Lean Remanufacturing –
Material Flows at Volvo Parts Flen

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Abstract

The after market is of great importance of a company’s competitiveness and an increasing part of its revenues can be derived from it. Remanufacturing, in focus of this thesis, is 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, targeted in this thesis, sells approximately 60 million remanufactured automotive products compared to 15 million products in Europe for an equivalent stock of vehicles.

Compared to manufacturing, the remanufacturing environment is a more complex business due to the high degree of uncertainty in the production process, mainly caused by two factors: the quantity and quality of returned cores. Overall, seven characteristics that make the remanufacturing material flow harder to control have been identified. Emerging in the 1990’s the concept of Lean production is a well-known method for improving the manufacturing capabilities of a company. Lean production, which is said to increase productivity, decrease lead-time and costs and enhance quality, is widely adopted.

In this thesis, the purpose is to explore what characteristics of the remanufacturing environment that can hinder the implementation of Lean production principles of material flows and how Lean principles can be employed in a remanufacturing environment.

In accordance, the theories of Lean production and Remanufacturing are used and the research methodology chosen that of a case study. To assess material flow, the production flows of five major product groups in a car engine are assessed. For the collection of data, Value Stream Mapping (VSM) methodology has been used.

The main result about material flows and how Lean principles can be employed in a remanufacturing environment have resulted in eight generic proposals. The main conclusion from these proposals is that the inherent characteristics of variable processing times and uncertainty in materials recovered have major negative impact for implementing a lean production process. Vice versa, given an accurate supply of parts for reassembly, all the principles of Lean production can be fully implemented in the phases of reassembly and testing.

Keywords: Remanufacturing, Lean Production, Value Stream Mapping
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CNC  Computerised Numerical Control
EOQ  Economic Order Quantity
JIT  Just-In-Time
MRP  Material Requirement Planning
MRR  Material Rate of Recovery
MTO  Make-to-Order
MTS  Make-to-Stock
OEM  Original Equipment Manufacturer
RPA  Rapid Plant Assessment
TPS  Toyota Production System
VCC  Volvo Car Corporation
WIP  Work-in-Process
VSM  Value Stream Mapping
1 Remanufacturing – a growing industry with inherent instability

Sustainability is an important issue of most of today’s economies where product take back and product recovery laws have in the past few years been authorized in many nations. (Pyke et al. 2002:536) Together with these legislative demands from governments and a growing interest of a green image and environmental care, there is a lot of economical incentives for companies to take interest in product recovery and the after market. 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. (Toffel 2004:120 ff, De Brito & Dekker 2004:6 ff). The after market is of great importance of a company’s competitiveness and an increasing part of its revenues can be derived from it. Remanufacturing, in focus of this thesis, is 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, in focus in this thesis, sells approximately 60 million remanufactured automotive products compared to 15 million products in Europe, for an equivalent stock of vehicles. But volumes and revenues of the after market are characterised by high variability and are difficult to forecast since the demand could be described as low volume with immense fluctuations. (Ashenbaum 2006:5 ff, Guide 2000:467, Dowlatshahi 2005:3456, Seitz & Peattie 2004:77, Steinhilper 1998:60)

In remanufacturing, an industry born during the Second world war, a worn-out, discarded or broken product, a core, is being restored to a fully condition with the same performance as a new product but produced to a lower cost. (Amezquita et al., 1995:271) Compared to manufacturing, the remanufacturing batch sizes are smaller, the degree of automation is lower and the amount of manual labour is higher compared to a manufacturing plant. (Steinhilper 1998:54) It is a complex business due to the high degree of uncertainty in the production process, (Guide 2000:467, Seitz & Peattie 2004:83) mainly caused by two factors: the quantity and quality of returned cores. (Atasu & Van Wassenhove 2005:78, Umeda et al. 2005:2) This uncertainty also creates variations regarding how long the process will take and the yield of it. Guide (2000:472 ff) defines these factors in greater detail and present altogether seven characteristics of remanufacturing that are found in the current research literature and who increases the 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

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complication of material matching restrictions, and the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times.

As a reaction 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 customer, 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. 2001:2 f) To respond to these demands, Lean Production, which is said to increase productivity, decrease lead-time and costs and enhance quality, is widely adopted. (Martinez Sanchez & Perez Perez 2001:1433) The ideas are developed by Toyota and are 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 & Jones 1996:passim) In study made by Sundin (2004), using mainly a Rapid Plant Assessments (RPA) ranking methodology (see Figure 1), investigating how lean remanufacturing companies are compared to classic manufacturing companies, indicates that the additional complexes regarding material flows in remanufacturing may be a limiting factor for remanufacturing companies to apply Lean production principles. The same results were concluded in a study by Seitz and Peattie (2004) where big differences in comparison to manufacturing were observed. Further research is desired by both academy and industry. (Cf. e.g. Dowlatshahi 2005)

<table>
<thead>
<tr>
<th>CATEGORIES</th>
<th>RATINGS</th>
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<tbody>
<tr>
<td>1. Customer satisfaction</td>
<td>Poor (1)</td>
</tr>
<tr>
<td>2. Safety, environment, cleanliness &amp; order</td>
<td>Below average (3)</td>
</tr>
<tr>
<td>3. Visual management system</td>
<td>Average (5)</td>
</tr>
<tr>
<td>4. Scheduling system</td>
<td>Above Average (7)</td>
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<tr>
<td>5. Use of space, movement of materials, and product line flow</td>
<td>Excellent (9)</td>
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<td>6. Levels of inventory and work in progress</td>
<td>Best in class (11)</td>
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<td>7. Teamwork and motivation</td>
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<td>8. Condition and maintenance of equipment and tools</td>
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<td>9. Management of complexity and variability</td>
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<td>10. Supply chain integration</td>
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<td>11. Commitment to quality</td>
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Figure 1: RPA scoring sheets of the companies in the Sundin-study. (Sundin 2004)
1.1 Purpose

Due to the growth potential of the remanufacturing industry and to increasing pressure from markets it is important to find methods that would make remanufacturing production more efficient. Such a method could be Lean production that has been widely adopted in recent years. The purpose of the thesis is to explore what characteristics of the remanufacturing environment that hinder the implementation of Lean production principles of material flows and how Lean principles can be employed in a remanufacturing environment. The thesis aims to generate generic propositions about hindrances and possibilities to implement Lean production in a remanufacturing environment. In accordance, a study regarding material flows of a car engine remanufacturing process is performed at Volvo Parts Flen AB.

The thesis is divided into three parts. First the theoretical framework and analytical foundation is given, thereafter follows the analysis of the current state of the material flow where characteristics of remanufacturing and its impact on waste and implementation of Lean principles are assessed. Finally, the last part suggests how a future state could be designed, which would enable further implementation of Lean principles. The thesis’ target group is business students at their last semester at Uppsala University, Volvo Parts Flen and other interested actors within the remanufacturing research area.

1.2 Earlier Research of Lean Production in Remanufacturing

As the remanufacturing industry is relatively young, research is limited; Robert Lund conducted the first studies in 1978 in the USA. In 1994 Brennan et al. (1994:58) observed that the technical literature was scarce and existing articles only dealt with those topics on a general level. Guide & Srivastava (1997:519) recognize a growing demand of extended research in the production planning and control area. Findings by Seitz & Peattie (2004:75) and Dowlatshahi (2005:3457 f) prove the research still to be on a general level, or when more in-depth, focused on mathematical solutions without no practical insights, and concludes that the research area of this thesis, due to its significant future implications is of utterly research interest. Although said to have a promising future, studies by for example Nasr (1998) shows that the remanufacturing industry growth possibility are threatened and limited by the few techniques and technologies specially developed for remanufacturing. (Guide 2000:470) Methods to address the inherent complexities are absent (Stanfield et al. 2005:597), which also was the result of the literature review done in the field of Lean remanufacturing. Case studies of implementing Lean in a remanufacturing environment have been performed (cf. e.g. Fargher, Sundin 2004 and Amezquita et al. 1998), but without any consideration to its special characteristics. The implementation of Lean principles and its impact on production has been discussed in company specific manners without attempt of industry generalization.

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2 Volvo, Volvo Flen, Volvo Parts will be used synonymously with Volvo Parts Flen AB throughout the thesis.
2 Waste reduction and uncertainty in the production – the theoretical framework

The theoretical chapter aims to give the foundation of the analytical framework, which consists of the theories of Remanufacturing and Lean Production, and will introduce these in the mentioned order. First the industry and nature of the remanufacturing production process will be explained followed by a more detailed description of its characteristics. The seven waste of Lean Production will then be introduced, thereafter the principles of Lean Production regarding the material flow. In the methodology chapter, these theories will be further developed into the thesis’ analytical framework.

