policy implies that when an inventory position of an item falls below a reorder point (r), then a new lot-size (Q) is ordered [14].

Reorder point policies can take the form of both installation stock (Q,r_i)-policy and echelon stock (Q,r_e)-policy. In the case installation stock is each installation, n,

Figure 1: A remanufacturing job-shop with work centers (WC) [9]
controlled by a \((Q, r_n)\)-rule and based on the installation stock position, i.e. stock on hand plus outstanding orders minus backorders. The echelon \((Q, r_n)\)-policy works in the same way. The difference is that the downstream stock at each installation is included as well as items in transit. [14]

**Two-bin System**

The two-bin system for material replenishment is based on visual control. The principle of the system is a creation of two bins, where one bin becomes the working bin and the other a spare bin. When the working bin is empty, an order request is created and the spare bin becomes the working bin and the former working bin generates a refill order. [15]

The two-bin system is actually a visual reorder point system with fixed reorder points \((r)\) and order quantities \((Q)\). Today are normally ROP systems integrated in computerised systems; however, the two-bin systems are not. All the items in a two-bin system are not registered in the system and therefore invisible. [16]

**Material Requirement Planning (MRP)**

This method is a little bit more complex compared to the ROP-policies. In a fixed planning horizon of periods, a production plan is generated based on: the external requirements of items for each period, the lead time of items, safety stock of the item and the order quantity. [14]

For a more detailed description see e.g. [17].

**Performance in Serial and Assembly Inventory Positions**

A comparison between different replenishment policies in a serial and assembly environment shows that the MRP-policies outperform \((Q, r_n)\)-policies, and that \((Q, r_n)\)-policies outperform the \((Q, r)\)-policies. The dominance of the MRP-system can be based on that any reorder point policy can be duplicated by an MRP-system. [14]

**4.5 Material Control in Remanufacturing**

The research on material control in remanufacturing environments has been focused on inventories and the connections to issues as: setup costs, setup times and economies of scale. These issues address the underlying problem of batching and lot sizing models. Models have been created for both constant production and recovery lot sizing as well as for dynamic lot sizing. However, even the simplest models tend to be very complex. [18]

A distant gap exists between material control in academic literature and in practice [10]. In industry the use of Material Requirement Planning (MRP) is frequent [11].

Today there are some proposed frameworks that consider MRP in a remanufacturing environment [11].

**4.6 ABC Analysis**

Controlling a valuable product, assembly or part with a major effect on the total result must be given more attention than the invaluables parts. But what is valuable then? Differentiated control must always have a purpose. One tool to classify different objects is the ABC (Pareto) analysis. The traditional ABC analysis is based on (1) the value of the item and (2) the demand for the same item. Multiplied they create the value of usage. In normal cases 10 % of the items constitute to 60 % of the value of usage (A-Items). These items are especially important and demand good control. C-Items are less important and represent about 60 % of the items and only ~ 5 % of the total value of usage. [19]

The ABC analysis can be a valuable tool when the need to categorise items arise.

**AC Analysis**

In respect to the ABC analysis, the AC analysis simply do not consider the B items in a control perspective and these items are instead spread to either the A or C group. The use of AC analysis as a tool when choosing replenishment policies has been documented by Hautaniemi and Pirttilä [16] (in a make-to-order case).

First the value of usage is used to find items with low value of usage. Then the items that have a shorter lead time than the final assembly schedule (FAS) are identified. The items with a longer lead time than the FAS are then divided up depending on the demand pattern. The groups are then associated to different MRP and ROP systems for control. One of the reasons to identify C-items is that the use of MRP creates higher administrative costs and therefore can other control methods be more feasible. [16]

**4.7 Obsolescence**

When the demand of an item decreases and finally no longer is desired or out of date, it is considered as obsolete [7]. Obsolete items are no longer usable, and the remaining items have no value and results in a cost for the company, both in value and disposal. Obsolescence can occur either through an expected pattern or a sudden decrease in demand (also referred to as sudden death). [8]

Some lot sizing and replenishment options for manufacturing have been created for both sudden death [7] and expected decrease in the final phase of the products life cycle [8]. To our knowledge there is no model that considers obsolescence in remanufacturing environments.

