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TOWARD LEAN REMANUFACTURING

CHALLENGES AND IMPROVEMENTS IN MATERIAL AND INFORMATION FLOWS

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ABSTRACT

Remanufacturing is an environmentally sound material recovery option which is essential to compete for sustainable manufacturing. The aim with remanufacturing at a majority of companies is to prolong physical product performance by delivering the same or better-than-original product quality. In general, remanufacturing is an industrial process that brings used products back to useful life by requiring less effort than is demanded by the initial production process. Consequently, from a product life-cycle perspective, remanufacturing generates great product value.

Remanufacturers lag behind manufacturers since they often face complex and unpredictable material and information flows. Based on a review of remanufacturing research, remanufacturing challenges in material and information flows can be classified into three groups: insufficient product quality, long and unstable process lead times, and an unpredictable level of inventory. While some remanufacturing researchers state that manufacturing and remanufacturing are significantly different, they have more in common than many other processes operations. Therefore, to sustain competitive remanufacturing, companies investigate an opportunity for improvement through the employment of lean production that generates significant benefits for manufacturers.

In order to investigate the potential to address remanufacturing challenges by lean production, a Minimum time for material and information flow analysis (MiniMifa) method was developed. This method originates from the value stream mapping (VSM) method, broadly practiced to bring lean to manufacturing companies. The focus of MiniMifa was to collect empirical data on the identified groups of remanufacturing challenges from the remanufacturing perspective, and to provide a basis for the development of improvements originating from lean principles.

Lean production was selected for this research due to its system perspective on material and information flows. Among the defined lean principles in remanufacturing, a pull principle was investigated at the case companies. The suggested principle demonstrated a reduction in lead time, followed by improvements in inventory level and product quality. However, in order to become lean, remanufacturers have to overcome three levels of lean remanufacturing challenges: external and internal challenges as well as lean wastes.

Finally, this research reduces the gap between academia and industry by contributing with a possible solution to the identified remanufacturing challenges in material and information flows.

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Jelena Kurilova-Palisaitiene

Linköping, June 2015

APPENDED PAPERS

The following papers are the main publications during the research presented in this licentiate thesis, as well as those with the greatest novelty.

PAPER I Kurilova-Palisaitiene J. and Sundin E. Minimum Time for Material and Information Flows Analysis at a Forklift Truck Remanufacturer. Proceedings of Sixth Swedish Production Symposium (SPS14). Göteborg, Sweden. September 16-18; 2014.

PAPER II Kurilova-Palisaitiene J. and Sundin E. Toward Pull Remanufacturing: a Case Study on Material and Information Flow Uncertainties at a German Engine Remanufacturer, 12th Global Conference on Sustainable Manufacturing – Emerging Potentials, Procedia CIRP, vol. 26; 2015, p. 270-275.

PAPER III Kurilova-Palisaitiene J. and Sundin E. Challenges and Opportunities of Lean Remanufacturing. International Journal of Automation Technology; vol.8 (5); 2014, p. 644-652.

OTHER PUBLICATIONS

Kurilova-Palisaitiene J. and Sundin E. Remanufacturing: Challenges and Opportunities to be Lean. In proceedings for the 8th International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2013), Jeju Island, South Korea; December 4-6, 2013.

Kurilova-Palisaitiene J., Lindkvist L. and Sundin E. Towards facilitating circular product life-cycle information flow via remanufacturing. In proceedings for the 22nd CIRP conference on Life Cycle Engineering, Sydney, Australia; April 7-9, 2015.

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ABBREVIATIONS

BOM	Bill of material
MiniMifa	Minimum time for material and information flows analysis
OEM	Original Equipment Manufacturer
PSS	Product Service Systems
SWOT	Strength, weakness, opportunity and threat
TPS	Toyota production system
VSM	Value stream mapping
WIP	Work-in-progress

1. INTRODUCTION

This chapter introduces remanufacturing as a sustainable material recovery option emphasizing its challenges and potential improvements through lean production. The objective and research questions are specified here as well. A presentation of the delimitations for the research performed finalizes this introduction chapter.

1.1 IMPORTANCE OF MATERIAL RECOVERY VIA REMANUFACTURING

Material recovery is essential to compete for sustainable manufacturing that implies optimal resource efficiency and minimum waste together with a life-cycle perspective and material development (Production, 2030). The rapid increase in global demand for raw material is a challenge to the traditional manufacturing industry. In addition, green regulations and raw material price growth are pushing developed countries to look for more sustainable and resource-efficient raw material extraction/collection options (Umeda et al., 2012; Sundin, 2011).

In Figure 1, four alternatives to material extraction/collection options are aligned in the end-of-life product hierarchy, ranging from least to most preferable from a resource efficiency perspective. At the top position is reuse option providing little or no resources added to recover a used product for subsequent use. Recycling is in the middle of the end-of-life product hierarchy, since this is a sustainable material recovery option that closes the material loop. However the least preferable option is recovery in energy since it provokes an employment of a great amount of resources needed to produce a new product to compensate the lost one.

Figure 1: End-of-life product hierarchy (adapted from Sundin and Lee, 2011)

Remanufacturing, placed above the recycling option, is an industrial process where the core (used and worn-out product or its spare part) is returned to a remanufacturing facility to be inspected, classified, reassembled, cleaned, repaired, assembled again, painted, and finally tested (Sundin and Bras, 2005; Steinhilper, 1998). Remanufacturing is established in different industries, such as heavy vehicles, automobiles, industrial machines and tools, electronics and IT, furniture and consumer goods to a limited extent. Hence, while companies perform remanufacturing for many economic, environmental and/or social reasons, the aim with remanufacturing is to deliver the same or better than original product quality and prolong physical product performance (Östlin et al., 2008;

Steinhilper, 1998). Simultaneous remanufacturing contributes to the dramatic savings in raw material, energy and water resources in comparison with new product manufacturing (Sundin and Lee, 2011).

1.2 CHALLENGES IN MATERIAL AND INFORMATION FLOWS

Figure 2 depicts the role of remanufacturing in a product life-cycle by focusing on material and information flows between stakeholders, i.e. product development, resource provision, manufacturing, use/service and end-of-life via reuse, remanufacturing and recycling. Along with reuse and material recycling, remanufacturing represents a sustainable product end-of-life alternative that in Figure 2 is represented by a reverse material flow arrow.

Figure 2: Product life-cycle (adapted from Lindkvist, L. and Sundin, E., 2013)

1.2.1 FORWARD MATERIAL FLOW

As a part of forward material flow, raw material extraction and processing are initiated by the resource provision stakeholder, and result in product part deliveries to the manufacturing stakeholder. Here, manufacturing operations convert the received parts into finished products, which are ready to be used. During the use phase, possible service activities are performed as well. When the product performance does not satisfy users' needs or the product is no longer in use due to other reasons, the used products appear with the end-of-life stakeholders (Lindkvist and Sundin, 2013). This is also the beginning for a reverse material flow.

1.2.2 REVERSE MATERIAL FLOW

Three preferable recovery options are linked to three stakeholders in the product life-cycle. The reuse option directly brings used products back to users for repetitive use. Remanufacturing usually brings cores back to the manufacturing stakeholder for industrial processing in order to deliver "as good as new" product appearance and functionality. Material recycling, in turn, brings the used product part to the material level, indicating a new start for any, but not necessarily the same as an initial, product life-cycle (Ellen McArthur Foundation, 2013).

1.2.3 FORWARD INFORMATION FLOW

In Figure 2, information flows are established in the product life-cycle and are marked with a red dotted line. While the product development stakeholder determines the product's properties and functionality, the users' data is vital to product developers (Ulrich and Eppinger, 2000). The information that is fed forward to the product life-cycle is known as feed-forward data. An example of feed-forward information might be assembly and disassembly instructions, a bill of material (BOM) from product development to manufacturing and service stakeholders, or condition monitoring data from service/users to remanufacturing (Lindkvist et al., 2013).

1.2.4 REVERSE INFORMATION FLOW

Information flow that goes toward the product life-cycle stakeholders in the beginning of the product life-cycle, like in product development and manufacturing, is called feedback information. Feedback information can facilitate efficient product design, effective manufacturing, service, and disassembly operations; however, few products today are designed for remanufacturing (Sundin and Lindahl, 2008; Hatcher et al., 2011). Few examples of feedback information flow are distinct from users and service, and most often are from manufacturing stakeholders back to product development. Manufacturing specifications data are transferred back to product development in order to design products suitable for manufacturing (see also Lindkvist et al., 2013).

1.3 CHALLENGES IN REMANUFACTURING

Today, remanufacturing faces challenges, mainly related to the lack/limited material and information flows from upstream product life-cycle stakeholders, specifically product development, manufacturing, customers, or user and service (Steihilper, 1998; Sundin, 2006; Lundmark et al., 2009). The remanufacturing challenges are caused by complexity in managing material flows (Steinhilper, 1998; Guide, 2000; Sundin et al. 2008) and information flows (Guide, 2000; Ferrer and Whybark, 2000; Lundmark et al., 2009; Golinska and Kawa, 2011).

The remanufacturing process is much more unstable and unpredictable in terms of the timing, quantity and quality of incoming cores (Guide, 2000; Steihilper, 1998) than the manufacturing process itself. This creates challenges in remanufacturing operations resulting in longer lead times. Additionally, a specific characteristic of remanufacturing is a very low level of automation due to small batch sizes and a high level of incoming core variety. Planning activities are difficult due to very little information coming from the use phase. Moreover, the remanufacturing process is not standard for the same type of item, due to a high difference in core quality. For example, it is typical for a machine remanufacturing facility to perform remanufacturing operations on 40-150 items per year, while serial production is accounted for in thousands by the Original Equipment Manufacturer's (OEM) same or similar machines. Therefore, internal operational and organisational issues related to remanufactured product quality, process lead time and

level of inventory must be managed (Seitz and Peattie, 2004). To address remanufacturing challenges, material and information flows via remanufacturing need to be analyzed.

1.4 LEAN IN REMANUFACTURING

The remanufacturing researchers emphasize that stable demand and supply are key success factors in the application of lean. Due to major remanufacturing challenges in material and information flows, some researchers have expressed concerns about the suitability of lean for remanufacturing (Seitz and Peattie, 2004; Pawlik et al., 2013).

Nevertheless, to address process instability and unpredictability remanufacturers must investigate opportunities to apply lean production. Moreover, the potential for applying lean to remanufacturing has been noted by several researchers (Jacobs and Chase, 2001; Fargher, 2006). Sundin (2006) identified a need for remanufacturing to gain efficiency through several lean production concepts, such as lowering the high level of inventories, material movements, product flow and use of space. Later, Östlin and Ekholm (2007) provided practical evidence on the benefits of lean production in remanufacturing. Remanufacturing covers part of manufacturing activities and lean production holds possible solutions to the remanufacturing challenges. Therefore, applying lean production to remanufacturing is logical step. It is critical to investigate how the application of lean to remanufacturing would address remanufacturing challenges of material and information flows, and consequently facilitate sustainable and resource-efficient remanufacturing processes.

1.5 OBJECTIVE

The objective of this licentiate thesis is to examine remanufacturing challenges in material and information flows, and to study how these challenges can be addressed by lean production.

1.6 RESEARCH QUESTIONS

To be able to fulfil the objective of this thesis the following research questions (RQs) will be answered:

RQ1: How can material and information flows be mapped and visualized at remanufacturing companies?

RQ2: What are the challenges in material and information flows at remanufacturing companies?

RQ3: How can the identified challenges be addressed by lean production?

1.7 DELIMITATIONS

This licentiate thesis covers a study on remanufacturing challenges in material and information flows. The scope of material and information flows is restricted to the

remanufacturing company's boundaries, however including receiving and sending out material and information beyond the factory's limits. A generic model of material and information flows within the product life-cycle is not a focus of this licentiate thesis. The scope of this study is further limited to the challenges regarding product quality, process lead time and inventory level in remanufacturing.