2.1 The Remanufacturing System

After the Second World War, material scarcity especially in the vehicle industry forced companies to repair parts instead of producing new ones. Small, independent remanufacturers continued to offer inexpensive replacement parts but the vehicle manufacturers ignored this business opportunity until recent years. Throughout the world, remanufacturing is a $100 billion industry; the USA accounts for $53 billion in total sales with costs derived for about $35 billion per year. The rate at which consumers will return used products are predicted to reach 15% of sales in the future years (Steinhilper 1998:60, Dowlatshahi 2005:3456). Still, the Original Equipment Manufacturers (OEM) only account for five percent of the industry’s total sales. Generally the European market can be considered immature compared to the north American, the OEM’s have now realized its potential and the industry is divided into three sectors: the OEM’s, their subcontracted partners and independent remanufacturers. (Seitz & Peattie 2004:77)

All products are not suitable for remanufacturing due to criteria of the products part variability and its suitability for remanufacturing operations; the availability of cores, the product’s lifetime and the technical progress regarding new verses remanufactured products. (Steinhilper 1998:95) Determining for profitability is whether the product can be restored using current technologies and be mass-produced. The value of the remanufactured product should be close, and the cost connected to the acquisition of the core should be low compared, to the original market value. Products appropriate are for example motor vehicle parts, office furniture, electrical apparatus, vending machines and photocopiers. (Sundin 2004:32)

2.1.1 The different steps of remanufacturing operations

The process within which the used product is remanufactured is called the remanufacturing process. It is an industrial process where the core is being returned to the remanufacturer where it passes through the typical steps of the remanufacturing process; inspection, disassembly, component repairing, reassembly and testing to ensure it meets desired product standards. (Sundin 2004:2 f) These
operations could be put in different order or even excluded, depending on the product type, volume and quality of the core, and different firms chose to execute the operations in different sequences. (Sundin 2004:28, 59)

Steinhilper (1998:40 f) arranges the process in the following order; disassembly, cleaning, inspection, reconditioning, reassembly and testing. Disassembly and cleaning can be viewed as new technologies on the industrial level where the industry itself has a pioneering role to set new standards and create new solutions. In disassembly, the product is disassembled to the single part level. Its parts are identified and inspected and it is decided whether each part is reprocessable, can be reused in its current state or if it should be scrapped or recycled. Here, all parts that are not fundamentally to be reconditioned, like gaskets, are separated. Oil, dirt and rust complicate disassembly operations and call for new solutions to be developed. Automation is rare even though some experiments with robots have been taking place in recent years. In the disassembly processes, the cores can also be cannibalised for parts. Component cannibalization is when parts or 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 part should be repaired. The uncertainty of the quality of a core, how much of its components that can be recovered, is measured by using the metric Material Rate of Recovery, the MRR (Guide 2000: 474). According to Guide (2000:477), the following operation cleaning is the most time consuming operation and means more than remove dirt; it means de-greasing, de-oiling, de-rusting and free parts from paint. For this complex task several methods have been developed, to be executed subsequently or concurrently; sand blasting, steel brushing, baking ovens, cleaning petrol, chemical and hot water bath etc. Following cleaning, reprocessing has the aim to repair or increase the quality of core. Geometrical change of the parts through metal cutting like grinding will change the dimensions and sometimes after reprocessing a highly worn-out product will not match the standard tolerance, such as the diameter of a crankshaft, and has to be scrapped. In the reassembly the separated parts will be assembled. This can be done with components that are reprocessed, replaced, reused or cannibalized. The reassembly of parts 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 1998:40 ff)

Bras and Hammond (Sundin 2004:29) uses an aggregated categorization of cleaning, damage correction, quality assurance (inspection and testing) and part interfacing (disassembly and reassembly). Arranging the steps in a standardized order could however be misguided since every remanufacturing process is unique. For example, inspection should be performed before disassembly and cleaning in order to prevent cores that have too fatal errors to enter the production flow, conversely, inspection could be performed with greater detail after the core has been cleaned. (Sundin
2004:59 f) Östlin (2006:57 ff) divides the remanufacturing process into the five different phases of pre-disassembly, disassembly, reprocessing, reassembly and post-reassembly where in each some key decisions of if and how to remanufacture the product have to be made and one or more of the earlier mentioned operations can take place. Below, the remanufacturing and the holistic remanufacturing system is illustrated (Figure 2).

Figure 2: The Remanufacturing System. Adapted from Östlin (2006).

2.1.2 The seven characteristics of remanufacturing
As mentioned in the introduction, seven characteristics of remanufacturing have been observed by Guide (2000:472-477) that separates it from traditional manufacturing and creates complexity and uncertainty in the remanufacturing process. These will be fully explicated below.

2.1.3 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 which make 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 be falling (Steinhilper 1998:36 ff). 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.
2.1.4 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 excessive 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, 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 problem affects the resource planning, the materials management and the lot sizing of replacing components, as well as production decisions such as scheduling.

2.1.5 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 refurbishment in adequate time and quantity. Pull (production generated by real time customer demand), push (production generated by forecasted demand) or pull/push mechanisms are used.

The operations time required for disassembly have a high variability, ranging from minutes to week. Even within the same product group the average time are variable, with such high coefficient of variance as 5.0. Due to this uncertainty, predicting production flow and lead times are incredibly difficult.

2.1.6 Uncertainty in materials recovered from returned items

A remanufactured product is estimated to consist of one third of replacement parts and to measure the uncertainty of the material that can be reused the MRR is applied. It is applied when determining batch sizes for purchasing and manufacturing. Simple methods to calculate 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 are using historical and statistical data or the procurer’s or planner’s subjective estimation, where the former is most common. When deciding the size of purchase batches, dynamic lot sizing techniques is most common, based on price, historical and statistical consumption patterns and service level.
A number of problems have been identified in the purchasing process: uncertainty in demand, long lead times, single suppliers for components and diminutive purchase orders, which leads 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.

2.1.7 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 and 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. Common is to call for a trade-in when the customer purchase a new engine and a kind of exchange system is employed. The other options are core brokers, who serve as middlemen for core collectors, third party agencies, who arrange for exchange of cores, leasing and seed stock, which consists of products that originally failed OEM specifications at the manufacturing plant.

2.1.8 Complication of material matching restrictions
When the customer retains the ownership of the product and wants the same remanufactured unit back, practiced by for example Xerox which uses this as a part of their 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.

2.1.9 Stochastic routings for materials for remanufacturing operations and highly variable processing times
This is referred to as the most complicating factor in remanufacturing. 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 fixturing and 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.

2.2 Lean Production

Taiichi Ohno is regarded as the founder of the Toyota Production System (TPS) that was first developed in 1950. TPS evolved out of need, as the market place 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 very different to e.g. 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 an approach that eliminates waste by reducing costs in the overall production process, in operations within that process, and in the utilization of production labor. The focus is on making the entire process flow, not the improvement of one or more individual operations. (Womack & Jones 1996:passim) A "waste" can be categorized as anything that the customer is not willing to pay for. Typically, the types of waste considered in manufacturing are: (Baudin 2002: 11-13)

Overproduction means making more than is required by the next process, making earlier than is required by the next process, or making faster than is required by the next process. This waste is generated when, for example, an operator is assembling parts to an already sufficient inventory because “It’s something to keep me busy”. The fundamental fault when overproduction arises is that the management has failed to design a job that keeps the operators generating value to the company; when an operator is idle, instead of overproduction (s)he should work with other value adding activities; help other operators at other workstations or improve work methods.

Waiting is the waste when parts or raw material is lacking. A waste of waiting can also arise when the balance between different processes is lacking that result in a struggle for some processes while other
processes are waiting for orders to arrive. When machines are used, there is always a risk that the operator is kept idle when waiting for the machine to finish. To solve this the principle is to maximize the utilization of the worker instead of maximizing the utilization of the machines.

**Transportation** does not add any value at all to the product. Moving parts between operations by for example a forklift truck requires both person-hours and forklifts that carry costs. This waste relates to the layout of the facility and the layout of workstations.

**Processing waste** relates to when operations are not performed in the best way. For example in an assembly situation some parts can be assembled in a wrong sequence, resulting in a more difficult way of assemble another part. The processing waste can also include unnecessary processes, for example the sorting of components that later in the process are mixed up aging.

**Excess Inventory** or Work-In-Process (WIP) is when nobody can explain the purpose of having a particular stack of parts on the shop floor. Most common reasons for excess inventory are overproduction and material being produced without an order (also called push, because of material being pushed trough the factory with no particular order waiting). One frequent waste in assembly situations is “cripples” - that is, products assembled to 99% but there is a lack of a specific part, and is common in companies with unreliable supply chains not supplying materials Just-in-Time. The practice of overproducing is misguiding for many reasons; not only does it create excess WIP-inventory, it also creates more work with a greater risk for errors.

**Motion** in an operation or process is easy to identify. The most frequent waste of motion is when someone picks one thing up and instead of assembling it straight away, places it in a different location and picks it up later. Other types of motion wastes can be to have to long distance between the assembly and the material of the assembly line storage.

**Making defective products** is the production of faulty products. The most common source of errors in an assembly situation is to use the wrong type of parts for the assembly of a product. To reduce the defects, it is important work with methods to prevent the occurrence of defects instead of finding and repairing them.

Nearly every waste in the production process can fit into at least one of these categories. Waste is viewed as the singular enemy that greatly limits business performance and threatens prosperity unless it is relentlessly eliminated over time.

### 2.3 Material Flow Issues in Lean Production

The principle of Lean production is to target these wastes in different ways with the aim to reduce 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 thesis 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.

2.3.1 Production to Customer Orders (Customer pull)

The idea of a customer pull is to produce only when there is a customer demand for a product, see Figure 4. This is the opposite of the push principle where products are produced according to future demands of products and thereby “pushed” to the customer, see Figure 4. By producing only to actual customer orders the waste of inventories is addressed. When products are pulled by customer orders, the risks in the process will be reduced due to the decreased risk of not being able to sell the product. The fundamental idea is that inventories bind up money that can be used for other activities. This cost is known as inventory carrying cost or inventory holding cost. Inventory carrying costs should include those costs that vary with the level of inventory stored. They can be divided into the four categories of
capital costs, inventory service costs, storage space costs and inventory risk costs, which in their turn can be divided into sub-categories. (Yamashina 1982: passim)

**Figure 4:** The push principle. Adapted from Yamashina (1982).

### 2.3.2 Create a levelled workload

The principle of a levelled workload aims to reduce the waste of overproduction and the build up of inventory as well as reducing waiting time. This waste is generated due to an uneven demand for products over time, see Figure 5. Lean production systems require a stable schedule over a lengthy time horizon to work properly (Jacobs *et al.* 200:237). This is accomplished by levelled workload (Figure 5), freeze windows and underutilization of capacity. Levelled workloads do also reduce the risk of not being able to produce wanted products from the customers which can be the case when capacity is low compared to customer orders. By distributing the peaks in demand to the situations when demand is less according to actual capacity, a more levelled production process can be generated, see Figure 5. To be able to move the peaks in time there is a need to “lock the orders” in a specific timeframe called the freeze window, where no additional orders can be placed. The freeze window generates stability in the amount of orders to produce, in respect to the instability in incoming orders. (Davis *et al.* 2005:352 f)

**Figure 5:** Left diagram – the variable demand for a product. Right diagram – a levelled workload for the same product. Adapted from Olhager (2000).