**4.8 Spare Parts Inventory Management**

One main difference between ordinary inventory control and the control of spare parts is the (usually low) demand pattern for spare parts. In an ordinary situation an ABC analysis is an appropriate tool, due to the fact that the products are more or less homogenou. However, the inventory control of spare parts differs, due to the more complex situations. For an effective analysis the characteristics of: criticality (process and control), specificity, demand patterns and value are good criterions when classifying spare parts. [20]

**4.9 Line Storage and Kitting**

Material movement in the line storage solution is the transportation of an item from a warehouse position to a storage position in connection to the assembly operation. The kitting operation is when the items of a specific assembly are collected, often on a specific part carrier, and brought to one or more assembly stations. [21]

Some pros and cons can be identified with each option. In an assembly situation some advantages with kitting can be identified as: a liberation of space connected to the assembly operation, a simplification of the material movement (especially in the case when items are stored at multiple positions, as in a parallel flow) and an improved control and visibility in the system. [22] Another advantage is a reduction in lead time for the assembly operation [21]. The disadvantages of kitting instead of line stocking are: the operation does not add any value to the product, it creates an extra need for space in the warehouse, increased need for control and an increased risk of errors in the handling of items due to human errors [23].

The kitting operation can be done in many ways using different picking techniques. Some factors that influence the kitting activity are: the storage solution of the inventory, number of items in a kit, the number of common items between kits, lead time for the kitting operation, the resources demanded by the process and the type of items to be picked. For an overview see e.g. [23].
5 ANALYSIS

As mentioned earlier the focus in this case is the reassembly activity and how it affects the: material control and replenishment strategies for spare parts, material movement and storage for both spare and reprocessed parts. A framework for material replenishment is created using material control theories integrated with proposed material movement and storage solutions.

The analysis is made by a combination of existing theory and experience from the case company.

5.1 Material Control

Compared to ordinary manufacturing, remanufacturing in this case suffer from low inventory turnover and large amounts of tied up inventory. One reason for the inventory levels is the obsolete items that have been accumulated over the years. Another is the relatively high amount of items with a low demand. For the replenishment of items a crucial decision is if there is a need to balance demands for the end item and the returns of items as well as on-hand stock of recoverable items. Items that are always replaced can and should be handled by normal control policies. Items that undergo some sort of repair and are associated to a yield or material recovery rate (MRR) demand special attention.

In this case the use of spare parts is actually used as a tool to handle fluctuations in the MRR.

Criteria for Differentiated Control

To get a foundation for the framework some criterions are needed to sort out the different key groups that are to be controlled in different ways. The AC analysis theory is used as foundation for these criterions [16]. Later in this paper we will see that the value and demand are used as separators for the items (they are also used in combination, which result in the value of usage). For an overview, see Figure 2. But first a presentation is made regarding the important criterions.

First the valuable items with a low demand are identified. These are referred to as problem items. This group should try to capture the items that have a large risk for obsolescence and have a control criticality to the assembly (long lead time, high price, etc).

Secondly the focus is on the items that need to be controlled more carefully and those that can be controlled easily. Here we use the value of usage to sort out the important items, and we add a constraint that the value of the item should be sufficient. These items are referred to as A-items and the remaining items are referred to as C-items. We also make a distinction between the C-items based on the demand pattern. Items with a higher and more stable demand rate on an aggregated level could be treated as independent.

Framework for Replenishment

After the identification of the characteristics, a framework is created. According to our criterions for differentiated control, four groups have been identified, see Figure 2. The method for using the model are: First identify Group I (by the criterions: Value > A and Demand < B), then Group II items are identified of the remaining items that are not associated to Group I items. The remaining groups are also sorted out in the same manner. How the practical sort-out is made between the groups and why are presented below.

Group I:

All the items in this group have a low demand, often as low as 1 item annually and a high value. The obsolescence problem is severe and different lot sizing problems can be adopted, but can be shown irrelevant due to procurement difficulties as mentioned earlier. Ad hoc solutions are frequent and understandable, due to the complexity of the problem. The items are often specific and the use of cannibalisation and reprocessing can be a solution, given that cores are available. The extra cost for cannibalisation of another engine for items might be valid if storekeeping and obsolescence costs can be kept at a minimum. A goal should also be to try to minimise the least order quantity and use stock out costs in the control. Both quantitative and qualitative considerations are taken into account to set the values of the variables A [price] and B [demand]. A minimum, sufficient price of the item should be chosen. The item should also have a relatively low demand. Also the number of items in this group should be adapted so that they can be practically managed, due to the fact that the control can take some time and be quite expensive. In this case about 5 % of the number of items is controlled by this method, although in reality the need to control this group is very limited, since the demand is so low for many items (less then 1 item/year).