Lean production is approached via looking at lean gap in remanufacturing. Lean production is employed as a concept to address remanufacturing challenges covering five lean principles: value, value stream, flow, pull and perfection (see Section 2.2.1 for further description), and thus in-depth discussions on lean tools and practices are avoided. The delimitation of lean production to lean principles is based on the research need to investigate the basics for lean suitability to remanufacturing. Moreover lean tools and practices attribute to the lean principles and might be involved in the following research in lean remanufacturing.

2 THEORETICAL BACKGROUND

This chapter satisfies the need for a theoretical foundation for this licentiate thesis. Three parts are distinct here: remanufacturing, Toyota Production System (TPS) or lean, and flow mapping and analysis methods. This chapter defines the starting point of this licentiate research, while providing the researcher's perception of the research questions and related research areas.

2.1 REMANUFACTURING

Remanufacturing is one of the most effective ways of managing a product's end-of-life (Ke et al., 2011; Steinhilper 1998). It brings used products that are typically treated as waste back to useful life with little effort, and consequently closes the product life-cycle into a sustainable loop (Steinhilper, 1998; Östlin et al., 2009). Remanufacturing is an industrial process and often consists of several steps, e.g., inspection, cleaning, disassembly, testing, reprocessing and reassembly (see Figure 3) (Sundin, 2004).

Figure 3: Generic remanufacturing process steps (Sundin, 2004).

Companies perform remanufacturing due to many economic, environmental and/or social reasons (Östlin et al., 2008). From an environmental perspective, remanufacturing has been found preferable in comparison with manufacturing and material recycling, mainly from a material recovery perspective; closing the loops of hazardous materials makes remanufacturing especially desirable (Sundin and Lee, 2011). Moreover, the recent social trend towards green and sustainable product solutions, dictated by price-sensitive and environmentally-aware customers, contributes to the development of the remanufacturing industry worldwide.

Today, remanufacturing is an attractive business niche with little raw material acquisition costs, which has turned many OEM and other independent actors into remanufacturers. There are three different categories of remanufacturers: OEMs that remanufacture, contracted remanufacturers, and independent remanufacturers (Östlin et al., 2008). OEMs that remanufacture are in control of both product development and product recovery, while a contracted remanufacturer has limited access to the OEM expertise, and an independent remanufacturer is an OEM competitor (Ramani et al., 2010).

According to remanufacturing researchers, remanufacturing companies are challenged by insufficient product quality, long and unpredictable process lead times, and an unpredictable level of inventory (Hammond et al., 1996; Guide, 2000; Lundmark et al.,

2009; Van Nunen and Zuidwijk, 2004; Sundin, 2006). The reasons for this emerge from the major remanufacturing constraints, such as the uncertainty and complexity of information and material flows.

Remanufacturing companies operate in an end-of-life environment, and usually depend on other product life-cycle stakeholders such as product developers, OEMs and users/service (see Figure 2). The insufficient information flow within the product life-cycle and poor cooperation hinders closing the product life-cycle loop via remanufacturing (Steinhilper, 1998; Östlin et al., 2009).

2.2 TOYOTA PRODUCTION SYSTEM / LEAN

Industrial awareness of the lean philosophy increased remarkably when Toyota's Production System (TPS) followers dramatically improved their performance indicators and moved up to the top of the productivity/turnover ranking list (Fullerton et al., 2003; Krafcik, 1988; Womack and Jones, 1996; Holweg, 2006). Since then, lean, originating from Japanese car manufacturer Toyota's Production System, has become a well-known enterprise management phenomenon (Womack and Jones, 1996). Pettersen (2009) stated that lean implies continuous improvement through elimination of unnecessary activities and creation of value for the customer. The value is emphasized by the lean initiative of doing more with less time, less human effort, less machinery, and less material, and at the same time delivering the products customers demand (Pascal, 2002). Bicheno (2004) pointed out that lean is about making only what is required by the next process. Consequently, lean is a system where all parts are highly integrated and all team members share a clear vision in their way of seeking improvement (Pascal 2002).

2.2.1 LEAN PRINCIPLES

Womack and Jones (1996) reinforced lean concept through **5 lean principles** of specified **value**, **value streaming**, continuous **flow**, a **pull** or pulled ordering system, and pursued **perfection**.

VALUE

Value is defined by the customer. According to Ohno, value is some kind of processing that the customer is eager to pay for (Ohno, 1988). Consequently, only value-added work matters, and therefore any non-value added activities are treated as waste that has to be eliminated. Value generation in each process step and by all process stakeholders is a aim of both TPS and lean. Lean deals with the main production system inhibitors of waste, inflexibility and variability, and specifies value by separating it from waste. Pascal (2002) claims that waste elimination is one of the most effective ways to increase profitability. To understand the groups of typical waste, the seven wastes concept was developed by Taiichi Ohno for the Toyota Production System: motion, waiting, conveyance/transporting, correction/rework, overprocessing, overproduction and inventory. The most dangerous source of waste is inventory, especially work-in-progress inventory (WIP), since it hides problems (Ohno, 1988; Ahlstrom, 1997). Inflexibility is

an inability to effectively respond to changes in the current system, resulting in the additional costs incurred by not giving the customer exactly what they want: product or product mix, volume, or delivery. Variability is process instability through deviation from standard material, information, people, process, and environment.

VALUE STREAMING

As a set of actions are needed to produce a product, the value stream becomes a base for waste separation from the value-added activities. Value streaming denotes a step-by-step description of a production process where all tasks, material and information are inspected to define their contribution to value generation. Womack and Jones (2007) provoke stream thinking by requesting one stop looking at comprehensive activities and isolated machines; instead, these authors recommend focusing on the specific actions required to produce specific products.

FLOW

Value flow links the processes in chains of process-oriented activities to facilitate the critical product path (Parry and Turner, 2006). Creating continuous process flow is essential to bringing problems to the surface. The continuous flow of products and spare parts tends to eliminate stagnation. To achieve continuous flow, lean companies employ a system of triggers and control mechanisms that, for example, eliminate unnecessary material transportation and storage between sequential process steps (Ohno, 1988). The efficient flow is possible with smart production steps regarding the place, quantity, and time of production. Flow is a key attribute of stream thinking. Material and information flows are the key flows to follow the raw material pathway towards finished products (Jones and Womack, 2003).

PULL

Pull enables a needed production pace and reflects real customer demand. Krafcik (1988) states that lean is most conducive to improved productivity and quality performance; additionally, lean appears to provide a tighter control on inventory than can be attained via computer-based approaches (Schonberger, 1982). According to Liker (2004), pull refers to a system that triggers the production process to refill what has been taken to fulfil customer demand. The actual demand is linked to production pace and is enabled by a trigger that sends a signal to the upstream process. In this way, the downstream process pulls products from upstream, creating a linked product chain. The pull ordering mechanism is aimed at delivering on-time and to fulfilling customer demand, with a main focus on keeping the right product quality while maintaining short lead times and an optimal level of inventory. These three lean control functions, as they are defined by Hunter and Black, are also in the scope of this research and can be specified as:

- Three key aspects of lean product quality: on time, in the right quantity and right quality products, delivered to the customer

- Production time is a lead time from the point when raw material reached the factory until the finished product leaves the factory
- Inventory level is a level of inventory that can be stored as a raw material, but not finished products, called work-in-process (WIP) inventory and finished goods.

PERFECTION

Seeking perfection is a vital aspect of lean. Ahlstrom (1997) wrote about perfection as a superior quality and doing things right the first time. Perfection is a goal of lean and consists of reaching for the best quality, lowest costs, shortest lead times, highest safety and highest morale.

2.3 FLOW MAPPING AND ANALYSIS METHODS

2.3.1 PROCESS MAPPING

According to Hellström and Eriksson (2008), “by identifying and mapping the processes, architecture is developed as a means of understanding the organisation and improvement opportunities are identified.” Hines and Rich (1997) have developed a decision-making process to help choose between seven different process mapping tools:

- process activity mapping, well established in industrial engineering research
- supply chain response matrix, practiced in the area of logistics
- production variety funnel for operations management
- demand amplification mapping in a systems dynamics area
- decision point analysis originating from efficient consumer response area
- physical structure mapping
- quality filter mapping

2.3.2 FOLLOWING THE FLOW

Latour (1987), Marcus (1998) and Green (1999) agree that in order to identify connection of the sites to define the network it is suitable to follow objects, people or stories. Following material and information flows dictates the way the research is performed. Flow mapping techniques imply following the virtual flows of participants who are involved in everyday activities related to these flows. Physically, participants stay in one place and develop holistic knowledge about the processes on a piece of paper. This is similar to “spatial drawing”, described by Burrell (2009).

According to Appadurai (1986), following the object across sites allowed the author to gain access to those spaces and connections between things and human, where the boundaries of meaning, action and values circulate. Green (1999) elaborated on the topic of following the object, and explains that by using mapping strategy, he began to see links among people and discourses associated with objects, and began to move through network of other people, discourses and objects.

2.3.3 VALUES STREAM MAPPING (VSM)

Value stream mapping (VSM) is a recognised stream thinking method that helps to distinguish value-added and non-value added activities in the process (Jones and Womack, 2003). According to Basu (2004), a value stream map is a visual representation of all steps required to produce a product from the raw material until customer delivery. By illustrating the production process, possible areas for improvement are discovered. Therefore, while mapping the value stream Basu (2004) advises one to question every process step to discover which activities are unavoidable and which can be eliminated as waste. Bicheno (2004) stresses the importance of mapping the information flow in addition to the material flow, since smooth and efficient information supports and controls the overall production process. Additionally, Summer (2009) advises on extend the data represented in the map by including cycle and changeover times, batch sizes, number of operators, product amount, and scrap rate.

Value stream mapping can be easily done with paper and pencil. According to Rother and Shook (2003), a VSM process starts with current state process mapping (see Figure 4), followed by flow assessment with respect to the lean value stream that leads to the future-state or desired value stream development. Current state VSM describes the actual situation of the production process. Based on the improvement ideas originating from a current state map, a future state map may be developed.

In line with drawing VSM a set of symbols or icons is used (see Figure 4). The differently shaped icons and data boxes are helpful to show information regarding each process stakeholder (either internal like the company's department/division, or external such as suppliers and customers) and process step: the number of produced items, cycle time, changeover time, number of people and other typical process data. Rother and Shook (2003) advise using a "warning triangle" icon to mark the place and quantity of inventory. The bold material flow arrow in Figure 4 indicates the movement of goods between process steps or to the customer. The information flow arrow is denoted as a thin line. There is also a striped arrow to point out the push movement of the material; this push arrow usually appears between the processes in the factory.

2.3.4 VISUAL TOOLS

Warren (2002) noticed that visual tools, commonly practiced in performativity and interactive research, bring a "can-opener" effect. Bramming (2012) claims that the mechanics of performativity are less obvious and subject to different interpretations. Visual methods in organizational research are powerful vehicles of articulation. Barad (2007) and Law (2004) study the implication of performativity theory and determined that methods not only represent the object of study; they also help produce, constrain and enable their object in various ways.

Figure 4: The current state value stream map (Rother and Shook, 2003)

Harper (2002) concluded that introducing visual methods in the interview gives access to “other parts of the human consciousness”. Visual methods generate an entirely different kind of data than that resulting from interviews. The author claims that when two or more people discuss the meaning of illustration they try to figure out something together, and that this is an ideal model for research. Physical artefacts, such a map, provide a better interpretation and visualization of the discussed process, which leads to a better group understanding of the underlying issues.

3 METHODOLOGICAL APPROACH

This chapter depicts the methodological research approach used for this licentiate thesis. Here, the design of the research is outlined, referring to the time span and the level of analysis performed on the specific research activity. The main body of this chapter is dedicated to the presentation of the case study approach and data collection methods used. This chapter also encompasses a stepwise development of material and information flows mapping and analysis methods, which becomes a central part of this licentiate thesis. The issues of research validity and reliability are also discussed in the methodological approach chapter.