When having the choice of using over capacity to either build up inventory or keeping processes idle, the later have been proven the most effective. The reasons for this conclusion is mainly due to the possibilities of reassigning idle personnel to other tasks such as working
with potential process improvements as well as using the extra machine time as a hedge against shortfalls in production resulting from e.g. poor quality. (Davis et al. 2005:352 f)

2.3.3 One piece flow and reduced setup times

One important issue in a Lean production flow is the overall lead-time. Traditionally the material flow has been dominated by the use of large batches of product. Large order quantities have been motivated by the need of scale economics and the need to spread fixed cost of setups for machines over several products. The main critique from Lean practitioners is that setup times are considered fixed and not improvable; a Lean perspective prescribes a constant reduction of setups, ultimately resulting in a number of advantages. By reducing the setups for operations lower batch sizes can be motivated as an economic order quantity – EOQ – (see details about EOQ further down). (Olhager 2000:210) Reduced order quantities reduce the amount of WIP mainly by reducing the number of parts waiting in queues before operations, which affects the lead-time of the total process. For example, if an individual operation has an output of ten products each day and 50 products wait to be processed, it will take five days until all of the products have been completed. Instead, if batch sizes are lower, say five products, the time to complete the batch is half a day, theoretically reducing the lead-time tenfold. This is also called Little’s law. (Davis, et al. 2005:594)

By using a one-piece flow the waste of inventories is also addressed. In an ideal case the products should flow between operations one by one, also called a one-piece flow. When products are moving directly from one station to the other there is no need for products waiting to be produced and hence no WIP is created, see Figure 6.

![Figure 6: Work-In-Process in a material flow. Adapted from Olhager (2000).](image)

Reducing lead times, by for example a one-piece flow, is also very important in a make-to-order environment with freeze windows. Here lead-time has to be shorter than the freeze window, if not then manufacturing orders would have to be made according to forecasts (pushed) and not to actual orders (pulled). Even if major setup times are present, a one-piece flow could be realised. This principle is called order splitting and is realised by splitting a batch in to smaller pieces (ideally only one piece), as illustrated in Figure 7. The figure illustrates one batch of three products that are processed in four operations. The upper flow represents a situation where the complete batch is

---

3 Lead-time defined as the time between placed order and delivery.
processed before passed on to the next operation. In the lower flow the first part that is finished is sent
directly to the next operation and the order is split, hence order splitting. The result of the order
splitting is that the lead-time is significantly reduced. Olhager (2000:286 f)

![Figure 7: Effects of order splitting. Adapted from Olhager (2000).](image)

When deciding which order quantity should be used, the economic order quantity (EOQ) is one of the
simplest lot sizing technique used. EOQ is an equation that describes the linkage between costs of set
up, costs of carrying inventory and the quantity of an order to be produced. The EOQ apply some
simplifying assumptions such as constant demand rate, non-fluctuating costs, and unlimited
production and inventory capacity. Although these demands are not satisfied for most manufacturing
companies, it is widely used as a “good enough” approximation. The main reasons for this is that if
some of the values used as input is wrong it can still result in a close to optimal solution. For example
if the costs of carrying inventory is under estimated 50% the result is an increase of total costs of 6 %,
an if it is over estimated by 50% the result is an increase in total costs of 2 % (Olhager 2000: 213).

Due to the specific characteristics of remanufacturing, calculation of order quantities is different since
there is a need to consider other variables that do not exist in manufacturing environments, e.g. rate of
returned cores. The following formulas apply for the optimal order quantity for remanufacturing:
(Teunter & van der Laan 2005:1186 f) For comparison with EOQ in manufacturing, see Appendix 1.

$$EOQ_m = \sqrt{\frac{2C_{pm}(\lambda - \gamma)}{\gamma / \lambda C_{hr} + (1 - \gamma / \lambda)C_{hs}}}$$

$$EOQ_r = \sqrt{\frac{2C_{pr} \gamma}{C_{hr} (\gamma / \lambda) + C_{hs}}}$$

Where:
- $C_{pm}$ = Fixed manufacturing cost ($ per order)
- $C_{pr}$ = Fixed remanufacturing cost ($ per order)
- $C_{hr}$ = Holding cost rate for remanufactured products ($ per component per unit time)
- $C_{hs}$ = Holding cost rate for operatives ($ per component per unit time)
- $\lambda$ = Demand rate (number of components per unit time)
- $\gamma$ = Return rate (number of components per unit time)

One hindrance for industry to begin using these specialised EOQ formulas is that the software for
computerised systems has not yet been adapted to them.
2.3.4 **Takt time**

The word takt comes from the German word “Takt” and is the technical term for “a regular beat”. The principle of a takt time is derived from a constant material flow in a production line, ideally using a one-piece flow, defined as the time that must elapse between two successive unit completions in order to meet the demand if the product is produced at constant rate during available production time. The advantage of a flow based on takt time is that products are moving directly between different operations with the result of reduced waiting time, work-in-process and overall lead-time. Variations in cycle time limit the possibility for the direct transferring to other stations. Takt time is a function of the two variables net demand for products and net available time, giving the following formula:

(Baudin 2002: 41-50)

\[
\text{Takt time} = \frac{\text{Net available production time}}{\text{Demand from customers}}
\]

If customer demand is 90 units a week and the factory employs one shift of 8 hours the takt time is:

\[
\text{Takt time} = \frac{5 \text{ days} \times 8 \text{ hours} \times 60 \text{ minutes}}{90} = 27 \text{ minutes}
\]

If total production time would be equal to 27 minutes the product could be completed with only one worker at one workstation, but in reality total production time is longer than that, and work has to be divided in between several workers or machines in different workstations. In the case of a product that demands a total production time of 200 minutes to be produced, the need for workstations containing one operator will be the following:

\[
\text{Number of workstations} = \frac{\text{Total operation time}}{\text{Takt time}} = \frac{200}{27} = 7.2 \text{ workstations}
\]

Because different operations of the total operation time demands different times to complete, the possibility to group operations into workstations is limited, see Figure 8. Calculating the minimum workstations needed does not per see conclude that 8 workstations are enough to generate the total output, it says that it demands at least 7.2 workstations. If 9 operators are needed because of problems fitting operations within the takt time a balancing loss (waste of waiting) will occur.

**Figure 8**: The total operation time divided in to individual operations that cannot be separated within the takt time.
An appropriate takt time is recommended to range between 1 to 10 minutes if possible. A takt time below one minute might result in repetitive motions that stretch limits of human endurance in both physical and psychological ways. If the takt time exceeds 10 minutes it is considered too long, resulting in different kinds of problems, e.g. quality can be affected with the increased risk of forgetting to assemble a part. (Baudin 2002:54)

2.3.5 Just-in-Time deliveries (JIT)
When producing to customer order by the pull principle, to be able to acquire components within the lead-time is fundamental. If the product cannot be sourced within the lead-time it has to be ordered in advanced and stocked according to forecasted customer orders. The lead-time for deliveries of components will set the limits of the lead-time of the produced product. Just as customers and employees are key components of a lean system, suppliers are also important to the process. The basis for a JIT system to run properly is confidence between suppliers and vendors, and the ability to share information, especially the long-run picture regarding future demands that will be placed on their production and distribution system. Confidence in the supplier deliveries commitment allows reduction of buffer inventories. Maintaining a lean stock level normally require frequent deliveries during the day. (Jacobs et al. 2006:238)

2.3.6 Stable production process
When producing products by a Lean production philosophy, the aim is to decrease WIP and final inventories which demands high stability of the process. Whether a process is stable is related to the ability to perform as expected, for example to generate the correct product quality in the right time without disturbances. If one of the operations or deliveries in the material flow fails or starts to produce incorrect parts, the stability of the process is highly reduced. Variation of cycle time other than expected is another source of instability. Overall these factors increases the variability in the system and if the buffers are small or inexistent, as in a lean environment, the result can be that the entire process will be become idle. Earlier the lack of process quality has been compensated for by inventories that hedge against malfunctions, which is not a possibility in a lean material flow. (Jacobs et al. 2006:245)
3 Method

This chapter introduces the methodological considerations of the thesis. Firstly, the analytical framework is build up from the theoretical chapter. Thereafter, the line of approach is briefly introduced followed by the passage where the research methodology and its scientific considerations are discussed. This is followed by the sections where the process of data collection is introduced and the operationalisation of the analytical framework is developed. Finally, the thesis trustworthiness and ethical considerations are discussed.

3.1 Analytical framework

As presented in the theoretical chapter, there is no standardized design or order of the different operations that are to be performed in the remanufacturing process. Therefore, a modified model of the process based on the models in the theoretical chapter will be employed: the different operations are divided into the different phases of pre-disassembly, disassembly, cleaning, reprocessing, reassembly and testing. The term phase is employed instead of operations or steps, since the division of the process into phases will generate a better understanding of it, allow a better possibility to generalize the results of the study to use it in other studies and enable benchmarking. Some might argue that cleaning is an operation that can take place before as well as after reprocessing. Cleaning operations made after reprocessing are regarded as “washing operations”; these are most commonly done in order to wash the part before reassembly and is a clearly standardized operation in comparison to the initial cleaning which treats cores of different qualities. Hence, they are to be regarded as a part of reprocessing. Further, inspection is considered to take place as an inherent activity in each operation carried out, and not as an individual operation.

3.2 Line of approach

The purpose of the thesis is to explore which characteristics of remanufacturing that hinder a lean material flow and which principles of Lean production that could actually be employed in a remanufacturing environment. In accordance, the theories of Lean Production and Remanufacturing is being used and the research methodology chosen that of a case study. To assess material flow, the production flows of five major product groups in a car engine are assessed. For the collection of data, a Value Stream Mapping (VSM) methodology has been used. VSM is a major scientifically validated method for structuring a study regarding waste in a material flow (Rother & Shook 2002). Supplementary interviews, both standardized and unstructured, have been carried out with operators, production planner and management. The analysis is based on the analytical framework developed from the theories. The first analysis of the collected data explore what characteristic of remanufacturing that cause waste in the phases of pre-disassembly, disassembly, cleaning, reprocessing, reassembly and testing and hinder the implementation of any Lean principle in each of the phases. In the second analysis a suggestion as to how the material flow could be improved is
proposed, which enables the introduction of further principles of Lean production in the different phases of remanufacturing. The hindrances of Lean that still are left will be analysed and finally some generic proposition will be presented.