Group II:

In this group the items are valuable and have a high demand. The control becomes most important here. Lot sizing decisions and safety stock levels are important. A simple customised MRP program, developed by an ERP software company, is used to handle the material control. Due to the lack of developed tools using sophisticated

![Figure 2: Criteria for differentiated control. (A-E are constant variables)](image-url)
models for remanufacturing, this control principle has to be used, even if a MRP method adapted to remanufacturing would be preferred. Using sophisticated manually methods outside the MRP system could be feasible for some key products but not for the thousands of items that could need it. Basically it takes to much time and effort compared to the effect it makes.

For choosing the appropriate control variables C [value*demand] and E [value] the well known ABC analysis is used. Here we see that 10 % of the items make out about 80 % of the value of usage. See Figure 3 for an overview. Due to the need to adapt material movement and storage to the model another condition is needed. Some items that have a really low value and a high demand can pass the C criteria. But the material handling should be completely different, more about this in the material and storage section. Therefore, these items are sorted out by applying a minimal value condition E.

Group III:
These items are of low value and have a low demand. For this type of items one wants to minimise the cost of material handling, stock outs and stock keeping. Obsolescence is also an issue here, although due to the low value of items the effects are not as severe as for Group I. The demand patterns for these items are often lumpy or singular. Using current complex control methods adapted for remanufacturing is not feasible here and more simple options are recommended instead. Due to uncertainties in demand in a remanufacturing environment a MRP approach is not feasible [18]. Therefore a reorder point (ROP) approach is proposed.

The remaining items to be sorted into Group III and IV are of low value and hereby the control is made in regard of the demand pattern. The main objective to separate them is also here made in regard to material movement and storage options.

Group IV:
The low value and the relatively high demand make these items relatively easy to control. Like Group III items, the value is low and the cost for material handling should be minimised. Due to the demand pattern an easy and cheap ROP approach is feasible.

5.2 Material Movement and Storage
The analysis of the material movement and storage is concentrated to the reassembly activity, hence involving the inventory of remanufactured and spare parts. For the movement of items from the inventory to the assembly facility there are two major options: transportation of items to a designated location (line storage), and the kitting operation that transports unique sets of items to be combined in the assembly operation. The choice of material movement and the material control principles together affects the appropriate solution storage.

Two-bin System Control
The two-bin system is a common tool for material movement and storage in assembly situations. The method is cheap and easy to use. The system is used in situations where there is a high demand for the items and in many situations where the turnarounds in the bins are high. In the remanufacturing situation this type of control is feasible for Group IV items with a high demand and low value. Typical items in this group can be screws and plugs. The items are stored in a central warehouse and then refilled when the refill order arrives. The inventory position in the central storage is known, but not in the two-bin system. This gives us an installation stock type of inventory, although an echelon inventory including the two-bin system would be preferred. To increase the visibility of the system, the second reserve bin could be minimised due to the short lead time for replenishment from the central warehouse. A complete elimination of a second bin would be impossible due to the fact that there is a lead time and that a trigger has to make sure that the order for new items really is released when the first bin is empty. If the safety stock in the second bin is drastically reduced to a small part of the order quantity, the safety stock can be moved to a central inventory, thus ensuring better performance. The effect of this method is enhanced if the different locations an item can be stored in is high and the total amount of items in the system is high compared to the amount in the central inventory, as for

<table>
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<th>Table 1: A summary of the framework</th>
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<td><strong>Group I</strong></td>
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<td>Type</td>
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<td>Price</td>
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<td>Demand</td>
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<td>Value of Usage</td>
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<td>Storage</td>
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<td>Control Priorities</td>
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this case. For Group III items the use of a two-bin system could sound feasible. However, the low demand, the high inventory levels, the invisibility and the obsolescence risk make the two-bin system infeasible for Group III.

Two-bin Storage
The area of the two-bin system is limited and the amount of space for items is hereby also limited. Some items in Group IV that are suited for the two-bin control can be unsuitable for two-bin storage, due to that they are too large or demand a lot of space. The items in the two-bin system are in our case quite small and take up limited amounts of space. As mentioned earlier, a central inventory exists. The reason for this inventory is that the order quantity is larger than the quantity in the bins. There could be cases when the order quantity is less than the order quantity in the bin, then the order could be initiated directly without passing through the central inventory (if lead time for replenishment is shorter than the time for usage of a order quantity) or handled by a kitting policy.

For the central storage of two-bin items an automated storage is used. The automated storage is feasible mainly because that the flow of material is high and the amount of space that it saves.

Kitting and Storage Keeping
For items that demand more control and total visibility the use of a kitting system is superior to the two-bin solution, especially for items with low demand. Group I, II and III are hereby most suitable for this type of material movement.