3.1 RESEARCH DESIGN

Similar to what is described by Dubois and Gadde (2002), the interactive research strategy of this thesis is enhanced via systematic combining, correlation and analysis of research findings from a literature study and data collected via flow mapping and analysis method at the case companies. A simplified generic research design in several phases is presented in Figure 5.

Figure 5: Research phases

To assist in targeting the research questions, a literature study on the topics of remanufacturing: challenges and opportunities to be lean was conducted. This study provided insight about the studied topic and helped to define the vital remanufacturing challenges of material and information flows, and even more detail on remanufacturing issues concerning product quality, process lead time and inventory level.

In order to further investigate the reasons behind the remanufacturing challenges and define possible lean production improvements, a material and information flows mapping and analysis method was developed and applied to two case companies. This interaction with industry is embodied in the Minimum time for material and information flow analysis method, or simply MiniMifa, developed in seven phases (for more details see Section 3.5.). The case study approach and data collection methods used to visualize and analyze remanufacturing challenges are described in Sections 3.3 and 3.4, respectively. Furthermore, the MiniMifa description together with an application to case companies is demonstrated in Sections 4.1, 4.2 and 4.3.

Material and information flows challenges collected from the literature study and the case studies are classified and analyzed. A lean gap in remanufacturing is identified. Consequently, an analysis of lean production principles to address the remanufacturing issues is performed. Finally three levels of remanufacturing challenges toward lean remanufacturing are presented.

3.2 INTERACTIVE RESEARCH

Interactive research contributes to the knowledge transfer between theory and practice, and therefore reduces the knowledge gap (Aagard-Nielsen and Svensson, 2006). This is an important motive for selecting the interactive form of research. As a part of this licentiate thesis, the interaction performed with the case companies facilitates the close integration for explicit data collection purposes, and contributes to the case companies' development by sharing the research results. The purpose of the interactive research in this licentiate thesis was to exchange knowledge with practitioners and develop a trustworthy relationship to stimulate future collaboration.

Among the broadly accepted prerequisites for interactive research in an organizational context is the researcher's presence as "being there" (Ellström et al., 1999; Bryman, 1989), or/and active participation in the organization as "being one variable, interacting with the organization or building a collaborative inquiry" (Bryman, 1989; Shadish et al., 2002; Acar Sesen and Mutlu, 2014), and systematically changing the research field by developing different applications of a studied phenomenon (Kuzu, 2009).

Interactive research provides the basis to research among the practitioners, and therefore provides access to the research question and research problem definition and perception from the practitioner's view. Being a part of the company for a limited data collection period is distinctive for this licentiate thesis. In this way, vital information from the employee's point of view is obtained during data collection sessions. This is another critical motive for selecting the interactive form of research. Moreover, in a dialogue with the practitioner the researcher could reflect the common experience. To interpret the relations between researchers and practitioners, Ellström et al. (1999), emphasize the importance of a clear division of labour between researchers and practitioners based on their different interests, responsibilities, and competencies.

3.3 CASE STUDY APPROACH

The case study is the main research strategy in this licentiate thesis, which has a rather flexible approach with regard to data collection methods. Eisenhardt (1989), Yin (1994), and Law (2004) all describe advantages of case study research, emphasizing its suitability to investigate complex research questions in a real-world context. The complexity of the research questions and a need to investigate the issues in a real context are some of the motives for selecting the case study approach. Yin (1994, 2009) emphasizes that the purpose of case study research as a method is to describe the

empirical phenomenon and/or to explain the reason, conditions, circumstances and other issues related to that phenomenon. According to the Yin (1994), case studies can generate theory from the interpretation of observations made in natural settings. Here, the researcher defines the case study as a process or means-oriented instrument to analyze why a certain phenomenon may emerge. In this licentiate thesis, the research questions *how* and *what* are answered through the case study approach.

Flyvbjerg states that the choice of method should clearly depend on the problem under study and its circumstances. In 2006, Flyvbjerg summarized some arguments for everyone making case study research. He states that predictive theories cannot be found in the study of human affairs. According to Flyvbjerg: "Concrete, context-dependent knowledge is more valuable than the vain search for predictive theories and universals." He continues, "One can often generalize on the basis of a single case,... but formal generalization is overvalued as a source of scientific development, whereas 'the force of example' is underestimated." Kuper and Kuper (1985) conclude that more discoveries have arisen from intense observations than from statistics applied to large groups.

In this licentiate thesis, the case study focuses on three issues important to remanufacturers concerning material and information flows: product quality, process lead time and inventory control. Three mentioned issues are identically studied at both case companies. Following standard case study execution procedures and applying the same data collection methods, these cases are easy to compare. Comparability of the results from the executed case studies simplifies the generation. In general, the case study explains the actual conditions of remanufacturing companies and their readiness to work according to lean. However, the research object in a case study is not a remanufacturing company or a group of people representing them in the case studies, but rather a system of information and material interaction in a remanufacturing company. The in-depth study of this research object is strengthened by using multiple sources of evidence (information sources, like employees in different positions, and information collection tools, like observations, interviews, and paper and post-it notes).

3.4 DATA COLLECTION METHODS

Data collection methods reminds one of Law's (2004) notion on method assemblage. According to this author, the world around us is not easy to understand due to the processes that we are unable to control, and therefore a method assemblage is the right way to study a complex phenomenon. The variety of data collecting methods used in this licentiate thesis leads to a greater understanding of the research questions and answers, as well as ensures data validity and reliability.

Table 1: Data collection methods (x – used for or addressed in RQs)

Research Questions	Case Study Approach				Papers		
	Literature Study	Observations	Focus Group Interviews	Workshop	x – moderate focus xx - major focus		
					1	2	3
RQ1	x				xx	x	
RQ2	x	x	x	x	x	xx	xx
RQ3	x	x	x	x	x	x	xx

3.4.1 LITERATURE STUDY

Research is the tool for theory building, and the researcher is the instrument of observation and interpretation (Andersen and Kragh, 2010). Theoretical pre-understanding is important in theory building. Campbell (1975) raises the interest of researchers to execute case study research by matching theoretical predictions about a phenomenon to the observed outcome. Eisenhardt (1989) also recommends a priori development of constructs to shape the initial design of theory-building research.

A need to balance the use of theory in new theory building is later explained by Andersen and Kragh (2010). They claim that the researcher should consciously question how and when to involve pre-existing theory in research. An in-depth study of the literature on the current knowledge in research topics satisfies the need for theoretical pre-understanding. According to Evans and Kowanko (2000), literature studies summarize past efforts in the research field. Originating from the literature study on the remanufacturing characteristics and challenges as well as opportunities to be lean, the research areas critical to remanufacturing and most interesting for remanufacturing have been selected for further in-depth investigation via case studies.

The sources of the literature review are the academic publications in databases, such as Scopus and Science Direct, using the key search words of *remanufacturing*, *refurbishment* and *reconditioning* alone and with a combination of *lean* in front of each key search word. Moreover, as recommended by peer researchers, literature and literature obtained by the author while working with lean production concept in industry are also used.

3.4.2 OBSERVATIONS

Observation can provide rich qualitative data (Geertz, 1973). An insight into the company's production processes facilitates an understanding of the company's operations practice, information exchange, people interaction channels, shop-floor layout and machinery. An observation of remanufacturing operations serves a base or standpoint for case study research. The production process observation is performed together with the production manager and takes between 30 minutes and 1 hour.

3.4.3 FOCUS GROUP INTERVIEWS

O'Donnell (1988) emphasizes the importance of discussing a particular topic with a homogeneous grouping of participants. Focus group participants must share a common denominator, such as affiliation with an organization. According to Morgan (1992), smaller focus groups were more appropriate, with topics sensible and highly important to them and which generated high levels of participant involvement.

Focus group interviews provide overall background as well as detailed information on material and information flows in a company. Bellenger et al. (2011) have identified several more uses of focus groups from a research perspective. These uses vary from information collection and hypotheses generation for further testing, to idea generation of a new and creative process or product concept.

According to Lydecker (1986), focus groups deal with complex subjects and bring out information that might be missed by a statistical study. Moreover, focus groups successfully gather in-depth information about many topics in a relatively short time. Focus groups follow a predefined pattern, however vary between groups. The flexibility of focus groups is another advantage, since participants improvise to pursue unexpected but potentially valuable topics of discussion.

Focus groups are efficient in collecting data from a number of participants simultaneously. The idea is to collect less biased information on the issues important for the participant. The results of a focus group session tend to exceed the separate interview with regard to resource efficiency and data accuracy. The collection of high-value data from focus group interviewing presents an opportunity for on-site data triangulation. Some of the biggest benefits of a focus group are noted by Barnett (1989). This researcher identified an economic and a resource-efficient approach of a focus group in terms of gathering data and providing /obtaining participant feedback.

To sum up, focus group interviews are well-suited to collecting in-depth, qualitative data about individuals' definitions of problems, opinions and meanings associated with various phenomena.

3.4.4 WORKSHOPS

A workshop is characterized as a platform for interaction between workshop participants, often under the assistance of workshop leader or mentor (Morgan, 1996). The benefit of a

workshop is the participants' perception of the workshop as teamwork in a game atmosphere which enables active participation and interaction. In its turn, the interaction between participants promotes an open discussion on difficult topics and creates an atmosphere for constructive dialogue (Basch, 1987).

3.5 MATERIAL AND INFORMATION FLOWS MAPPING AND ANALYSIS METHOD DEVELOPMENT

The material and information flows mapping and analysis method plays a central role in this research. This method originates from the value stream mapping (VSM) method presented in Section 2.3.3. Through an assemblage of the data collection methods of focus group interviews and interactive workshops supported by company observation and literature study, a suitable method was developed and applied at the case companies.

Seven material and information flows mapping and analysis method development phases are presented in Figure 6, namely development, testing, improvements, application and evaluation. The improve and apply phases tend to dominate.

Figure 6: Material and information flows analysis method development phases.

1. Develop a conceptual material and information flows analysis method based on the researcher's industrial experience, a literature study and VSM.
2. Test the method at Pilot Case Company A in the form of an interactive workshop with a focus group.
3. Improve the method by simplifying the visual tools and physical artefacts. The 15-minute time savings led to the expansion of several underdeveloped interview questions.
4. Apply the material and information flows analysis method at Case Company B to verify improvements and suitability to study complex issues in remanufacturing.
5. Improve introduction of the method to the case companies by providing them a filmed presentation prior to execution.
6. Apply the material and information flows analysis method at two additional remanufacturing companies (not a part of this licentiate thesis).
7. Evaluate the method by SWOT (strength, weakness, opportunities and threats) analysis based on feedback from industrial companies and academic parties, as well as the researcher's reflections.

3.6 VALIDITY AND RELIABILITY

According to Eisenhardt (1989), the case study focuses on the dynamics present within single settings, and employs multiple levels of analysis and multiple types of data collection methods. These multiple methods facilitate triangulation of the data and therefore contribute to strengthened hypotheses and constructs. According to Yin (1994), the need for triangulation originates from the research validation. Eisenhardt (1989) encourages not only multiple methods of data collection, but multiple investigators. She also recommends that researchers overlap data analysis and collection.

According to Merriam (1988), internal validity refers to how congruent one's findings are with reality. The question could be asked: Are we observing or measuring what we think we are observing or measuring? Reliability reflects the phenomenon's repeatability together with the result stability. The question to be answered here is: If the inquiry is replicated, would the findings be the same? External validity or generalizability in its turn covers the issues of research result generalization to a population from the case study. However, going from a sample to a population is not the goal with case study research, but rather the intention to generate in-depth knowledge about a phenomenon (Merriam, 1988).