3.3 The case of Volvo Parts Flen AB

The thesis is a descriptive, explanatory single-case designed study as it documents and describes activities as well as it is focused on generating new, generic insights of Lean principles in a remanufacturing environment (Yin 1994). Generalizations of results are in case studies made to theory and not to populations, where a multiple case study enhances confidence in the theory’s robustness since it might strengthen the result more than does a single case study. Criticism regarding the poor foundation of scientific generality that case studies are said to provide is also common. (Yin 1994) Even though the study concerns five different flows, it is regarded as a single case study and therefore the grade of generalization is low. Nevertheless, according to Merriam (1994), case studies have some advantages since they may employ data from multiple sources, for example observations and interviews used in the thesis, and they can describe a state over a period of time. They also illustrate that the complexity of a state might be affected by multiple variables and not a single one, like the different characteristics of remanufacturing, they give an explanatory framework of how a situation emerged and its underlying reasons as well as what solutions to apply. Yin (1994) raises some disadvantages in using case studies, mostly connected to the biases that arise since case studies rely on analytical generalizations, which are associated with all qualitative research methods. These biases might arise due to the subjectivity and selective presumptions of the researcher. This raises the important issues of reliability and validity.

The case company Volvo Parts Flen AB was chosen since they are a remanufacturer of diesel and gasoline engines. In Sweden, Volvo Flen is one of the major remanufacturers in the automotive branch. The five product groups assessed in the flow are cylinder heads, crankshafts, camshaft, engine blocks and connecting rods. Since they are the the most valuable parts of the engine and each one have their own special route in the production flow, they have a great impact on the production costs and lead time. The opportunity of accomplishing this kind of study was given because of Volvo’s need to map the current state of the engine production line.

3.4 Theoretical Foundation and Data Collection

The theoretical foundation of the thesis, Remanufacturing and Lean Production, has been build from different prerequisites. The ideas of Lean Production have been widely discussed and the research comprehensive, whereas the Remanufacturing research is poorer. The theory of Lean Production can therefore be argued to be validated and the foundation, upon which the thesis’ theoretical framework is build, has not been extensively discussed. A literature review of Lean Production in remanufacturing
was performed and none of the few case studies found generated general principles for Lean Remanufacturing. The scarce research within remanufacturing extorts the need of a deeper theory review and presentation of different approaches, why scientific articles and research papers constitute the theoretical foundation. Due to the resent development of Remanufacturing and the use of recent research about Lean, the criteria of employing contemporary resources has been fulfilled. To suppress the tendency of dependence in between different sources that refers to the same researcher, primary sources have been considered. (Wiedersheim-Paul & Eriksson 1999)

The empirical data was collected with the method Value Stream Mapping (Rother & Shook 2002), which is developed to map out the processes regarding material and information flow and has been referred to as the language of Lean. It is said to give a complete view of the production process and not only does it observe waste, it is a suitable tool to find the causes of it and for generating possible solutions. In this study, only the material flow was regarded. The value stream is defined as all activities that are necessary to refine a product (Rother & Shook 2002:1). The method is divided into two steps; mapping the current state of a flow and propose a future state of it. The initial step to document the current state of the flow involves following a chosen product and accompanying it along its way through the flow. First, an initial observation of each of the five product flows was obtained by a quick walk through it to gain an overview. Thereafter followed a more precise documentation. Each product group was followed and observed and its flow drew by hand from an up stream-perspective. Operations, cycle times, setup times, transportation distance and inventories were observed. The reason for following the flow up stream is that in this way each operation is the closest one to the customer’s demand, and therefore controls the pace of the operations up stream. Such perspective will enable a pull production. The method demands the observed times to be checked manually. In this study, the cycle times and setup times were estimated by the operators. Data of the mapped flow were projected into spreadsheets in order to create tables and graphs to enable an analysis of the flow.

Supplementary respondent interviews have been carried out for collection of data used in the analysis of the current flow. In order to gain a greater understanding of the whole production process, three interviews have been carried out with production planners and management, which have been of an unstructured kind. With the operators the interviews have been structured asking questions of for example cycle times, but the operators were also asked to tell about their perceived problems at their workstations and their origins. See Appendix 6 for interview guide. Lists of inventories and future demand etcetera have been projected in the MRP-system (Material Requirement Planning) Movex.

The second step of the VSM-method prescribes a wished, ideal future state of the material flow to be drawn and mapped as a suggestion. This is a proposal of how the material flow could be arranged differently and thereby be improved. The suggestion is based on the initial analysis of the current state.
3.5 Operationalisation

To measure which of the seven characteristics of remanufacturing, uncertain timing and quantity of returns, need to balance returns with demand, disassembly of returned products, uncertainty in materials recovered from returned items, requirement for a reverse logistics network, the complication of material matching restrictions, and problems of stochastic routings for materials for remanufacturing operations and highly variable processing times, that affect the flow and hinder the implementation of the Lean principles Production to customer orders (Customer pull), A levelled workload, One piece flow and reduced setup times, Takt time, Just-in-Time deliveries and a Stable production process, five metrics were chosen and will be used when evaluating and mapping the value stream. They are all common when conducting a production flow analysis. (Rother & Shook 2000:16 f). The metrics are also employed to find and trace the different wastes of the Lean philosophy. The existence of wastes in the flow is an indicator that the flow is not lean as well as that it is not efficient. Since the focus of this thesis is material flow, the different kinds of waste considered are overproduction, processing waste, excess inventory, transportation, making of defective products and waiting. Motion will be excluded because it regards the execution of the operation itself, and even though affecting the flow, it is mainly connected to operations design, which is beyond the scope of the thesis. In this thesis a modified definition of making of defective products adapted to a remanufacturing environment is used. It is considered a waste in the classical sense of manufacturing, production of malfunctioning products, but also considered as finding a defective core non-reusable in a later phase than necessary. One example would be to find a core to be non-reusable in the reassembly phase when this error could have been found in an earlier phase, for example after the initial cleaning. The five metrics are:

- **Setup time**
  
  To reduce setup times is a foundation for reducing the economic order quantities and is a basic foundation to create a one-piece flow and to apply takt time. Long setup times might cause excess inventory and waiting. Setup time is important to identify to be able to calculate the appropriate batch sizes. Usually, when long setup times are present, operators want to run large batches due to the economic order quantity. Since the remanufacturing operation routings are stochastic, and batches often are small, small set-up times are preferable in order to enable a flexible production.

- **Cycle time**
  
  Variations in cycle times are an indicator of highly variable processing times. The disassembly of returned products and material matching requirement might cause extra material handling, which might affect cycle times. Large fluctuations of different operations make it hard to takt the flow. Variations in cycle time do also influence the stability of the production process and, because of
unpredictable capacity need; cycle time might also influence the possibilities to a levelled production. Large cycle time causes waiting and excess inventory.

- **Lead time**
  A long lead-time is an indicator of stochastic routings for materials for remanufacturing operations and highly variable processing times. The need for a reverse logistic network, uncertain timing and quantity of returns and problems with the need to balance returns with demand also affect it. The lead-time of a production process sets the boundaries of the freeze window, if the process cannot be completed within the freeze window the possibility of a levelled workload is significantly reduced. The freeze window and its consequence to lead time of the process also put limitations on total supply chain inventories and waste, due to increased needs of security. Lead-time is defined as time for a product to advance in the flow from one point to another. It is calculated according to Little’s law as daily output through Work-In-Process in between these points.

- **Work-In-Process (WIP)**
  Large amount of WIP is an indicator of stochastic routings for materials for remanufacturing operations and highly variable processing times. Uncertain timing and quantity of returns and problems with the need to balance returns with demand might also determine the level of WIP. Large amount of WIP might cause waiting and excessive inventory. It might also be an indicator of overproduction. WIP are important to recognize in order to observe bottlenecks that are due to under capacity or has been created because of lack of material, which might be due to uncertainty in materials recovered. Moreover, it may be an indicator of a buffer that was created because of instability in the operation before and inventories are created as a hedge against shortages in the material flow.

- **Transportation**
  Does not add any value to the product. Transportation in it self does also introduce additional lead-time to the process, especially if transports have to wait for common transportation operators. Stochastic routings for materials for remanufacturing operations might cause need for extra transportation, which in effect might cause waiting and excess inventories. It might constrain a one-piece flow.

The metrics used are both indicators of not well functioning operations and/or planning, like WIP, as well as sheer determinants impacting the flow, like set-up times of the machines. The impact of the characteristic requirement for a reverse logistics network might not be completely covered by the above quantification. The characteristic complication of material matching restrictions is not quantified, neither is processing waste to define in pure numerical metrics. Although it might be argued that processing waste is linked to operations design, is this waste important to determine in order to create a future, lean flow. These three determinants have been defined by asking the operators
open questions like “what problems are present in this operation?”,”from where could they be derived?” and “what possible solutions are there”. The uncertainty in materials recovered from returned items and its impact on the material flow has also been assessed by interviews with the personnel, asking questions like “are you scrapping any parts in this phase?” and “what is the effects of scrapped materials?” Other issues as the existence of a customer pull and Just-In-Time deliveries are also captured by using interviews with management asking questions like “what materials are produced by confirmed customer orders?” and “can parts be purchased within the freeze window?”. For a complete review, please see Interview Guide in Appendix 6. The charts and tables regarding the collected data will not be presented in nominal numbers due to the Volvo confidentiality regulations. Instead, relations and fluctuations will be projected in a ratio scale.