The parts that are most suitable for picking into kits are the ones which are ordered to be picked the most times. The number of times depends on the demand of the item but also on the "normal" order quantity of an item. There are a number of different solutions for inventory see e.g. [24]. The system used today is ordinary storage shelves at ground level with up to 12 different types of items in each. The item is picked in one specific route through the warehouse.

Some items can not be picked from storage due to some practical issues, for example they can be too spacious or too heavy. These items have to be moved to the assembly operation and using line storage, for example by a forklift. When moving a single unit from the inventory to the assembly operation a cost arises and that has to be minimised. One way is to minimise the time to find and retrieve an item based on the input/output position in the inventory.

The use of an ABC divided inventory where the most frequent items (A-items) are placed closest to the ground and the input/output point and Group II is placed close to the input/output point, due to its demand pattern.

6 RESULTS
A short summary of the proposed framework for material handling in a diesel engine remanufacturing environment is presented in Table 1:

Today a similar system is used for the material movement and the storage solutions. The main difference between the proposed framework and the system used today is the control methods. A structured way of working with material handling issues has been lacking in the company. The work made on material handling has been mostly reactive. The demand for different engines varies through the product's life cycle, usually with a decreasing pattern. Therefore, it is feasible to adjust control principles to the current demand situation. For example an item with two-bin control needs to be transferred to kitting policy if its demand decreases.

By implementing the proposed framework it is easier to handle this type of problems, by continually applying the most appropriate control methods during the whole product's life cycle.

6.1 Product examples
To give some examples how to apply the model, some examples from the case study are presented. The items are: belt pulley, fuel injection pump, screw and a camshaft.

Belt Pulley
First check for Group I: the value is medium high and the demand low, although not low enough to be a problem item. Then check Group II: the value of usage is low and hereby we check the demand pattern to decide between Group III and IV. The demand is low and singular therefore group III is appropriate for the belt pulley. Regarding the material handling a reorder point option is preferred. The item should also be kitted and stored in a central storage.

Fuel Injection Pump
This is an expensive item with a low demand. Therefore it is to be considered as a problem item and should be controlled as a Group I item. This item should be under tight observation and controlled by MRP. Regarding material movement and storage it should be: kitted and stored preferably in a cost-effective way.

Screw
This item is of low value and has a high demand. After checking the criterions for Group I, II and III we see that this item should be a Group IV item. This item should be controlled by the two-bin system in connection to the reassembly operation, and in our case an upstream automated storage solution using an echelon inventory. In order to create a cost effective material handling and minimising the stock out costs.

Camshaft
Regarding this item the value is high; although, not as high as the fuel injection pump, and the demand is medium high. This makes the value of usage quite high and the item is linked to Group II. This item should be closely watched by using the MRP system. Close attention should be given to: correct order quantities, effective safety stocks, forecasting, and good supplier collaboration. This item should be kitted and compared to the other items in Group II, be put in a high or a low flow zone.

6.2 Potential Improvements
The characteristics of today's inventory applied on the proposed framework are presented in Figure 3. From this figure some potential improvements can be made by using the framework:

For Group I there is potential for reduced obsolescence risk, and decreased inventory levels due to better control as well as possible cost reductions by using cannibalised parts. In Group II the proposed framework enables a stronger focus on the important items. For Group III substantial effects can be made on the inventory levels, due to a changed material handling from two-bin to kitting policy. The proposed framework leads to a more cost effective and appropriate material control for items in Group IV.

7 CONCLUSIONS AND FURTHER RESEARCH
Earlier studies have developed similar frameworks for manufacturing. In this framework a solution is presented
that specialises in a remanufacturing environment. Models for different areas in material handling, in both manufacturing and remanufacturing have been studied earlier by different authors, although partly separated from each other. This paper proposes a framework that can help to bridge the gap between industry and practise by combining theories and solutions in an engine remanufacturing case.

The framework presented could also be applied to other remanufacturing cases. The framework is feasible for environments similar to this case where the cost for stock keeping and material handling is high. For cases with low expenses for material handling other issues as production and operations analysis could be regarded as more important.

During this project a number of different research questions have risen. Regarding the problem of balancing capacity of the plant, a solution might be found in the coordination of purchasing and manufacturing of spare parts and the reprocessing activity by using cost control principles. Another problem regarding the material handling is how in an effective and economic way handle the movement and storage of cores and items from the core storage through the disassembly, reprocessing and to the inventory, before the product is ready to be reassembled.

![Figure 3: Characteristics of today's inventory.](image)

**REFERENCES**