Merriam (1988) approaches case study research internal validity, reliability and external validity (generalizability) through several strategies, some of which were used to strengthen the research performed:

- triangulation (multiple data collection method, source of information to contribute to the research validity and reliability)
- member check (assessment from company employees - participants during data collection sessions)
- peer examination (assessment from peer researchers and experts in the remanufacturing and lean areas)
- detailed description (providing the details on collected data and the detailed explanation of the performed analysis that lead to research results)

Validity is ensured by triangulation, a member check and peer examination. The need for triangulation is satisfied through the multiple data collection methods (see Table 1). Another technique to ensure internal research validity is the member check, which ensures that the data collected at the industrial case companies is properly interpreted. The findings in each case company are tested by the participants in a separate meeting after application of the material and information flows analysis method. This final data check brings additional details to already performed observations. This added discussion is necessary for data validity and reliability, and is a key step in verification of the collected facts, results and conclusion. Additionally, a peer examination technique is utilised to strengthen research findings by questioning senior colleagues and experts in the area of lean and remanufacturing.

Reliability is covered through triangulation and the member check. Case study reliability is also based on the research conduction stability, flow mapping and analysis method accuracy, and precision of evidence comparison. A pilot case study ensured that the flow mapping and analysis method is a suitable data collection method. A well-documented flow mapping and analysis method can be easily repeated following the standard procedures.

A detailed description of the data collection method, analysis and research results is suitable for ensuring generalizability, and implies providing explicit information about the phenomenon under study, which helps to determine other researchers' positions in respect to the research performed.

4 RESEARCH RESULTS

This chapter is the key part of the licentiate thesis, since it delivers answers to the three research questions. The chapter is divided into four sections: a presentation of the material and information flows analysis method (MiniMifa); the developed method application to two case companies; the analysis of remanufacturing challenges in material and information flows; and the analysis of lean production opportunities to address these challenges.

4.1 MINIMUM TIME FOR MATERIAL AND INFORMATION FLOWS ANALYSIS (MINIMIFA)

The combination of material and information challenges turns the remanufacturing process into a complex material and information flows “Labyrinth” (see Figure 7). At the same time, a complete system perspective of remanufacturing challenges and improvement opportunities is lacking, leading to a situation where improvements in one area may cause problems in another (Deming, 1994). Therefore, a method that satisfies the need for a system analysis of remanufacturing challenges in material and information flows is vital to develop a holistic solution for the remanufacturing process.

Figure 7: Material and information flows “Labyrinth” (black Labyrinth frame with fixed roots = remanufacturing facility and processes; green arrow = information flow; blue arrows = material flow; and yellow arches = “bridges” to improve connection and/or “doors” to remove barriers).

The absence of a system perspective to study complex material and information flows in remanufacturing led to the development of a flow mapping and analysis method, called Minimum time for material and information flows analysis (MiniMifa).

4.1.1 WHAT IS MINIMIFA?

Minimum time for material and information flows analysis, or MiniMifa, is a flow mapping and analysis method originating from Value Stream mapping (VSM) and based on focus group interviews and a workshop. By adopting the simplicity of VSM, MiniMifa aims to obtain an overview of the entire remanufacturing process interconnected to its suppliers, customers and other departments and to define value and non-value added activities. The main interest in MiniMifa is the movement of material (products, parts, and cores) and information (standards, training, and communication). As in VSM, the company’s operations are schematically plotted in the actual sequence to reflect the production process steps, inventory, and operators, as well as other relevant process information. With the help of VSM, companies are able to focus on the vital

process steps, optimize and simplify the operations, and reduce or eliminate activities that bring no value to customers.

Three focus areas for remanufacturing challenges and opportunities to be lean are encompassed in MiniMifa: remanufactured product quality, process lead time and inventory level. The focus areas are studied through the analysis of real-life conditions, practices and issues of material and information exchange in a remanufacturing company. Moreover, the method supports the discussion around the system of material and information interaction. The physical items, such as a large piece of paper, post-it notes, and markers are used to create the process flow map (see Figure 8).

Figure 8: MiniMifa process flow maps at the case companies (adapted from Kurilova-Palisaitiene and Sundin, 2014a, 2015)

4.1.2 MINIMIFA EXECUTION AT THE CASE COMPANIES

There are several distinct steps for performing MiniMifa:

0. Preparation step implies getting in contact with the company manager to introduce the MiniMifa method and discuss conditions several months before the method implementation (usually 2-6 months). Filmed MiniMifa presentation and digital material, including a MiniMifa questionnaire, provided to the company for better understanding of underlying issues and MiniMifa process.
1. Mapping of the process with a focus on a standard product:
 - To draw all important process steps and process actors that influence remanufacturing (OEM, customers, service, etc.)
 - To draw a material flow
 - To draw an information flow (see Figures 8 and 9)

One remanufactured product critical to the remanufacturing business is selected for study to follow the path it moves (like shadowing or following the object, and information about the object (Czarniawska, 2007) from one involved actor (department/function) to another, and from one process step to the next. In line with following the

material/product (cores and spare parts) flow, the information about that particular product's routes is studied. By following material and information flows along the remanufacturing process and beyond the factory borders, a complete picture of the remanufacturing process is constructed. Different icons and colors represent external and internal actors/process steps, inventory, operators and transport.

2. Discussing challenges (what are the constraints to increase quality, shorten lead time, and control inventory level) (see Figure 9)
3. Collecting and prioritizing improvement ideas (what are the possible ideas/solutions for the identified challenges) (see Figure 9)
4. MiniMifa analysis of the collected challenges and improvement opportunities
5. Analysis of lean production to address identified remanufacturing challenges and compare to or combine with the ones developed by the MiniMifa participants
6. MiniMifa findings presentation and data verification at the case companies (usually two months after MiniMifa execution).

Figure 9: Steps 1, 2 and 3 in MiniMifa execution at the case companies

4.1.3 MINIMIFA PARTICIPANTS

MiniMifa participants are the employees working in the different remanufacturing departments/functions. They sit around a table while their discussion is recorded. MiniMifa requires active participant interaction and discussion about the questions written on the paper and post-it notes. Here, the focus is on the remanufacturing process and thus the employees are not a subject of interest, just the process they interact with. By bringing together people from different departments, the method creates a platform to share information and solve the problems holistically. Welch (1985) found that focus groups provide a significant quantity of ideas and attitudes due to the participants' reactions to the topic discussed. This is because MiniMifa gathers the participants' experiences from real-life facts, not based on their feelings.

It is crucial to select MiniMifa participants who represent the viewpoint of the company as a whole. The group of participants belonging to the same company represents different functions or departments involved in material and information exchange. Sampling of MiniMifa participants is left to the manager of each company. The most common number of MiniMifa participants is from 5-7 people.

Usually, the participants' competences span the functions of facility manager, planner, shop-floor operator or technician, administrator, sales manager, or logistics manager. By bringing people from different departments together, MiniMifa creates an information-sharing and problem-solving platform. This combination provides a great platform for internal information exchange between different layers of employees. Moreover, MiniMifa is conducted in a comfortable and intimate environment for participants. As a rule, MiniMifa was performed in the company's meeting room. Participants occupy the round table and sit as close to each other as they feel comfortable to listen and speak.

The role of a moderator in MiniMifa is less monitoring or controlling, and more navigating the participants toward answering the predefined, focused questions. In this way, the moderator tends to be a listener rather than a speaker and the participants take a very active role in the discussion. This is an important aspect of MiniMifa. The discussion is structured upon MiniMifa standard procedures and is generated on the basis of MiniMifa questions, provided in advance. In this way, the participant action becomes much more dynamic (Morgan, 1996).

4.1.4 OUTPUT FROM MINIMIFA

The list of the collected data can be separated into four points:

1. Initial information from the production manager based on questions prior to the MiniMifa workshop (see Appendix 1)
2. Transcribed MiniMifa participant discussion based on predefined questions (see Appendix 1)
3. Remanufacturing process map with the process flow, process characteristics and all the challenges faced by remanufacturer (see Figures 10 and 13)
4. MiniMifa solution square with the proposed improvement ideas (see Figures 12 and 15)

The analysis of each case is based on the above four points. The process information and material flow are analysed in order to show the current situation, communication, information exchange, material exchange and logistics links. The challenges of the current process are documented and well-defined. The process lead time is calculated, and both value-added and non-value added activities are presented. The possible new lead time is calculated and compared to a current one. A future map is developed based on recommendation of the solution square and MiniMifa discussions.

4.2 MIMIMIFA APPLICATION TO PILOT CASE COMPANY A

Case Company A is an Original Equipment Manufacturer (OEM) remanufacturer with over 20 years of forklift truck remanufacturing experience. The main source of the returned products is forklift trucks that have been leased for 5-6 years and collected back according to the OEM rental agreement. However, a small part of remanufactured forklift trucks are used, broken forklift trucks without rental agreement. An increasing demand for remanufactured products tends to challenge Case Company A's capability to deal with remanufacturing process variables. Nevertheless, the process complexity of the remanufactured trucks has grown steadily, along with product sales, amounting to 1,600 forklift trucks in 2013. MiniMifa depicts the process map with material and information flows for Case Company A in Figure 10.

The returned cores arrive to Gates, where they are visually inspected, documented and classified on a scale of 1-3, with 1 being best and 3 being worst (see Figure 11). Their condition is checked, the operating time is examined, and a test run is performed. A picture of the forklift truck in the condition it has arrived is placed online for second-time sale. Core inventory is often a long-term placement for every used forklift truck received, except for the leased ones. If the customer places an order for a remanufactured forklift truck, the priority is given to the forklift trucks waiting in the remanufactured product inventory. If the customer can find an acceptable product among that available in inventory, the remanufacturing process is initiated.

Typically, one work station is occupied by two forklift trucks waiting or in the process of being remanufactured. The common issue with remanufactured products is the absence of spare parts after the forklift truck has been disassembled. On average, the waiting time for spare parts is 3-4 weeks (see Figure 11). Therefore, it is reasonable to remanufacture two or three forklift trucks simultaneously. After the remanufacturing operations have been accomplished the final step is the quality inspection, usually performed by the facility manager or planner. The forklift truck is then sent to customer. Often, standard types of remanufactured forklift trucks appear in the inventory storage at the end of the remanufacturing process, awaiting a placed order.

Figure 10: Material and information flows map with challenges at Case Company A, developed by MiniMifa participants (a blue line defines a material flow, while green line stands for information flow)

Figure 11: Lead time at Case Company A (in working days); best case - 1 week and worst case – from 29 weeks

On average, there are around 100 remanufactured forklift trucks of the most popular types in the remanufactured products inventory. Possible delivery of the remanufactured forklift truck from this inventory is 2-3 days. The OEM sales department is the representative for the remanufacturing company in negotiations with customers where direct contact with the customer is absent. Sales reports on remanufactured forklift truck defects/fails, discovered at the customer site, while OEM service personnel take care of these cases.

Nevertheless, despite being a short distance (about 5 km) from the OEM, the remanufacturing company has experienced a lack of collaboration with the OEM regarding remanufactured forklift trucks, which are often perceived as direct competitors to the new ones. When a new forklift truck model is launched at the OEM, meaning that it will be returned back to the remanufacturing facility in 5-6 years, the information is spread to technicians/operators of Case Company A. The training is performed together with maintenance personnel and the OEM operator. This time, however, accounts for only 4% of working time.