3.6 Trustworthiness of the thesis

Data has been collected through the VSM-method and interviews, and the study is to regard as a qualitative, structured observation study with quantitative data employed. The demand of data used in a quantitative study is that they have to be representative and reliable, which is not the case in a qualitative study, where more in depth factors, like the origins of waste in production, are to be analysed. A qualitative study demands certain proximity to the object studied to create a deeper understanding for the phenomenon. (Holme & Krohn Solvang 1997) The authors have earlier written a thesis on the case company, why a basic understanding for the business is present. This could also be a disadvantage in a scientific aspect since it might create expectations of the individuals.

As a research method, observation has some advantages over interviews. (Sapsford & Jupp 2006) Like data collected in the VSM-study, information is recorded by researchers without having to rely on secondary sources, which prevents data to be inaccurate. The researcher also has the possibility to note what observed operators cannot because of their “tunnel vision” due to old habits. Data collected could also be a mean of controlling information collected from other sources. There are also some limitations of the method. Operators observed might change their behaviour because they are observed and evaluated. Observations are always carried out by the researcher as an individual with interpretations, why the objectivity of the study always can be questioned. This bias might also arise since the authors earlier have written a thesis at Volvo as well as after the theoretical literature review; the authors might have had some expectations of what to observe during the VSM-study. Such limitations are reduced by the display of quantitative data presented in nominal numbers that are entirely objective, e.g. number of cylinder heads in stock. Still, some information is based upon subjective judgment, like problems of operations perceived by the operators. Unlike what the VSM-method prescribes, operators have estimated the times collected. The bias that might arise when operators are being observed diminish but is replaced by the risk of getting false information from operators. The constraint of not being able to display data in nominal numbers, e.g. minutes of an
operation, should not be considered a weakness since fluctuations, important determinants of the ability of employing Lean principles, are displayed. The presentation of data transferred into ratio scales also enables a generalization of concluded results as well as company specific and research related benchmarking. The grade of generalization in case studies are, as earlier mentioned, low and the results of this study are not statistically significant. Still, this does not hinder the thesis’ purpose since it is to explore, not to determine, the characteristics that hinder Lean Production principles.

The construct validity, whether the operational measures employed are sufficient for the study or not, must be considered secured since the operationalisation of theory is common in this kind of mapping material flow. The questions asked, regarding problems and their causes, are used in order to find out the reasons for the different kinds of waste in the production flow. The internal validity of the study, which refers to the design of the study and to which extent wanted results of the study could be generated, is also considered fulfilled since the authors could draw some basic conclusions regarding Lean production and remanufacturing. The external validity, which refers to what extent the results of the study could be applied in other environments than the research, is enhanced by the division of the remanufacturing process into generic phases. The reliability, to what extent the study could be carried out again with the same result, might be divided into two answers. The observation of material being processed in the flow, as well as transportation distance and some setup times for machines, increases the reliability of the study, whereas the more qualitative part where operators are asked to estimate the cycle time and the reasons for waste in production, decreases the reliability of the study. Different operators might give different answers in time estimated, and different researchers might interpret the reasons behind waste and the possibility of implementing Lean differently. Criticism regarding the criteria of tendency and dependence (Wiedersheim-Paul & Eriksson 1999) might be righteous, since operators might not want to report disadvantageous cycle times and perceived problems of operations might have been discussed by management, planners and operators, which might create biases of observed problems. The criterion of using contemporary sources has been noticed.

3.7 Ethical issues

The execution of an observations study where operators are observed at work is a subject of sensitive matter. Before beginning the study, the labour union Metall was asked permission as well as the different production leaders and their teams. It was important to gain the trust from the operators to conduct the study. The operators might have a feeling of discomfort when observers are exactly clocking their work. It was agreed upon that cycle times and setup times are to be estimated by the operator. Before each interview was performed at the workstations, the operator was told about the purpose of the study and asked whether (s)he wanted to participate.
4 The material flows of a car engine

This empirical chapter deals with this thesis’ first purpose to explore what remanufacturing characteristics that hinder the implementation of Lean principles and causes waste. It starts with a brief introduction of the case company and its business. Thereafter follows a more detailed description of the current state of the material flow and the planning structure of the whole production process. Finally, the results of the Value Stream Mapping and complementary data collected of the six phases of remanufacturing will be discussed and analysed.

4.1 Volvo Parts Flen

In 1850, the Flen plant started to manufacture harvest machines and nearly a 100 years later, in 1960, the production was replaced by the remanufacturing of automotive and marine engines. As of 1998 Volvo Flen is a fraction of Volvo Parts, a business unit of the Volvo Group. Volvo Parts supports the six business areas Volvo trucks, Renault trucks, Mack trucks, Volvo Penta, Volvo buses and Volvo Construction Equipment. It provides services and tools for the aftermarket, throughout the whole supply chain. The vision of the Parts division is to be number one in the after sales market and perceived as easy to do business with.

Volvo Parts Flen AB has 220 employees and total sales are approximately 55 million Euros a year. The main activities are remanufacturing of petrol and diesel engines for trucks, buses and cars where remanufacturing of bus, truck and car engines account for half of total sales and the remaining part is made up of remanufacturing and manufacturing water pumps and packaging of cylinder liner kits. Flen was for a long time the only remanufacturer among the current three within the Volvo Group; today its vision is to develop into a “Centre of Excellence”, to provide knowledge to other remanufacturing plants. About 1500 car engines and 1500 truck engines are remanufactured in Flen per year. These are divided to ca. 20 engine families and 100 car engine versions, depending on whether they consist of four, five or six cylinders. Volvo has a guarantee time, which differs between the engine families, that there will be spare parts available for a sold engine and that a remanufactured engine is available for exchange. The car engines are remanufactured mostly for Volvo Car Corporation (VCC), a company of the Ford group, but also for SAAB.

4.2 The current car engine flow

This section will explain the current situation regarding the material flow of a car engine. A simplified overview of the current situation is given in Figure 9. The cores are acquired from the subcontracted core broker “Sittard” located in Belgium. When arriving at the Flen plant they are stored at the courtyard waiting for disassembly. In the disassembly section the parts of the core are separated from the core and grouped together with parts from other engines according to product groups. Each product group has its own specific route in the parallel material flow between disassembly and
reassembly. The routings of the material flow depends on the operations needed to repair each part. In this study five of the major product groups are studied: cylinder heads, crankshafts, camshaft, engine blocks and connecting rods. An engine normally consist of one cylinder head, one block, one crankshaft, two camshafts and depending on the number of cylinders, four, five or six connecting rods. In the process there are parts that cannot be reused and therefore these parts have to be purchased. Before entering the reassembly operations a majority of the parts, both new and repaired, are stored in a parts inventory, and from this inventory the parts are collected before reassembly. After reassembly the complete engine is sent for testing and packaging before delivery to the customer. Normally the products are delivered to the customers’ inventory waiting for an end customer to place an order.

Figure 9: The current material flow.

4.2.1 Planning structure
In order to enable an efficient material flow, the material planning must also be considered. The Figure 10 presents an overview of the current planning structure. In the current situation long-term forecasts from customers are given for one year, and in the short run orders are frozen 3 weeks before scheduled delivery. A customer order within the freeze window triggers both reassembly orders (about 1.5 week before delivery) and disassembly orders (2 to 3 weeks before delivery); a timeline illustration regarding the current remanufacturing process is given in Figure 11. In the current situation there is a “one for one” (1:1) situation; a core is only entering the disassembly phase if there is a need for a remanufactured engine.
Disassembly orders

Cores for disassembly are delivered by truck once every two weeks, with the consequence of cores for a two-week production is kept waiting for disassembly. Sometimes, due to faulty forecast, some of the cores turn out to be cancelled and they are therefore kept in an inventory in Flen, waiting for a new order. A placed remanufacturing order triggers disassembly of the core and the core enters the disassembly area were parts are separated according to product groups – in a planning perspective these parts are “pushed” forward to the reprocessed inventory. In some cases cores enter disassembly just because some of its parts are need due to different specification of the final engine, and the residual parts are stored in the disassembled parts inventory, which is also the case for parts that are cannibalised from cores.

Reassembly orders

The reassembly operations are supplied with parts listed in the final parts inventory, constituted of purchased, reused and repaired parts. The final “ready to be assembled” parts inventory is refilled with reprocessed parts pushed from the disassembly operation – although the push principle is limited not to push parts with no customer order further to reprocessing operations. New parts are ordered according to demand for products with a forecast calculated on the material recovery rate. Many purchased parts have a relatively long lead-time (longer than two weeks) and are to be ordered in advance according to forecasts resulting in a push principle. There are also some parts that are always purchased for each engine, for example spark plugs. These parts are pulled and delivered within the freeze window.
Coordination between disassembly (push) and reassembly (pull)

In the current situation there is a maximum time for repair and cleaning of the individual parts of 1.5 weeks (7 to 8 days) to be able to use the same parts from the disassembled core in the reassembled engine. If the part is not ready after two weeks previously repaired or purchased parts has to be used. This situation is created because of the gap between the push disassembly and the pull of reassembly. To enable coordination between disassembly of a core and the reassembly of an engine, and hereby closing the gap, there can be a maximum lead-time for repair and cleaning of about 8 days.

4.3 Presentation of results and analysis of the current state

The analysis of the VSM-study will be divided into the different phases of remanufacturing. The characteristic of remanufacturing that impacts the phase, causes waste or hinders Lean principles to be implemented will be discussed. All data presented in the following sections are fully displayed in Appendix 5.

4.3.1 Pre-disassembly

Before disassembly is undertaken, the cores, packed individually in a paper box, are registered in the MRP-system. Before cores enter the disassembly area, they are unpacked from their packaging in a transit area where they – under winter conditions - are kept temporarily to reheat. At the Flen plant there is no inspection made before entering the disassembly phase.

Reverse logistics network and Timing and quantity of returns: Waste in this phase is accounted to excess inventories due to the two weeks inventory of engines to be produced. The magnitude of the inventory is dependent on the delivering frequency, which is dependent upon a well functioning reverse logistic network. The deliveries every second week are not based upon a Just-In-Time
principle. This adds additional lead-time to the production process. One common problem mentioned is that the supplier has delivered wrong cores. The absence of a well functioning reverse logistic network has great implications on the whole production process.