Case Company A challenges discovered during MiniMifa, listed below, are marked with red colored stars on the map shown in Figure 10:

1. Waiting time for spare parts
2. Waiting for information on a requested order
3. Wrong forklift truck due to incorrect bill of lading (detailed information about every delivered item upon its arrival to the remanufacturer)
4. Poor sales of forklift trucks from finished goods inventory
5. Shortage of storing space
6. Lead time / delivery time
7. Truck registration
8. Wrong forklift trucks in finished goods inventory
9. Unqualified personnel
10. Booking of special vehicle

Improvement ideas collected from MiniMifa participants, corresponding to the challenges listed above and prioritized in Figure 12, are listed below:

1. Order spare parts as early as possible
2. Design online orders with mandatory fields;
sellers' orders without serial numbers;
more technical knowledge about the administration and sellers
3. Order vehicles themselves – the driver comes with a bill of lading
4. Trade more actively, advertising on forklift trucks;
better info, contact and meeting with sellers
5. Space shortage motivates keeping the right number of forklift trucks
6. Lead time depends on challenges nr. 1, 2, 4
7. Forklift truck registration depends on challenge nr.1
8. Maximum number of same-model forklift trucks in finished goods;
sellers take care of the website for second-hand trucks
9. Control the need and provide proper training
10. Prepare ordering of special vehicles in advance

The majority of ideas are placed in the square marked nr. 1, which together with square nr. 2 stands for “Quick Wins”: high impact and easy to implement. Since problem Nr. 1 - waiting time for spare parts - is the biggest challenge, it becomes obvious that two other challenges (nr. 6 and nr. 7) are dependent on it. Challenge Nr. 4 - to sell a remanufactured forklift truck - is declared to be strongly desired, however is difficult to implement due to the large number of stakeholders involved and the resources required.

Figure 12: Prioritized improvement ideas at Case Company A

4.3 MINIMIFA APPLICATION AT CASE COMPANY B

The German engine remanufacturer is a contracted remanufacturer with the OEM. The remanufacturing contract (reman-contract) conditions imply no investments in core acquisition and pre-determined amounts of core demand and supply, while the OEM remains a supplier of spare parts (Lind et al., 2014; Sundin and Dunbäck, 2013). An agreed upon monthly demand is 40 remanufactured engines. This number is ordered when the final customer wants to replace a broken or worn-out engine. When the returned core arrives at the warehouse the sales or product planning team informs the warehouse manager to start the remanufacturing process. A typical engine remanufacturing process is shown in Figure 13.

From the warehouse, the cores are processed for dismantling, where the quality is checked, a picture is taken and the damages are documented. Later, the core is disassembled into four master parts. Each of the parts follows its own material and information flow through cleaning and remanufacturing until all parts meet at the assembly of the short block. Finally, all spare parts are assembled together in a long block. When the remanufacturing process is finished the engine is sent in batches of eight engines.

Figure 13: Material and Information flows map with challenges at Case Company B, developed by MiniMifa participants (blue lines define material flow, green line - information flow)

The typical time for each remanufacturing process step, as well as the waiting time between the operations and for the spare parts, is represented in Figure 14 (adapted from Kurilova-Palisaitiene and Sundin, 2015).

Usually, the remanufacturing process can take from 0.8 weeks (best case) up to 13.8 weeks (worst case). A large variation in lead time is often a result of irregular material and information flows that cause some non-value-added activities, such as waiting for a driver, waiting to start an order, waiting for standard spare parts, transportation between processes, and waiting for a special spare part (Kurilova-Palisaitiene and Sundin, 2014b). The large variation identified in the product lead time causes considerable production losses at a German Engine remanufacturer.

Figure 14: Lead time at Case Company B (in working days); best case – 0,8 week, worst case - 13,8 weeks

The largest remanufacturing challenge, disclosed during the MiniMifa workshop, was the waiting time for special parts (see Figure 14). This time accounts for more than 85% of the lead time in the worst case. Nevertheless, the waiting time for standard parts contributes with a relatively small portion; it occurs 9 times more often compared with the waiting time for special parts. In general, a portion of non-value-added time is 13 times larger than value-added time, which contributes to a 65-day longer lead time. This finding reveals an urgent need to investigate the reasons behind long waiting times for special spare parts and the challenges associated with spare parts deliveries in general.

Identified challenges during the MiniMifa workshop:

1. First order of standard spare parts
2. Second order of special spare parts
3. Bad connection to external special parts supplier
4. Need for easier information flow and an information/status of job loads
5. Difficult to find spare parts
6. Missing parts on trolley

Improvement ideas developed by MiniMifa participants at Case Company B:

- 1-3.Improve communication between employees and partners
4. Share responsibility; the workshop manager becomes a group manager
5. Start production/assembly if all parts have gone through remanufacturing
6. Control data from scrap report and second order to see what parts are missing
 - a) Control lead time
 - b) Backwards planning (time schedule)
 - c) Pull production

Figure 15: Prioritised improvement ideas at Case Company B, developed by MiniMifa participants.

As can be seen in Figure15 the c option, standing for pull production, is prioritised as having the greatest impact on a company's performance with regard to product quality, lead time and inventory level, as well as ease of implementation.

4.4 REMANUFACTURING CHALLENGES IN MATERIAL AND INFORMATION FLOWS

Based on a literature study of 50 research articles, academic books and industrial reports on remanufacturing characteristics as well as two case studies, two major areas of remanufacturing challenges, material and information flows, were found.

4.4.1 MATERIAL FLOW

The obstacles in the product life-cycle return process as well as supply and demand balance often avert remanufacturing from a sustainable development (Steinhilper, 1998; Östlin et al., 2009). **Missing, late, defective and non-available spare parts** are other big challenges for both case companies. Both remanufacturers perform all process steps as manufacturer as well as additional process steps like disassembling, cleaning and checking (see also Steinhilper, 1998). This makes the remanufacturing process complex and much longer than manufacturing. None of the case remanufacturers have established standard procedures to measure and evaluate process lead time, and consequently do not usually monitor the lead time (this is especially valid in Case Company A). Different employees perform remanufacturing operations at different times, depending on the employees' qualifications and experience as well as the quality of the core and spare parts.

4.4.2 INFORMATION FLOW

Disrupted, uneven, chaotic and inaccessible information between remanufacturing process operations and product life-cycle actors is a big challenge for the case companies. **Information deficit** regarding the incoming core and remanufactured spare parts' quality, quantity and timing suspends a long-term development. Often, dealing with remanufacturing challenges can be associated with daily troubleshooting. The information tends to get stuck between organisational layers, often represented by a single person, and deteriorates towards shop-floor operational process steps.

Moreover, a lack of **feed-forward** information is highlighted in both case companies. Indeed, the closed-loop supply chain still fails to deal with communication and collaboration deficit among product life-cycle stakeholders (Inman Reverse Logistics, 2009). Case Company B experienced difficulties in product and process information acquisition in the beginning of remanufacturing activities, when no one in the product life-cycle shared information. The company confirmed that remanufacturing is dependent on the OEM in the question of eligibility to perform the remanufacturing on the OEM's products. However, evidence the feedback of information is missing in both cases as well, which can be attributed to an absence of the information exchange channels, or even a lack of awareness of the available feedback information from the remanufacturer.

4.4.3 THREE GROUPS OF REMANUFACTURING CHALLENGES

Based on the analysis of remanufacturing constraints identified from literature and case study analysis, their interrelations and interdependence, three critical groups of remanufacturing challenges were identified for further investigation: product quality, process lead time and inventory level (see Figure 16). All identified remanufacturing constraints can be addressed at least in one of the remanufacturing challenge groups, however often in two or even three groups. Therefore, solving these three challenges could facilitate improvement in the 15 identified remanufacturing constraints.

Figure 16: 15 major remanufacturing constraints of material (blue frame) and information (green frame) flows classified into three groups (orange frame) (developed from Kurilova-Palisaitiene and Sundin, 2014b).

One of the most often declared remanufacturing constraints is remanufactured product quality and remanufacturing process time. Additionally, the following shop floor challenges have been observed: insufficient quantity of cores, increased product variability, process bottlenecks, and product design-related problems, as well as a low level of employee skills (Hammond 1996; Kurilova-Palisaitiene and Sundin, 2013). The issues of unpredictable and long processing and waiting times, an unknown number of required operations in process, a high level of inventory and a deficit of information about incoming cores contribute to the process complexity (Steinhiper, 1998; Sundin, 2006; Lundmark et al., 2009; Van Nunen and Zuidwijk, 2009). The obstacles in the core return process, supply and demand imbalance, poor information exchange within a product life-cycle, and multiple networks of stakeholders conclude the list of remanufacturing

constraints identified during the literature study (Lundmark et al., 2009; Östlin et al., 2009; Lindkvist et al., 2013, Kurilova-Palisaitiene and Sundin 2014b; Phelan et al., 2000). As noticed by (Sundin, 2006; Lundmark et al., 2009; Van Nunen and Zuidwijk, 2009; Seitz, 2004), in order to make remanufacturing profitable it is crucial to solve the issues of unpredictable and extremely long processing and waiting times, an unknown number of required operations in process, a high level of inventory and a deficit of information about incoming cores.

The analysis of the case study also supports the findings of the literature analysis and reveals more details about the remanufacturing constraints. The following remanufacturing constraints were collected during the MiniMifa workshop at the case companies (see Table 2; a detailed description of the case studies can be read in Sections 4.2 and 4.3).

Table 2: Remanufacturing constraints at the case companies (x- observed at case company)

Nr	Constraints	Details:	Case Company	
			A	B
1	Core information flow	Incoming order (late, missing, incomplete, wrong order info, lack of logistics info)	x	x
2	Core material flow	Incoming cores (unclear timing, incomplete, defective, wrong)	x	x
3	Spare parts information flow	Spare parts (lack of feedback from supplier)	x	x
4	Spare parts material flow	Spare parts (late, missing, wrong, never coming)	x	x
5	Quality standards	No or poor practice of quality standard (not following standards, quality control gates, lack of employee qualification)	x	
6	Inventory	Storing space - difficult to find items;	x	
		wrong remanufactured products in finished goods inventory	x	
7	Production process	Stochastic, long lead times	x	
8	Control/monitoring system	Lack of well-functioning control, ordering, and communication system (manual, lack of flexibility)	x	x

PRODUCT QUALITY

Remanufacturing product quality covers three areas: incoming core quality, work in progress (WIP) product quality, and remanufactured product quality.

INCOMING CORE QUALITY

On-time, full quantity and right quality delivery: these are essential for cores in successful remanufacturing operations (Lind et al., 2014). Typically, the incoming core quality control determines the conditions for the following remanufacturing operations. The *initial quality control* is a challenging task that requires both time and knowledge to identify possible quality deviations and vital product defects (Seitz and Peattie, 2004; Kurilova-Palisaitiene and Sundin, 2014b). Both case companies dedicate the necessary resources to deal with the incoming core quality. However, limited utilization of available product in-use quality monitoring methods was observed at the case companies (Kurilova-Palisaitiene and Sundin, 2014a, 2015).

Case Company B does not perform a hot or cold test on the product, which is a common test in manufacturing. Case Company B operators can visually inspect cores for defects as well as and listen to noise. Besides, a more intensive, detailed and time-consuming test is not required by the customer.

WORK IN PROGRESS (WIP) PRODUCT QUALITY

WIP products refer to the products that are selected from incoming cores for remanufacturing operations, but which have not been completely remanufactured yet. WIP product quality mainly depends on three parameters: core quality, spare part quality and process quality.

The quality of spare parts is assured by the supplier, who, in both case companies, is an original spare part manufacturer. In Case Company A, some spare parts stem directly from internal spare part inventory containing cannibalized cores (cores which spare parts are of different product origin, but assembled together). The absence of the right type and amount of spare parts as well as delays in delivery considerably harm the efficiency of the remanufacturing process in both case companies.

While process quality implies the capability of process to add the right value at the right time, the challenges in process and product knowledge acquisition are experienced by both companies. However, only in Case Company A is this the result of possible competition with the OEM. Case Company B confirmed that it had to establish product knowledge itself. Nevertheless, in both case companies a lack of information exchange and weak interest from product life-cycle stakeholders contribute to the challenges in WIP product quality (Steinhilper, 1998; Östlin et al., 2009; Inmar reverse logistics, 2009; Kurilova-Palisaitiene and Sundin, 2014b).

REMANUFACTURED PRODUCT QUALITY

The purpose of remanufacturing is to deliver same-as-new or better product quality (Steinhipler, 1998). Final remanufactured product quality control for each remanufactured item is common practice in Case Company A; Case Company B, however, relies on its employees, who are responsible for step-by-step quality control during the remanufacturing process. Moreover, in Case Company B, remanufactured products come with a service warranty and a “return back” option that complements the quality support provided by the remanufacturer.

Typically, both case companies meet customer quality expectations for remanufactured products. In both companies, the need for remanufactured product quality overcomes the need for on-time delivery and the remanufacturer’s struggle to set routines that guarantee on-time, in-full delivery to the customer.

PROCESS LEAD TIME

Remanufacturing process lead time is usually longer and more variable than in manufacturing (Sundin, 2006; Guide, 2000; Seitz and Peattie, 2004). These two issues partly arise from the product quality challenges mentioned earlier.

In remanufacturing, process lead time typically starts from core acquisition and lasts until delivery to the customer. Process lead time consists of an actual time used to perform value and non-valued added remanufacturing activities, like waiting time between the activities.

ACTUAL TIME FOR REMANUFACTURING ACTIVITIES

- Time for value added activities
- Time for non-value added activities

The process lead time is demonstrated in Sections 4.2 and 4.3, where value and non-value-added activities are specified. However, the main problem with process time is delays in each process step due to operational issues, or if the spare parts are not delivered on time. This requires an improvement, as it is important to eliminate/minimize the non-value added time. For example, remanufacturing activities can be simplified, combined or performed in parallel.

WAITING TIME BETWEEN ACTIVITIES

It is clearly seen in Figure 14 that waiting time occupies a few times larger share of process time than value-added activities needed to perform remanufacturing activity (Hammond et al., 1996, Seitz and Peattie, 2004).

Interesting is that in both case companies, waiting time for spare parts has a huge impact on remanufacturing time. Case Company A is dependent on waiting time for spare parts and spends 3-4 weeks in waiting time for spare parts. However, the most costly waiting

time has been found in Case Company A, after products are transported to remanufactured products inventory to wait for the customer.

INVENTORY LEVEL

Three inventory types could be distinguished along the core transformation to a remanufactured product: core raw material inventory, WIP inventory and remanufactured product inventory.

CORE RAW MATERIAL

Core raw material inventory is collected at the facility, inspected and selected for further processing with little work added. In Case A, the remanufacturer has a high level of raw material and remanufactured product inventory, which is typical in the remanufacturing industry (Seitz and Peattie, 2004; Dowlathshahi, 2005). Mainly in Case Company A, the situation of unpredictable and uneven core delivery pushes the remanufacturer to store a vast amount of inventory for a long time. This core inventory occupies a lot of space, causing operating complexity inside the facility. On the contrary, Case Company B typically keeps no raw material inventory due to a contracted condition with the OEM with the OEM regarding a defined quantity of incoming cores.

WIP PRODUCT INVENTORY

WIP inventory accounts for a moderate work added to cores. In remanufacturing, the WIP inventory level is rather low compared with manufacturing, since manufacturing throughput is higher than remanufacturing. Remanufacturing deals with several items at a time, while manufacturing companies employ automated processes to handle larger batch sizes (Guide, 2000; Dowlathshahi, 2005). In the case companies, WIP inventory often emerges due to waiting time for cores or spare parts ordered in order to compensate for poor incoming core or spare part product quality, and therefore uneven process lead time. This is evident at Case Company B, where the largest remanufacturing challenge was the waiting time for special parts. This time accounts for at least 85% of the lead time in the worst case (see Figure 14). Nevertheless, the waiting time for standard parts contributes to a relatively small portion of non-value-added time, however it occurs much more often compared with the waiting time for special parts (Kurilova-Palisaitiene and Sundin, 2014 b).

REMANUFACTURED PRODUCT INVENTORY

Remanufactured product inventory is inventory ready to be distributed to products, with maximum work added. Remanufactured product inventory is the most costly inventory, since maximum value has been added. Sometimes, remanufacturing companies hold this inventory without finding a customer, which is often the case for Company A. It is common to store up to 100 pieces of remanufactured products on site without actual demand for an unlimited and uncontrolled time period. This overproduction creates useless resource utilization. This is a case of push manufacturing, where actual demand is absent.

These three groups of challenges: **product quality**, **process lead time** and **inventory level**, are well-known in companies working according to a philosophy of continuous improvement, also known as lean production or TPS. Lean is employed in order to enhance product quality, shorten and standardize lead time as well as optimize inventory level. Therefore, it is reasonable to consider lean principles while dealing with identified remanufacturing challenges.

4.5 MATERIAL AND INFORMATION FLOWS CHALLENGES ADDRESSED BY LEAN PRODUCTION

4.5.1 LEAN GAP IN REMANUFACTURING

An assessment of 19 categories of industrial (automobile, forklift trucks, trucks, vehicles and their part/components) performance indicators finds a considerable difference between manufacturing and remanufacturing operations (see Table 3). Facing a very complex material flow, a very low level of automation, insufficient remanufacturing volumes, and an ineffective planning horizon resulting in extensive lead time, remanufacturers are lagging behind manufacturers. The gap between manufacturing and remanufacturers with respect to lean becomes more evident by looking at Figure 17, originating from an assessment demonstrated in Table 3.

Nevertheless, a significant difference in operations manufacturing and remanufacturing have more in common than any other business processes (Sundin, 2006). An emerging need to deal with complexity and uncertainty in material and information flows chases remanufacturers' interest in lean. Vivid manufacturers' achievements in competitive advantage, boosted by lean initiatives, encourage remanufacturers to investigate their potential to apply lean.

Figure 17: Gap between manufacturing and remanufacturing with respect to lean (based on scores presented in Table 3).

Table 3: Scores comparing automobiles, trucks, vehicles and their part/components remanufacturing (R) and manufacturing (M) in 19 categories (Kurilova-Palisaitiene and Sundin, 2014b).

Category	Score				Score for		References
	1	2	3	4	R.	M.	
Revenue forecast	Very unstable/ Impossible to forecast	Variable/ Difficult to forecast	Stable/ Possible to forecast	Very stable/ Easy to forecast	2	3	Seitz and Peattie, 2004; Amezcua et al, 1998
Operating costs	Very high	High	Low	Very low	3	2	Dowlatsahi, 2005; Mentzer et al., 2001
Competition	Very low	Low	High	Very high	2	3.5	Dowlatsahi, 2005
Material flow	Very complex	Less complex	Simple	Very simple	1	2.5	Sundin, 2006
Lead time	Very long/ Uncertain, variable	Long/ Predictable	Short/ Predictable	Very short/ Standard	1	3.5	Sundin, 2006; Guide, 2000; Seitz and Peattie, 2004; Dowlatsahi, 2005
Volume	Very low	Low	High	Very high	1	3.5	Guide, 2000; Seitz and Peattie, 2004 ; Steinhilper, 1998 ; Mentzer et al., 2001
Automation	Very low	Low	High	Very high	1	3	Steinhilper, 1998
Batch size	Uncertain/ Insufficient	Certain/ Insufficient	Standard/ Sufficient enough	One-piece flow/ Perfectly sufficient	1	3.5	Steinhilper, 1998
Planning horizon	No freeze window/ Bad planning	Ineffective freeze window	Effective freeze window	Very effective freeze window with JIT	2	3.5	Ashenbaum, 2006; Davis and Heineke, 2005
Product variation	Very high/ Difficult to forecast	High / Possible to forecast	Customised/ Possible to forecast	Customised Module-based	1	2.5	Sundin, 2006; Guide, 2000; Steinhilper, 1998; Olhager, 2000, Dowlatsahi, 2005
DFRem	Very low	Low	High	Very high	1	1	Sundin, 2006; Steinhilper, 1998
Inventory level	Very high	High	Low	Very low	2	2.5	Seitz and Peattie, 2004; Dowlatsahi, 2005
Yield	Very low/ Uncertain	Low/ Predictable	High/ Predictable	Very high/ Predictable	1	2.5	[Sundin, 2006; Guide, 2000; Dowlatsahi, 2005]
Quantity	Very uncertain	Difficult, but possible to forecast	Easy to forecast	Standard/ Stable	1.5	3.5	Guide, 2000 ; Steinhilper, 1998 ; Umeda et al, 2005 ; Atasu A. and Van Wassenhove, 2005
Quality	Uncertain/ Bad	Certain/ Not sufficient	Good/ Sufficient	Very good/ Standard	1.5	3.5	Guide, 2000; Dowlatsahi, 2005
Timing	Very uncertain	Difficult, but possible to forecast	Easy to forecast	Standard / Stable	1	3	Guide, 2000
Communication	Not functioning	Functioning in a shop floor scope	Functioning in a company scope	Functioning in a product life-cycle scope	1	3	Phelan et al., 2000
Collaboration	Not functioning	Functioning in a shop floor scope	Functioning in a company scope	Functioning in a product life-cycle scope	1	3	Phelan et al., 2000
Sharing risk	Not functioning	Functioning in a shop floor scope	Functioning in a company scope	Functioning in a product life-cycle scope	1	3	Phelan et al., 2000

4.5.2 LEAN REMANUFACTURING

Lean Remanufacturing is typically treated as a set of principles and tools to gain operational efficiency, reduce process waste, and increase productivity in remanufacturing by keeping the original lean principles and adjusting lean tools according to the level of product variety and volume in remanufacturing (Jacobs and Chase, 2001; Fargher, 2006, Sundin, 2006; Östlin and Ekholm, 2007). However, the definition of lean remanufacturing lacks a clear and distinct explanation, mainly due to the absence of the explicit and consistent industrial or case company evidence of lean application to remanufacturing, as well as the long-term lean implication on remanufacturing challenges in material and information flows.

4.5.3 LEAN PRINCIPLES IN REMANUFACTURING

To facilitate improvements in remanufacturing material and information flows focusing on product quality, process lead time and inventory level, five lean production principles can be investigated.

VALUE

In pursuing lean remanufacturing **value**, one has to consider customer influence on remanufacturing operations needed to deliver a certain product with certain characteristics on demand. There was little customer involvement observed in the remanufacturing process; insufficient attempts to require certain quality were noticed in Case Company B. Remanufacturing value could be anticipated as delivering “as same as new or better” product quality at lower costs than an original product, and in a reasonably short time. The value definition by the case company customers was challenged due to lacking feedback and feedforward information flows. As discussed in the theoretical background chapter, Ohno (1988) describes value as some kind of processing that the customer is eager to pay for, which implies keeping value-added processes and eliminating non-value-added activities. Consequently, value in lean remanufacturing could be generated through value-added operations needed to deliver “as good as new or better” product quality. To understand the possible value-added and non-value-added activities the MiniMifa method was applied to the case companies.

VALUE STREAM

As demonstrated in the case companies, MiniMifa encompasses the **value stream** principle, which enables the identification of the entire value stream of a product and eliminates waste. Value stream thinking, promoted by Womack and Jones (2007), requests one to look at remanufacturing from a system perspective, identifying specific actions required to produce specific products critical to business. A step-by-step description of the remanufacturing process with important tasks and material and information flows was presented to define their contribution to value generation.

FLOW

Flow is a critical part of stream thinking. Creating continuous **flow** in remanufacturing is presented via following and visualizing material and information flows. Two flows of one business product critical to remanufacturing were inspected at the case companies in order to emphasize each contribution to value generation. Material flow is inspected for missing links in the chain of process-oriented activities, while information flow is considered for limited or absent information links between employees in subsequent operations.

PULL

The **pull** principle is developed to fulfill customer demand and therefore is vital in value generation through the remanufacturing process. Pull in remanufacturing implies an introduction of triggers that control the material withdrawal and reordering by sending the demand command from the downstream to upstream process, creating linked material and information flows (see Section 4.5.4). Since the pull ordering mechanism is aimed at delivering on-time and to fulfilling customer demand, and with a main focus on keeping the right product quality while maintaining short lead times and an optimal level of inventory, it carries a potential solution for remanufacturing challenges and was examined at both case companies.