**Need to balance demand with returns:** Since the cores are delivered every second week, some of the cores are acquired based on a forecast that are beyond the freeze window and some orders might therefore be cancelled when entering the Flen plant. This might cause excessive inventory.

### 4.3.2 Disassembly

In the disassembly phase the engine is disbanded and the five different product groups are split up and placed in boxes and upon rackets. Before disassembly can be undertaken, all boxes and rackets must be replaced and in some cases these have to be assembled, which results in major setup time when switching between different engine families. Setup time of the disassembly phase is about 60 minutes, which, along with the setup time for the grinding machine for crankshafts, is the greatest setup time of all operations. Setup time is dependent upon the current way of dealing with the material and parts handling and separation. During disassembly, the operator decides which parts that are to be scrapped or forwarded to the cleaning phase by a quick visual inspection based on their subjective judgement and experience.

**Material matching restrictions:** The cylinder head, consisting of two parts, has to be kept together due to demands on specific geometrical forms. This is constraining on the current material handling, but it is not a limitation on any of the Lean production principle that could be employed in this phase.

**Need to balance returns with demand:** When the customer places an order on a remanufactured engine, there an uncertainty whether an equivalent core is available for remanufacturing. When this is the case, the engine could still be disassembled and other parts could be used in the reassembly and upgraded to the requested engine. This means that the disassembled engine is not fully reused in the first place, which causes waste of overproduction of not needed parts and this in term causes excessive inventory. For example, the WIP and excessive inventory of camshaft accounts for 189% and crankshaft for 98% of total annual demand. Although this characteristic generates waste, it is not a limitation on any of the Lean production principle that could be employed in this phase.

**Stochastic routing and processing times:** Depending on the quality of the core; rust, dirt etcetera, the cycle time for disassembly is highly variable varying with a variation of 3 times as much when maximum cycle time is demanded. This strongly limits the possibility to introduce takt time, a levelled workload and it limits a stable production process. The main reason for not being able to employ a
takt time in the flow is mainly due to the waiting time that is generated when the cycle times of the operations is variable – see further explanation in Appendix 4.

**Uncertainty in materials recovered:** During disassembly, defective parts are scrapped or sent to recycling and no record is kept of which parts that are scrapped, even though this rate are said to diverge with reality. Today, the MRR used for material planning is fixed according to pre-estimations made when the product was introduced. Although this characteristic has no impact in this phase, it will strongly influence the forthcoming process and the insecurity affects the possibility to enable a stable production process.

**Disassembly:** The operations of disassembling acquire the need of sorting the different separated parts into different material holders, which causes the waste of processing. It might limit the possibility of a one-piece flow due to the need of batching parts together for transportation.

**4.3.3 Cleaning**

After disassembly, the five different product groups are split up into five different flows until they are reassembled again. The groups share the same cleaning stations as other parts in the flow, which might result in a bottleneck. Two different methods of cleaning the cores are used, cleaning in water washing machines and blasting. No setup times are observed.

**Stochastic routing and processing times:** Cylinder heads and blocks are put to soak before entering the washing machine, the time dependent upon the quality of the core ranging from the normal soaking time up to the double time for cylinder heads and 0.3 to 24 times (24 due to soaking over night) the average for engine blocks.

The cleaning operation cycles are fixed in all cases but the cylinder heads, which are cleaned manually and therefore has a variation of up to 1.5 times average washing time. Due to the condition of the core, it might not be clean enough in the first cleaning operation and therefore needs to pass through the cleaning station again. This affects the possibilities of implementing principles like a stable production process, levelled workload and takt time. The operation output capacity from the cleaning operation is limited due to the size of the washing volume in the cleaning machine. For example engine blocks occupy much more space per unit than camshafts. To achieve economy of scale in the machine the parts are grouped together in batches that have an impact on the possibility of a one-piece flow.

During cleaning, the cores are heated and before performing any reprocessing operation, they have to dry and regain room temperature which takes at least two days, which causes the waste of waiting as
well as generating *excessive inventory* and prolonging lead-time. The same consequences apply for parts that are blasted after cleaning. In between washing operations, over two weeks of production was found in WIP of three product groups. Due to the extensive cycle times up to a couple of hours the possibility to use a *takt time* is reduced, as well as the introduction of *one-piece flow* since the cores have to be batched in traditional washing machines. After cleaning, the cores are transferred to different storages without being further inspected or tested, with the consequence that a defective core might still be handled in the flow and not detected until a later phase, which causes the waste of making defective products.

4.3.4 Reprocessing

Depending on the characteristic and the quality of the core, it demands different kinds and intensity of reprocessing operations. The repair operations are commonly associated with different machines that have different amount of setup time. This phase of the flow can generally be said to be the most machine intense one that results in significant setup times, which make the principle of *reduced setup times* an important factor for employing low batch sizes and hence a *one-piece flow*. For example, connecting rods have setup times of up to 15 times the cycle time, the cylinder heads up to two times and crankshafts up to six times the cycle time, whereas camshaft only have a minor setup time of under 1 times the cycle time. After the reprocessing phase, the cores are put into storage.

**Stochastic routing and processing times:** Cycle times, dependent on the quality of the incoming parts, are different and highly variable. Some parts require less machining because of a lower wear, for example the cylinder heads and crankshafts have a variation between minimum and maximum cycle time with a factor of 2.5 and engine blocks up to 2.0 times. Also stochastic routings has an impact where crankshafts in approximately 30% of the cases has to be grinded before polishing. The wide-ranging cycle times complicate the implementation of a *takt time flow*, a *levelled production* and a *stable production process*.

**Uncertainty in materials recovered:** When reprocessing parts one common repair operation is to smoothen a surface from scratches. This is done by removing material from the surface reducing or expanding the geometrical form of a part, e.g. the diameter of a cylinder. But if too much is eradicated, the part will be non-reusable and has to be scrapped. This results in an uncertainty if the part can be used
after the processing, in the Volvo case these rates are set in advance and it is later adjusted for according to the actual outcome. The material recovery rate is extremely individual for different product groups and ranges between 0.1 and 1.0. If the part is scrapped after being processed the missing part has to be replaced with another one, cannibalised or purchased. As illustrated in Figure 12 the material recovery rate will create a waiting time when the part from the (scrapped) fourth and the sixth core are supposed to be reprocessed. If the scrapped part is available as a cannibalised part it will also demand a cycle time, resulting in a doubling of the total time to produce a repaired part. This will limit the possibility to employ *takt-time* as well as *levelled production* and a *stable production*. To reduce this effect one solution is to purchase a part to replace the old when a part is discarded. 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 maximum capacity is not exceeded. When some parts of the core have been scrapped, for instance the block, and a purchased item is not replacing it, it will generate a disassembly of yet another engine, which in turn generates *excessive inventory* of the parts that not have been scrapped and *waiting* for the block to be disassembled and parts to be reprocessed. This has implications on the implementation of a *one-piece flow* and a *stable production process*.

### 4.3.5 Reassembly

After being stored in central storage, the parts are reassembled as a mix of purchased and reprocessed parts. In this phase the setup times as well as the cycle times, are not as variable and fluctuating as in the reprocessing phase. Some variations exist in between product families depending on the number of cylinders.

**Uncertainty in materials recovered:** When material requirements are set the material recovery rate is used to calculate the need for purchased parts. If the estimated MRR is false, part shortage or *excess inventories* of new parts might occur in this phase, with in turn 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. If a purchase lead-time extends the freeze window the products has to be ordered according to forecasts or kept stocked. If just-in-time deliveries and contracts could be used the principle of customer pull could be realised although, according to management, the importance of the remanufacturing process are not high on the agenda when forming the purchase contracts with suppliers.

**Stochastic routing and processing times:** The cycle time of the re-assembly operations have variations of up to 13 %, mainly due to switching between engine families. Since these variations in between families are known with certainty – they are not stochastic – this is not per se a hindrance for an implementation of Lean principles.
Material matching: In the cylinder head reprocessing flow there is a need to keep the two pieces together. This phenomenon does not pose any additional influence for the possibilities of lean methods. If one of the two pieces is found broken, the other piece is non-reusable as well, which might result in the waste of excessive inventory of its belonging parts and waiting just like the block case mentioned above, and the consequences for a one-piece flow and a stable production process are equivalent.

4.3.6 Testing
After the reassembly the engine is tested to meet the specified performance standards. The test is performed in another building. If withstanding the assessment performed within a fixed cycle time, the engine is placed to cool down before it is being packed. Today’s packaging consists of two different kinds, a paper box on a pallet or a racket. In comparison to the racket, the paper box has to be prepared, which is time consuming. If only using rackets, processing waste could be eliminated. Waste caused by specific characteristics of remanufacturing was not observed. If failing the test, the engine will be examined; parts might be replaced and then the engine will be tested again.

4.4 Hindrance of Lean principles on aggregated level
In the following passage, waste and obstacles of implementing Lean that were found on an aggregated level will be discussed.

4.4.1 Planning principle
Due to the production and MTO policy, and the fact that demand is based on statistical prognosis, customers might re-schedule purchase orders, which results in cores in the flow that are not attached to an order. Normally, these are processed together with the cores that still have a purchase order, but then stored in the storage or not fully repaired. This results in two different kinds of waste; overproduction and excess inventory.

4.4.2 A parallel flow and transportation
The design of the current parallel flows in the Flen plant are partly to be called a functional layout which means that the different operation stations in the flow are divided into departments, for example reprocessing of cylinder heads, some even physically separated from each other, e.g. testing. The cores are therefore transported by forklift truck between operation stations, generating enormous transportation distances. The five flows are each about 1,100 meters in between the different operations, where transportation to and from the testing accounts for about half of the distance. Transportation in between disassembly and cleaning operations account for about one sixth of total distance and from the reprocessing operations to the storage and to the final reassembly area, the distance account for about one fifth to one third. The extensive distances call for transportation of batches, if not, it would generate extensive amounts of parts that have to be transported one by one,
which in turn causes waiting and high levels of WIP. The disadvantage of a parallel flows is that it makes the one-piece flow principle inappropriate for the majority of the parts due to the need of batching. Waste caused by transportation is however not caused by any of the identified characteristics of remanufacturing. But it can be argued that the operations of disassembly and cleaning are such dirty and loud activities that they have to be separated physically from for example reassembly due to work guidance rules.