According to Hopp and Spearman (2004), pull production is recognized for controlled and limited WIP inventory. Pull is accompanied with a triggering mechanism that authorizes a certain production task to be performed (Gonzalez et al., 2012). One of the well-known triggering mechanisms is a Kanban system, and there have been at least nine Kanban replenishment scenarios developed for remanufacturing (Kanikula and Koch, 2011). The variation in Kanban arises from different remanufacturing system characteristics: customer behavior (constant vs. stochastic demand), availability of raw material (infinite or finite availability) and correspondingly shop floor operating conditions (distribution of processing time, breakdowns, reworking and set-up times).

One typical pull production aspect, WIP inventory control and limitation, is critical to reconsider in remanufacturing. Dealing with much smaller batches and higher product variation than in manufacturing implies certain differences in managing WIP inventory for remanufacturing (Womack and Jones, 2007). Contrary to serial manufacturing, remanufacturing cannot operate owning small quantities of cores and spare parts on-site. This implies greater control of acquired cores and spare parts, and that the introduction of minimum and maximum required level of WIP is critical to remanufacturing. Due to an observed lack of suitable cores and spare parts in the remanufacturing case companies, the Kanban reordering system tends to increase the portion of spare parts and WIP.

Figures 18 and 19 represent the possible pull implementation on Case Company B. The key difference from the contemporary ordering system is the reverse information flow regarding the demanded product, as well as the previously noted increase in inventory

level. According to pull production, information from sales reaches a warehouse manager, who gives a command to assemble a long block. The long block spare parts, including the short block, are then withdrawn from the parts buffer (or controlled inventory) in front of *Assembly 2*.

Figure 18: Possible lead time at Case Company B (0.8 - 4 weeks).

This is the signal for operators in *Assembly 1* to collect parts from the remanufacturing of master parts and start their operations. Simultaneously, external spare parts are collected from the supplier. This is the non-stop process of withdrawal of spare parts until the disassembly process step. In disassembly, the cores are dismantled and controlled, sorted or scraped. Since today remanufacturing has very little or no power to influence a supplier, it cannot determine the quantity and quality as well as timing of spare parts; therefore, keeping them on-site is reasonable (Sundin, 2006; Womack et al. 2007).

In the future, when the total product life-cycle will be integrated in a sustainable symbiosis with open and shared information and material flow, a new investigation of the ordering system will be performed (Kurilova-Palisaitiene and Sundin, 2015). A pull implication at Case Company B of lead time is demonstrated in Figure 19. The suggested improvements correspond to a lead time reduction of 69% compared with the original lead time (see Figures 14 and 18). When the pull system was suggested for a pilot at Case Company A, dramatic improvement in lead time was noticed. After applying the pull system, a possible lead time was calculated to be 1-2 weeks. The shortened lead time results in a reduction of 93% compared with the original lead time (see Figure 11).

Figure 19: Pull ordering system demonstration at Case Company B

Indeed, the application of the pull system contributes to the dramatic and relatively quick improvements in lead time of the case companies, however it cannot be treated as the only or the best possible lean principle to improve remanufacturing challenges in material and information flows. Therefore, a deeper analysis of lean production at remanufacturing case companies is needed.

PERFECTION

Seeking continuous improvement is distinct in lean production. Remanufacturing challenges in product quality, process lead time and inventory level are identified to be key aspects of seeking lean remanufacturing. The proposed improvements following use of the MiniMifa method (see Sections 4.2 and 4.3) lead to the continuous improvement principle, known also as **perfection**. Perfection is a goal of lean remanufacturing and consists of reaching for “as good as new or better” product quality, lower than original manufacturing costs, shorter lead times and optimal inventory level.

4.5.4 CHALLENGES TOWARD LEAN REMANUFACTURING

However, in order to become lean, remanufacturing has to overcome three levels of lean remanufacturing challenges. Based on the literature and case study analysis of remanufacturing challenges and improvement opportunities, a model for remanufacturing companies’ transformation towards lean is developed through a Lean remanufacturing pyramid (see Figure 20). The Lean remanufacturing pyramid contains internal and external remanufacturing challenges and perspectives for improvements in **material** and **information** flows. Lean remanufacturing is reached when the product **quality**, process lead **time** and **inventory** level (QTI) circles meet at the top of the pyramid.

Figure 20: Lean remanufacturing pyramid (Q - product Quality, T – process lead Time, I – Inventory level).

The Lean remanufacturing pyramid is based on three levels of remanufacturing transformation to lean. These levels are placed on a time axis that defines a direction for lean transformation with no start or endpoint. The Lean remanufacturing pyramid delivers a comprehensive approach to lean remanufacturing and emphasizes the importance the improvement of material and information flows along the transformation to lean (Kurilova-Palisaitiene and Sundin, 2014b).

Lean remanufacturing transformation begins at a bottom point of the material and information axis, where QTI are placed. The reduction of the level of **uncertainty** and **complexity** in remanufacturing entitles lifting QTI up from the initial position; this step was found to be one of the largest challenges according to Lundmark et al. (2009). On the second level of the pyramid, remanufacturing focuses on reducing material and information **variability** and **inflexibility**. However, in order to become a lean company, remanufacturing has to overcome the third level, which stands for lean remanufacturing waste. Consequently, rising up along the material and information axis, remanufacturing comes closer to the ideal lean remanufacturing case. Achieving perfection through continuous improvement makes this lean transformation a long-term journey for remanufacturing (Kurilova-Palisaitiene and Sundin, 2014b).

LEVEL 1: EXTERNAL LEAN CHALLENGES

Uncertainty stands for difficulties to foresee characteristics and patterns for remanufacturing activities. Information uncertainty mainly refers to a weak collaboration with Product Life-cycle stakeholders. Lack of Information harms remanufacturing development. This constraint escalates in line with complexity in the remanufacturing process, which is related to material supply and demand (Lundmark et al., 2009).

To overcome the uncertainty level, information flow in the reverse logistics system regarding incoming cores' quality, quantity, and timing needs to be established to reflect the need for returns and demand (Guide, 2000; Inderfurth, 2005). Information streaming down to remanufacturing would enable common value creation along the product life-cycle.

Complexity attributes the difficulties to operate due to a vast amount of product life-cycle variables (Kurilova-Palisaitiene and Sundin, 2014b). Usual dimensions that characterize remanufacturing complexity are the complexity of cores and products or a lack of them. Reducing product complexity would imply considerable efforts in designing products suitable for remanufacturing.

Additionally, usual bottlenecks, sudden material starvation and inefficient equipment deployment speak for considerable obstacles and complexity of the remanufacturing process (Guide, 2000). Remanufacturing complexity in operations planning, controlling and management partly refers to information uncertainty (Kurilova-Palisaitiene and Sundin, 2014b).

LEVEL 2: INTERNAL LEAN CHALLENGES

Flexibility can be defined as the capability and ease of systems to change from one state to another (Slack, 2005). Inflexibility comes along with an inability to effectively respond to customer demand, and therefore additional costs occur [Womack 1996]. Therefore, in this research **Inflexibility** implies the possibility to foresee remanufacturing operations, however blocks the respond function.

According to Östlin et al. (2009), flexibility is essential for efficient response to complexities and uncertainties of the environment. Information flexibility can be improved by investing in multiskilling employees on various operations and through better internal collaboration. Operational flexibility refers to the ability to quickly model reconfiguration, capability to select among different options/alternatives, adjustments in process capacity, frequency, remanufacturing volume and resource utilization as well as product mix (Bai and Sarkis, 2013; Kurilova-Palisaitiene and Sundin, 2014b). Moreover, remanufacturing work stations are subject to extreme fluctuations in material inventory due to stochastic routings and highly variable processing times (Guide, 1997).

Variability means that it is possible to operate standards, but difficult to follow them due to process instability and many internal material deviations (Kurilova-Palisaitiene and Sundin, 2014b). Process and material instability are any deviations from standards of cores, spare parts, process, employee skills, and operational environment (Womack and Jones, 1996, Sundin, 2006; Lundmark et al., 2009). Remanufacturing work stations are subject to extreme fluctuations in material inventory due to stochastic routings and highly variable processing times (Guide, 2003). Internal material variability signals unsolved issues of external lean challenges, and determines the need to focus on material standards for the whole product life-cycle (Kurilova-Palisaitiene and Sundin, 2014b).

LEVEL 3: LEAN REMANUFACTURING WASTE

Lean remanufacturing **Waste** originates from the 7 lean wastes (Womack and Jones, 1996) and delivers the possibility to respond and follow standards, however with some difficulties in value creation (Kurilova-Palisaitiene and Sundin, 2014b). In lean, waste is any work that does not add value. In lean remanufacturing, waste refers to the use of resources beyond what is needed to meet customers' requirements (waiting, inventory, motion, over-processing, transport, overproduction, rework and scrap) (Womack and Jones, 1996). The most contradictory remanufacturing waste is certainly inventory. Inventory level reduction, especially WIP, is one of the key lean goals in manufacturing. In remanufacturing, uncontrolled inventory control comes along with elimination and reduction of unnecessary material and an increase in required cores and spare parts. Therefore, in lean remanufacturing a lack of cores and spare parts is concluded by the research to be a waste, something which is obviously experienced through waiting time in both case companies.

5 DISCUSSION AND CONCLUSION

This chapter discusses the research results based on the previous chapters. The chapter is divided into three parts corresponding to the research questions. The result assessment and correlation with the similar research are included in this chapter. Moreover, this chapter presents an answer to the research objective, followed by the academic and industrial contribution of the research. The chapter concludes with suggestions for future research.

The objective of this licentiate thesis is to examine remanufacturing challenges in material and information flows and to study how these challenges can be addressed by lean production.

To target the objective of this licentiate thesis, remanufacturing challenges in material and information flows were analyzed. The choice of the remanufacturing challenges selected for further analysis at the case companies were primarily derived from a literature study. Based on the defined challenges, a MiniMifa method was developed, applied and evaluated at two case companies. Lean production principles in remanufacturing were investigated for their potential to address the identified remanufacturing challenges. Pull principles carry a possible solution to challenges in product quality, process lead time and inventory level, and therefore were suggested to both case companies. A possible pull application to a remanufacturing company is demonstrated leading to dramatic improvement in lead time, followed by improvements in inventory level and product quality.

5.1 MATERIAL AND INFORMATION FLOW MAPPING AND ANALYSIS METHOD

RQ1: How can material and information flows be mapped and visualized at remanufacturing companies?

The need to study remanufacturing challenges in material and information flows from a system perspective was determined by the complexity of the underlying issues. Maintaining a system focus was essential to develop a suitable flow mapping and analysis method, called **Minimum time for Material and Information flow Analysis**, or simply **MiniMifa**. This method, based on value stream mapping (VSM), enables visualization of the process challenges and helps to discover the areas of needed improvements. The development of the method was influenced by the researcher's industrial experience and a literature study of lean production.

Interactions with industrial case companies let the researcher test, improve and continuously apply MiniMifa, providing insight into remanufacturing challenges. Apart from MiniMifa's capability to visualize and analyze remanufacturing challenges, the method offers a systematic analysis of remanufacturing challenges and possible lean improvement opportunities.

MiniMifa is beneficial to both academia and industry, since this method delivers a map of remanufacturing processes with the main remanufacturing operations, organizations, functions and people involved in the process as well as quantitative and time characteristics. Moreover, the challenges of current material and information flows with the possible improvement initiatives are visualised directly on the map. This visual representation of the remanufacturing process is constructed via a dialog between remanufacturing employees working in different departments/functions. The details from

the viewpoint of participants are reached through 2.5-3 hours of constructive discussions, and often lead to a group consensus on each particular question. However, the biggest advantage of this method is reduced complexity when a broad variety of questions on material and information flow are covered during one MiniMifa session.

The strengths, weaknesses, opportunities and threats of MiniMifa were identified and evaluated in the case studies. An evaluation of MiniMifa is presented in Table 4.

Table 4: MiniMifa SWOT analysis

Strength	Weakness
<ul style="list-style-type: none"> • Data triangulation is obtained from multiple sources such as focus group interviews, workshops and observations • Easy to use, apply, collect data and evaluate • Integrates knowledge from different functions of the company • Fosters open communication and a collaboration atmosphere • Flexible dialogues provide deeper understanding of the discussed issues • Visual tools enable greater understanding of the issues under investigation • Collect challenges and possible improvement initiatives from the employee's perspectives 	<ul style="list-style-type: none"> • Information has to be recorded and transcribed, since the moderator has no opportunity to take notes • Participants are selected in advance by the company's manager, which can influence the findings • The analysis focuses on the material and information flow of one product • Managerial participants tend to dominate over the workshop employees • MiniMifa does not provide all possible solutions to the identified material and information challenges • MiniMifa alone does not provide incentives on how to implement solutions and how to continue with the improvements
Opportunities	Threats
<ul style="list-style-type: none"> • Can be applied to different industrial companies, organisations and within academia • Can be used to analyze production processes, project management activities, and planning horizon • Can become a visual management tool at industrial companies • MiniMifa analysis is useful to determine a company's situation and willingness/readiness to apply lean principles and tools 	<ul style="list-style-type: none"> • Biasness in conducting MiniMifa might influence the results • MiniMifa results can vary due to the different circumstances and participants

5.2 REMANUFACTURING CHALLENGES IN MATERIAL AND INFORMATION FLOWS

RQ2: What are the challenges in material and information flows at remanufacturing companies?

The majority of the remanufacturing challenges/constraints identified through the literature study were observed at the two case companies. In general, the 15 categories of remanufacturing constraints identified could be attributed to material and information flow challenges with constant overlap. The interdependence of these constraints generated three groups of **remanufacturing challenges in material and information flows**:

- **product quality**
- **process lead time**
- **inventory level**

At the same time, Hunter and Black (2007) point out four critical control functions in lean production that are closely related to the remanufacturing challenges, namely quality, production, process and inventory. Therefore, these three remanufacturing challenges are selected for a deeper MiniMifa analysis at the industrial case companies. This licentiate thesis offers a unique possibility to look at the reasons behind these three challenges and carries a distinct value to the research in lean remanufacturing.

MiniMifa analysis of product quality outlined three problematic product quality areas:

- Incoming core quality
- Work in progress (WIP) product quality
- Remanufactured product quality

Correspondingly, the analysis of process lead time at the case companies separated the value-added time and identified sources of long lead time:

- Actual time for remanufacturing activities:
 - Time for value-added activities
 - Time for non-value-added activities
- Waiting time between activities

Finally, MiniMifa provided insight on remanufacturing inventory level challenges in three inventory placement areas:

- Cores – raw material inventory, collected at facility, inspected and selected for further processing with little work added
- WIP inventory - cores and spare parts with moderate work added
- Remanufactured products inventory – inventory of ready-to-be-distributed products, with maximum work added

Material flow challenges are found to be critical in WIP product management due to **missing, late, defective and non-available spare parts**. It was discovered that the control and management of spare parts overcomes the core challenges. Contrary to some remanufacturing researchers (Sundin, 2006; Östlin et al., 2009), an on-site excess of material is not experienced as the greatest challenge, however the lack of needed material is intimidating. **Information flow challenges** can be characterized as **disrupted, uneven, chaotic and inaccessible**, especially between remanufacturing companies and other product life-cycle stakeholders. This finding is in line with the study of Lindkvist and Sundin (2013) on information flow between product life-cycle stakeholders. Additionally, none of the case remanufacturers established standard measurement and monitoring initiatives to control process lead time, material quality and quantity.

An in-depth MiniMifa analysis of product quality, process lead time and inventory level revealed the specific process challenges, the source of these challenges, and facilitated the development of solutions based on lean production.

5.3 MATERIAL AND INFORMATION FLOWS CHALLENGES ADDRESSED BY LEAN PRODUCTION

RQ3: How can the identified challenges be addressed by lean production?

The gap between manufacturing and remanufacturers with respect to lean was identified. Facing a very complex material flow, a very low level of automation, insufficient remanufacturing volumes, and an ineffective planning horizon resulting in extensive lead time, remanufacturers are lagging behind manufacturers. Due to major remanufacturing challenges in material and information flows, some researchers have expressed a concern about the suitability of lean for remanufacturing. They emphasize that stable demand and supply are key success factors to apply lean. Indeed, demand and supply stability could facilitate the application of lean to remanufacturing.

To facilitate improvements in remanufacturing material and information flows focusing on product quality, process lead time and inventory level, five lean production principles in remanufacturing were defined. Among the five lean principles, the pull principle was investigated for its potential to address remanufacturing challenges in product quality, process lead time and inventory level. In order to close the gap between theory and practice, the empirical investigation on pull principle employment to remanufacturing was executed via the MiniMifa method at two case companies. To tie information and material flows together into a well-functioning and efficient system, a pull ordering system was suggested. If the pull principle is applied, the possibility to reduce lead time by 93% and 69% is observed in Case Companies A and B, respectively.

The key difference from the contemporary ordering system is the reverse information flow regarding the demanded product quality, quantity and timing as well as the increased WIP product inventory level. Since today remanufacturing has very little or no

power to influence a supplier, keeping limited and controlled WIP inventory on-site is reasonable. Nevertheless, the costs for holding WIP will stay adequate due to a moderate value added during the initiated remanufacturing operations supported by low core acquisition costs. Consequently, pull production facilitates an optimal buffer and not a low buffer remanufacturing system. Therefore, lean remanufacturing will be different from typical lean regarding inventory.

However, in order to become lean, remanufacturing has to overcome three levels of lean remanufacturing challenges. These challenges are developed in the Lean remanufacturing pyramid, which delivers a comprehensive approach to lean remanufacturing and emphasizes the importance of material and information flow improvements along the transformation to lean.

Three levels of challenges towards lean remanufacturing are:

1. **External lean challenges** attributed to **uncertainty** and **complexity** in material and information flows.
2. **Internal lean challenges** indicate remanufacturing process **inflexibility** and **variability** in product quality, process lead time and inventory level.
3. **Lean remanufacturing waste** originating from the **7 wastes of lean**.

The two higher levels (2 and 3) are relevant to every company pursuing lean, however level one is specific for remanufacturing industries due to the defined challenges in material and information flows.

5.4 CONTRIBUTION TO ACADEMIA

The contribution of this licentiate thesis is an in-depth analysis and classification of remanufacturing challenges in material and information flows. Furthermore, as a result of this thesis, a method to map and visualize material and information flows in remanufacturing was developed. It was proven that MiniMifa is suitable for empirical data collection to study complex issues. The flexibility of the method makes it possible to study large processes within multiple networks of product life-cycle stakeholders as well as single workshop operations in organisational context.

This research contributes to the minimisation of the gap between academia and industry. The empirical data is collected and analyzed from the remanufacturing perspective. An in-depth analysis of the three remanufacturing challenges of product quality, process lead time and inventory level contributes to the greater understanding of the reasons behind unpredictable and complicated remanufacturing process operations.

Lean production principles addressing remanufacturing challenges were analyzed and suggested for the case companies. A pull principle potential to improve remanufacturing challenges in material and information flows was demonstrated. Therefore, a step toward bringing remanufacturing closer to lean has been presented.

5.5 CONTRIBUTION TO INDUSTRY

The contribution of this research to industry is the development of material and information flow mapping and analysis method that can help remanufacturing companies to identify their challenges and possible improvement opportunities. The MiniMifa flow mapping and analysis method proved to be efficient tool to visualize companies' challenges. This method's simplicity and easy-to-perform data analysis can be applied to a great number of companies. An overview of the companies' challenges will facilitate a common understanding and engage and motivate company employees to discuss issues openly, analyze challenges, prioritize improvement ideas and develop suitable solutions, including lean production principles.

Lean principles are development for remanufacturing. Suggested pull principles have been accepted by the case companies as a suitable solution to remanufacturing challenges in material and information flows. The research results have been communicated to the case companies and the remanufacturing society. An analysis to apply lean in remanufacturing operations has been performed by providing the basis for future development of the lean principle and tools suitable specifically for remanufacturing companies.

5.6 FUTURE RESEARCH

There is a need to develop a deeper knowledge of lean principles and tools suitable to address remanufacturing challenges in material and information flows. Therefore, one possible suggestion for continuing research in lean remanufacturing is to verify the findings and the MiniMifa method to develop lean tools and practices suitable for remanufacturing.

On the other hand, the gap between remanufacturing and product life-cycle has to be addressed as well. The application of lean on remanufacturing has to be accompanied by the study of the remanufacturing role in the product life-cycle, and how the changes in remanufacturing can and will influence other product life-cycle stakeholders and vice versa. Therefore, another possible suggestion for future research is to investigate remanufacturing implications on the product life-cycle. Thus, the possibility to investigate lean considering the circular economy, and in particularly product service systems (PSS), is highlighted.

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7 APPENDIX

7.1 QUESTIONS PRIOR TO MINIMIFA

	Standard product	Special product
• Number of operators per product/process		
• Working hours (shift, hours per week)		
Quality % (number of products that are delivered in):		
• Right time		
• Right quantity		
• Right quality		
Lead time (weeks/days/hours):		
• Waiting time (in raw material buffer)		
• Time for remanufacturing		
• Waiting time for components (WIP buffer)		
• Waiting time (finished goods buffer)		
Inventory level (quantity):		
• Raw material		
• WIP		
• Finished goods		
Customer demand:		
• Number of products and tendency to increase/decrease		
• Frequency (how often customer orders)		
• Waiting for order (from the order placement to the arrival to customer)		

7.2 DISCUSSION DURING MINIMIFA

1. What is remanufacturing and what is the aim with it at the company?
2. Is it difficult to remanufacture?
 - Knowledge: Very little_____Very much
 - Work tasks: Very simple_____Very complicated
 - Time: Very little_____Very much
 - Costs: Very little_____Very much
 - Do you have enough knowledge, experience and personnel to do remanufacturing?
 - Do you have all necessary equipment, machines, and tools to do remanufacturing?
 - Do you receive enough information to do remanufacturing?
 - Do you miss something/any information?
 - Which is the most important process step and which is the most complicated?
3. Who are you dependent upon in product life-cycle: manufacturers, service, customers, etc.?
 - Which product life-cycle actors influence you?
4. How do you deal with cores and components?
 - Do you know which products are coming in?
 - How often and in which quantity do you receive cores?
 - How do you control quality and quantity of incoming cores?
 - Do you have a regulation that states how much you can take in?
 - How do you control your inventory level (raw material, WIP, finished goods)?
 - Do you always have the cores/components that you need for processing?
 - How long do you need to wait for core/components after placing an order?
 - What is the problem with deficit/excess of cores/components?
 - How can you increase the amount of remanufactured products? What has to be done?
5. How often and through which channels do you receive information about products including cores and components?
 - What information on product (design certificates, operational instructions, maintenance reports, customer feedback, etc.) do you receive from product users/customers/service/maintenance/manufacturers/designers, etc.?
 - Which information (from above mentioned) can be utilized in remanufacturing process steps?
6. Who participate in the remanufacturing process?
 - How do you work:
 - Teamwork
 - Independantly
 - How do you receive and give feedback and to who?
 - How do you sell remanufactured products (%)?

- Active sales
- Passive sales

7. Do you have any challenges in the way remanufacturing is operated today?

- What is the biggest challenge?
- Can you influence it? Why? How?
- What is necessity to improve situation?

Thank you for your contribution!

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8 APPENDED PAPERS

Jelena Kurilova-Palisaitiene wrote the papers based on data collected through literature study and the Minimum time for material and information flow analysis (MiniMifa) method, developed and applied by Jelena Kurilova-Palisaitiene at two case companies. Erik Sundin supported the writing process and guided MiniMifa method development, testing and application.

Papers

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

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