4.4.3 Balancing demand with returns
As mentioned there is a problem in linking demand of a specific engine with an appropriate core that results in cores that are pushed through disassembly and the parts with no demand in the remanufactured engine is stocked for future demands. This fact combined with cannibalisation of cores for specific parts – also resulting in other spare parts – has created an extensive amount of disassembled parts. For example, the number of disassembled cylinder heads and crankshafts accounts for at least one annual demand. For other parts such as the connecting rod, disassembled parts account for only a couple of weeks’ demand. According to management, the reason for the excessive inventory for some parts is that they are becoming obsolete because of a lack of standardisation between the years – resulting in a low demand of the individual part. For other parts, such as connecting rods, the shape and functionality is more generic and can be used in different types of engines families and versions.

4.4.4 Determining economic order quantities
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 EOQ has been calculated (see Appendix 2). The major setup time has been identified to crankshaft operations, which has been used in calculation of the worst case. Results from this study indicate that economic order quantity in the worst operations amount to 14 parts. Order quantities for more average setup times yield order quantities of about 8 pieces. In this respect, it would be quite difficult to motivate a pure one-piece flow with the current setup times although the possibilities for order splitting should be investigated.

4.4.5 Lead-time analysis
The analysis of the current planning structure indicate a maximum lead-time for parts entering cleaning and reprocessing of about 8 days for a precise “one for one” (1:1) situation. The situation today is actually that the 1:1 is just a planning perspective. The analysis of the five product groups shows that the lead-time for cleaning and reprocessing operations are longer than the maximum 8 days. The main limitation of the lead-time is the amount of WIP that is currently in the flow – each product group has WIP that account for over eight days of production (see Appendix 3). This is a consequence of the gap between disassembly and reassembly, which results in that a core that enters
disassembly does not reach the reassembly phase to be reassembled according to the customer order it was generated from. Instead, parts from previous cores or purchased parts are used to reassemble the engine. The intended pull principle is reduced to a push principle where products are produced to end up in a final parts inventory instead of being delivered to customers. To resolve this situation there are mainly three options:

1. Expanding freeze time to more than 3 weeks.
2. Disassembling products outside the freeze window according to forecasts.
3. Reducing lead-time for cleaning and reprocessing.

The only option that does not add waste is to reduce the lead-time. In the following section solutions based on Lean principles on how to reduce the lead-time are presented.
5 Proposal of how to make the flow lean - a future state

In this chapter the overall proposal of how to make the flow more lean will be discussed on specific actions in each phase. These actions will enable further implementation of Lean principles. The characteristics of remanufacturing that still are present in each phase will be discussed.

5.1 Pre-disassembly

The major purpose of the pre-disassembly operation should be to receive information about incoming cores to control the forthcoming process. By introducing an inspection, additional information about the status of the core could be used to suppress the effects of the uncertainty in materials recovered and stochastic routings and variable processing times in later phases. The variability cannot be reduced per se, but the information could help to balance production on aggregated level. This could be done by the division of cores into different categories based on its quality and when there is available production capacity, remanufacture “hard” or time-consuming cores, and when capacity is scarce, remanufacture “easy” cores. A classification could be based on two initial determinants; the appurtenant engine family, as such divided into the three different cylinder sizes, and the quality of the core, as such affected by the two factors of how much material that are estimated to be recovered and processing time needed for the core.

The absence of a well-functioning reverse logistic network has a negative effect on total lead-time for the project. No inherent characteristic hinders the implementation of a JIT-principle as such; the low delivery frequency is motivated by the need to fill up a complete truck, even if quantity of cores available to be delivered might be determined by the inherent characteristic timing and quantity of returns. Other logistical solutions should be investigated.

5.2 Disassembly

The current disassembly flow is based on parallel workstations where engines are disassembled and parts sorted in different material holders that are separated in to different material flows. Instead of separating the parts from the core an alternative situation would be to have parts from the same engine stored together on a material carrier. The employment of such a carrier poses a number of advantages:

- Reduces the need for sorting and handling in the disassembly operation.
- Reduces setup times to almost nothing because of reduction in material carriers needed.
- Solves the problems with material matching restrictions.
A disadvantage (not necessarily; see reasoning in reprocessing section) of parts kept together might be the potential generation of an excessive lead-time. This problem emerges if the carrier is visiting all operations sequentially instead of the current parallel approach, see Figure 12. The upper figure represents lead-time when parts are reprocessed and cleaned in a parallel manner and the lower figure illustrates what happens to the lead-time if they would be processed one by one.

The earlier analysis shows that the variability in cycle times in the disassembly operation is great. The main reason for this is the insecurities in the quality of the core. The main hindering characteristic of Lean production is still the existence of variable processing time that reduces the possibility for a flow based on a *takt time* because the major risk for balancing losses. Although, the possibility for a *levelled workload* is not excluded due to the possibility of sorting cores into quality categories. The potential use of a *one-piece flow* is greatly improved with a material carrier since it *eliminates the setup time* of boxes employed in the current flow.

### 5.3 Cleaning

According to management, new technology in cleaning operations is available on the market. The investment of a Computerised Numerical Control (CNC) wet blaster would replace the cleaning operations of the washing machine and the blaster machine, whilst performing these in one and same operation. The wet blaster would primarily be utilized for cylinder heads and blocks. By programming the machine it would enable an equal cycle time for the product groups. For the cylinder head, total operation time would actually be increased by 14 % and in the case of the blocks it would remain about the same. The main profit would instead be gained in the merge of the two operations and the extermination of up to three days of waiting for the cores to dry, the transportation in between stations.
as well as the materials handling, where in the case of cylinder heads the cores are being totally manually cleaned, would be reduced. The wet blaster would be automated, which would enable a one-piece flow since the parts would enter it one by one and automatically be pushed through the machine. Even though the soak procedure still has to be performed it is possible to employ a one-piece flow since the procedure takes place in vats, and the cores can be immersed and collected without interrupting the procedure. Even though a flow based on a takt time still is constrained by soaking procedure, which is caused by the inherent characteristic of stochastic routings and variable processing times due to the quality of the core, the procedure could be balanced. That would mean different soaking times for different quality of cores balanced by the operator – enabled by inspection in the previous phase. The consequence is the cores’ order in the flow might overlap each other and change. The reduction of WIP will reduce the lead-time, which in turn is important to enable a customer pull.

5.4 Reprocessing
Transportation and economic order quantities are the hindrance of realising a one-piece flow in the current state. The use of material carriers, implementation of order splitting and re-location of workstations could to some extent solve these problems. If the reprocessing workstations would be located together with common input and output points, the need for transport between workstations is reduced, see Figure 13. Such a layout enables the possibility to send four different parts in a parallel manner to the workstations. First, the material carrier is transferred from the disassembly area to the input point of the two first operations. After offloading the parts to be reprocessed in the initial operations, the material carrier is moved to the common output point of the first two workstations, which is also the input point of the third and fourth workstation. The reduced need for transportation and decreased transportation batches would enable a one-piece flow that in turn would reduce the high WIP-levels of the current state and thereby reduce lead-time, which in turn enables a customer pull. Economic order quantities are still limited by the existing setup times, although this hindrance is not exclusive for the remanufacturing environment.

Figure 13: A theoretical solution on how to create a parallel flow of four products using a one-piece flow with a single material carrier.
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 could balance this waste but the possibility to introduce *takt time* is still constrained. But the main impact for the processes is variations in the material recovery rate that results in loss of parts to be reproduced, 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 value adding tasks when waiting time arise, e.g. perform setups when switching between orders. Another alternative is to reprocess cannibalised parts left over from previous cores.

### 5.5 Reassembly and testing

The characteristic uncertainty in recovered materials results in an *unstable production process* regarding the possibility to reassemble the engine in a given time and might cause waiting. 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 and that lead-time for purchased parts are sometimes extending the freeze window and thereby hinder a Just-in-Time material flow. No characteristic of remanufacturing was found in the testing phase. But in the Volvo case, the testing are has to be re-located in order to enable the utilization of a material carrier in respect to an economic order quantity. Beside the effects of the non-eradicable characteristic uncertainty in recovered materials it is possible to implement all the methods of a Lean production material flow in these phases.
6 Eight propositions of Lean Remanufacturing

The purpose of the thesis is to explore what characteristics of remanufacturing that hinder implementation of Lean principles and which Lean principles that can be employed and this final chapter will present the conclusions made in prior chapters. In addition, the aim of the thesis is to generate generic propositions of remanufacturing and Lean production, why the passage also introduces eight generic propositions about hindrances and possibilities to implement Lean production in a remanufacturing environment.

In the pre-disassembly phase, the absence of a well-functioning reverse logistic network and the problems of timing and quantity of returns, hinder the implementation of the Lean principle Just-In-Time in the current material flow. The effects of the characteristic of a reversed logistic network could to some extent be eliminated by a logistical solution. The pre-disassembly phase is also a crucial determinant for forthcoming phases and additional information about the quality of the cores is required to be able to control the forthcoming remanufacturing process. As a conclusion, the following propositions are given:

Proposition 1: Due to the inherent characteristic of the unpredictability in timing and quantity of returns and the difficulties to balance returns with demand, implementation of the Lean principle of Just-In-Time delivery is constrained.

Proposition 2: Detailed inspection and sorting of cores into 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 of the Lean principle a levelled workload.

In the disassembly phase, the variability of processing times are due to the quality of the core; this determinant being an inherent characteristic of remanufacturing that cannot be eliminated, although its effect on the workload partly can be alleviated by the division into quality categories. The introduction of a material carrier solves the characteristic of material matching restrictions and enables a one-piece flow. The uncertainty of materials recovered, first present in this phase of the remanufacturing process, does not impact this but sequent phases.

Proposition 3: Due to the inherent characteristic of variability of processing times, a stable production process and implementation of the Lean principles takt time and a levelled workload are constrained.
Proposition 4: The introduction of a material carrier that keeps the disassembled core together enables the implementation of the Lean principle one-piece flow in this and forthcoming phases.

In the cleaning phase, due to the quality of the cores is the processing time highly variable and stochastic routing might occur. This is an inherent characteristic of remanufacturing that is ineluctable although it some extent can be balanced by workers and division into quality categories. In the Volvo case the introduction of new cleaning technology enables the introduction of a one-piece flow.

Proposition 5: Due to the inherent characteristic of stochastic routings and variable processing times, a stable production process and implementation of a levelled workload and takt time are constrained.

In the reprocessing phase, highly variable processing times and stochastic routings imply major 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 cannot be obviated, although division of cores into quality categories can partly mitigate the former. By using order splitting techniques the possibility to use a one-piece flow remains.

Proposition 6: Due to the inherent characteristics of stochastic routings and variable processing times and uncertainty in materials recovered, a stable production process and implementation of a levelled workload and takt time are constrained. The major effect is constituted by the characteristic of uncertainty in materials recovered due the risk of a complete loss of parts to reprocess.

In the reassembly phase, the uncertainty of materials recovered might cause a stop in the processing of the parts to be reassembled, which might occur if the MRR is wrongly calculated. These engines to be reassembled will not enter the flow and therefore it has no impact on the flow as such. In the testing phase there is no characteristic of remanufacturing present to hinder implementation of Lean principles.

Proposition 7: In the reassembly phase the uncertainty in materials recovered can result in an unstable production process regarding the possibility to reassemble engines in a given time.

Proposition 8: Given an accurate supply of parts for reassembly, all principles of Lean production can be fully implemented in the phases of reassembly and testing.

To enable the implementation of a customer pull, lead-times between disassembly and reassembly has to be reduced. A one-piece flow enabled by a material carrier aims to reduce Work-in-Process and waiting thereby, as a result, decreasing lead-time.
The main conclusions that can be drawn from these propositions are that the inherent characteristics of variable processing times and uncertainty in materials recovered have the major negative impact for implementing Lean production principles. Vice versa, given an accurate supply of parts for reassembly, all the principles of a lean production material flow can be fully implemented in the phases of reassembly and testing.

6.1 Future Research

In this thesis, a number of propositions have been generated. For further validation of these propositions, an idea for further research would be to conduct similar case studies in other remanufacturing companies. Another interesting point in this study is the importance of assessing the quality levels of a core in as a detailed way as possible. An idea for further research is to investigate what possibilities there are to assess the quality of incoming cores both in an organisational and in a technological perspective.
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Appendix

1 Derivation of the economic order quantity
2 Calculation of economic order quantities
3 Estimation of lead times
4 Effects on takt time in a flow with variable cycle times
5 Value Stream Mapping Data
6 Interview guide
1 Derivation of the economic order quantity

TAC = Total Annual Cost (total cost per unit time)
A = Annual demand (number of components per unit time)
Q = Order quantity (number of units in order)
$C_p$ = Cost of order preparation ($ per order)
$C_H$ = Inventory carrying cost rate ($ per component per unit time)

In calculating TAC, the formula $TAC = \frac{A}{Q} C_P + \frac{Q}{2} C_H$ is used, where the first term represents the annual ordering costs and the second term represents annual inventory carrying costs. When it comes to calculating the optimal order quantity (EOQ), the TAC formula is derived with respect to the decision variable Q. It is then solved by setting the resulting equation equal to zero. (Vollmann et al., 2004).

$$\frac{dTAC}{dQ} = -C_P \frac{A}{Q^2} + \frac{C_H}{2}$$

$$-C_P \frac{A}{Q^2} + \frac{C_H}{2} = 0$$

$$Q^2 = \frac{2C_P A}{C_H}$$

$$EOQ = \sqrt{\frac{2C_P A}{C_H}}$$

![Figure A: Cost versus Order Quantity (Vollmann et al., 2004).](image-url)
2 Calculation of economic order quantities

For determining the worst case scenario for an economic order quantity the reprocessing operation with the longest setup time has been analysed. In this process, there are about 20 different version, each with different annual demand and different inventory carrying cost rates. Due to confidentiality reasons these numbers cannot be presented in detail here although the method of calculating can.

The formula used for calculating the economic order quantity in the reprocessing operation follows the following logic:

$$EOQ_r = \sqrt{\frac{2CP_r\gamma}{C_{Hr}(\gamma / \lambda) + C_{Hs}}}$$

Where:

- $C_{Pr}$ = Fixed remanufacturing cost
- $C_{Hr}$ = Holding cost rate for remanufactured products
- $C_{Hs}$ = Holding cost rate for operatives
- $\lambda$ = Demand rate
- $\gamma$ = Return rate

In the case when calculating the $\gamma / \lambda$ rate the one for one (1:1) principles gives that demand and return are equal, hence $\gamma / \lambda = 1$

When calculating the holding cost rate, the inventory rates for holding operatives and reprocessed parts a set to 16%. This value is given by management. The fixed remanufacturing cost is set for the hard cases to 1 hour of working time, and in normal cases to 20 minutes of working time.

The result was the following

**Large setup costs**

$$EOQ_r = 14$$

**Average setup costs**

$$EOQ_r = 8$$
3 Estimation of lead times

The lead times between disassembly and reassembly can be calculated as follows:

\[
\text{Lead time} = \frac{\text{Net production output}}{\text{Work - In - Process}}
\]

Due to confidentiality reasons, these numbers cannot be presented in detail.

Results

<table>
<thead>
<tr>
<th>Component</th>
<th>Lead time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder head</td>
<td>&gt; 8 days</td>
</tr>
<tr>
<td>Engine blocks</td>
<td>&gt; 8 days</td>
</tr>
<tr>
<td>Camshaft</td>
<td>&gt; 8 days</td>
</tr>
<tr>
<td>Connecting rod</td>
<td>&gt; 8 days</td>
</tr>
<tr>
<td>Crankshaft</td>
<td>&gt; 8 days</td>
</tr>
</tbody>
</table>
4 Effects on takt time in a flow with variable cycle times

In this example, a simulation is made about the effects of variable cycle times when using a takt time. When using a takt time in the flow it is set according to the customer demands for products. In an optimal solution, the cycle time would be the same as the takt time. The effect of a variable cycle time - for example in the disassembly operation - will introduce the waste of waiting as well as a lack of capacity in some situations.

![Diagram showing cycle time in relation to takt time](image-url)
5 Value Stream Mapping Data – Cylinder Head

Cycle Times

Setup-Times

Work-In-Process

Operations

Minutes

Operations

Number

Products in queues or operations
5 Value Stream Mapping Data – Camshaft

Cycle Times

Setup-times

Work-In-Process
5 Value Stream Mapping Data – Connecting Rod

Cycle Times

Operations

Setup-Times

Operations

Work-In-Process

Operations
5 Value Stream Mapping Data – Crankshaft

### Cycle times

<table>
<thead>
<tr>
<th>Operations</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembly</td>
<td></td>
</tr>
<tr>
<td>Washing</td>
<td></td>
</tr>
<tr>
<td>Grinding</td>
<td></td>
</tr>
<tr>
<td>Polishing</td>
<td></td>
</tr>
<tr>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
</tr>
<tr>
<td>Reassembly</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td></td>
</tr>
</tbody>
</table>

### Setup times

<table>
<thead>
<tr>
<th>Operations</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembly</td>
<td></td>
</tr>
<tr>
<td>Washing</td>
<td></td>
</tr>
<tr>
<td>Grinding</td>
<td></td>
</tr>
<tr>
<td>Polishing</td>
<td></td>
</tr>
<tr>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
</tr>
<tr>
<td>Reassembly</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td></td>
</tr>
</tbody>
</table>

### Work-In-Process

<table>
<thead>
<tr>
<th>Operations</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembly</td>
<td></td>
</tr>
<tr>
<td>Washing</td>
<td></td>
</tr>
<tr>
<td>Grinding</td>
<td></td>
</tr>
<tr>
<td>Polishing</td>
<td></td>
</tr>
<tr>
<td>Inspection</td>
<td></td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
</tr>
<tr>
<td>Reassembly</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td></td>
</tr>
<tr>
<td>waiting for delivery</td>
<td></td>
</tr>
</tbody>
</table>
5 Value Stream Mapping Data – Overall Inventory

Overall Inventory

Number

Cylinder head
Engine blocks
Camshaft
Connecting rod
Crankshaft

Product groups

Total
Disassembled parts
Reprocessed parts
New parts
6 Interview guide

Interview guide

Interviews with production planner and management. The same interview guide was used for the two initial interviews with the production planner and management. The third, complementary, interview was built upon the two first questions of “Planning process”, initially asked during the first interview.

General questions

- How are the production process and its material flow organized?

Production process

- What are the effects of scrapped materials?

Planning process

- How is the planning process organized?
- What materials are produced by confirmed customer orders?
- Can parts be purchased within the freeze window?

Interview schedule

Interview with operators.

Operation

- What activities are performed at this workstation?

Cycle time

- What is the minimum time required to perform this operation?
- What is the maximum time required to perform this operation?
- What is the average time required to perform this operation?
- What is the reason for the variation?

Setup time

- What is the setup time required to perform this operation?
- Is there a variation of setup time required to perform the operation?
Operation

-What problems are present in this operation?
-Why do they arise?
-Wherefrom could they be derived?
-What possible solutions are there?
-Are you scrapping any parts in this phase?
-What are the effects of scrapped materials?

The first initial phase of the VSM-study was a walk through the flow. Several ad hoc questions regard specific functions of the flow were generated during the walk. They contributed to the general understanding of the process but are too specific to account for.