Remanufacturing challenges and possible lean improvements

Jelena Kurilova, Erik Sundin and Bozena Poksinska

The self-archived postprint version of this journal article is available at Linköping University Institutional Repository (DiVA):
http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-144880

N.B.: When citing this work, cite the original publication.
https://doi.org/10.1016/j.jclepro.2017.11.023

Original publication available at:
https://doi.org/10.1016/j.jclepro.2017.11.023

Copyright: Elsevier
http://www.elsevier.com/
Remanufacturing challenges and possible Lean improvements

Jelena Kurilova-Palisaitiene*, Erik Sundin, Bonnie Poksinska
Department of Management and Engineering, Linköping University
SE-581 83 Linköping, Sweden
e-mail: [jelena.kurilova, erik.sundin, bonnie.poksinska]@liu.se
*Corresponding author: +46700895862
Remanufacturing challenges and possible Lean improvements

Abstract
Remanufacturing is a viable way to prolong the useful life of an end-of-use product or its parts. Despite its economic, environmental, and social benefits, remanufacturing is associated with many challenges related to core (used product or its part) availability, timing and quality. The aim of this paper is to study how lean production could be used to tackle remanufacturing process challenges and contribute to shorter lead times. To meet this aim, we conducted a literature review and case studies of four remanufacturing companies. The case companies’ remanufacturing challenges were: (1) a lack of material requirements planning system, (2) poor core information, (3) a lack of core material, (4) poor spare parts information, (5) a lack of spare parts material, (6) insufficient quality management practices, (7) large inventories, (8) stochastic remanufacturing processes, (9) a lack of supply-demand balance, and (10) insufficient automation. These challenges contribute to long and variable remanufacturing process lead times. To tackle remanufacturing challenges, seven lean-based improvements with a major effect on improvements in lead time were suggested: standard operations, continuous flow, Kanban, teamwork, employee cross-training, layout for continuous flow, and supplier partnership. Providing that the suggested improvements are implemented, a possible lead time reduction of 83–99 per cent was projected.

Keywords – Remanufacturing, Circular Economy, Lean production, Lead time

Word count: 11509 with list of references, 7280 without list of references

1. Introduction
Remanufacturing can be described as a series of manufacturing steps applied to an end-of-use part or product in order to return it to like-new or better performance, with warranty to match (CRR, 2007). Remanufacturing is becoming a critical element of a circular economy, where products are developed, manufactured, used, and recovered to prevent any sort of waste and reduce the extraction of raw materials. In Europe alone, the remanufacturing industry is estimated to generate billions of euros yearly; therefore, it involves encompasses significant financial and environmental benefits and offers opportunities to various stakeholders of the resource-efficient life-cycle system (Östlin et al., 2008; APSRG, 2014).

Nevertheless, despite successful growth into different industries, remanufacturing continues to face numerous challenges (APSRG, 2014). In 2015, the European Remanufacturing Network (ERN, 2015) underlined the challenges experienced by 188 European remanufacturers: lack of technology, lack of product knowledge, lack of sales channels, legislation restrictions, high labour costs, quality of feedstock, volume or availability, and customer recognition.

Lean production is one possible improvement strategy with which to address remanufacturing challenges. Lean delivers a set of principles and tools to gain operational efficiency, reduce process waste, and increase productivity in remanufacturing (Jacobs and Chase, 2001; Fargher, 2006; Sundin, 2006; Östlin and Ekholm,
Lean production originates from the Toyota Production System (TPS) and has five goals to improve companies’ performance: shortest lead time, best quality, lowest cost, best safety and high employee morale (Womack et al., 1990; Liker, 2004; Shah and Ward, 2007). While lean production has been successfully used in manufacturing companies (Fullerton et al., 2003), few studies have shown how lean production can help to tackle remanufacturing challenges, especially in terms of shortening lead times. Therefore, the aim of the present paper is to study how lean production could be used to tackle remanufacturing process challenges and contribute to shorter lead times.

2. Methodology
To fulfil the aim of the paper, we conducted a literature study and case studies at four remanufacturing companies.

2.1 Literature study
The purpose with the literature study was to define the current state of the research in the area of remanufacturing challenges and the use of lean production in remanufacturing. The search phrases used for the literature study were ‘remanufacturing’, ‘remanufacturing challenges’ and ‘lean remanufacturing’. We used a number of search and metasearch engines, including Science Direct, Scopus, Web of Knowledge, Journal of Remanufacturing and Google Scholar, to find relevant published works on this literature review.

In total, we found 590 papers published before February 2016 that met the above criteria. After reading the abstract of each paper and looking for the relevance in the paper’s content and structure, we selected 174 papers with high relevance to remanufacturing challenges and lean remanufacturing. After reading the selected papers, we excluded a further 55 papers with diverging aim and findings. Consequently, 119 papers were used for the analysis in this paper. We also identified a further 11 relevant papers from the reference list of the 119 collected papers and included these in the literature review. The authors’ previous experience and literature in remanufacturing and lean production was also used.

2.2 Case study
To study the complex phenomenon of remanufacturing challenges and improvement opportunities within a real-world context, a case study methodology (Eisenhardt, 1989; Yin, 1994; Law, 2004) was selected in this work. Yin (1994) emphasized that, through case studies one can generate theory from the interpretation of observations made in natural settings. Kuper and Kuper (1985) argued that more discoveries have arisen from single-case observations than from statistics applied to large groups.

In the present paper, the case study focuses on identifying remanufacturing challenges and possible improvements using lean production. These issues were studied at four companies by following standard case study procedures and applying the same data collection method, which enables a smooth cross-case analysis. The data collection method combined a focus group interview (Morgan, 1997) with the value stream mapping (VSM) method. The VSM method is often used as a mapping tool in Lean production to develop an overview of the production operations, including material and information flow as well as
connection to the external stakeholders (Rother and Shook, 2003). In VSM, the main company’s operations are schematically mapped in the actual sequence to reflect the production process steps, inventory, and other process-relevant information. With the help of VSM, companies are able to identify challenges and develop possible improvements (Jones and Womack, 2003). In the present study, the VSM method was used for visualization purposes in the data collection stage. Visual data representation enables transparent discussion and on-site data triangulation. The focus group interviews with VSM lasted between two and three hours each and included five to seven company employees whose competences cover different functions, such as facility or process managers, planners, operators or technicians, administrators, sales, logistics, and quality managers. The sessions were recorded, transcribed and analysed using qualitative content analysis.

Four remanufacturing companies were studied using the case study methodology. The selected companies represent different business areas and products, ensuring a broader perspective on remanufacturing challenges and possible lean-based improvements.

**Company A** belongs to an original forklift truck manufacturer and provides remanufacturing services for original equipment manufacturer (OEM) rental and used forklift trucks. After remanufacturing, the forklifts are sold through a rental contract again or in a second-hand market under the standard known as ‘approved used forklift’ with a guarantee of three to nine months.

**Company B** is a contracted engine remanufacturer with a monthly demand for remanufactured engines from the OEM, which remains a supplier of spare parts. When the user needs to replace a broken or worn-out engine, the OEM offers a remanufactured one. Only after the remanufactured core is delivered to the OEM is a remanufacturing operation on the returned one initiated.

**Company C** is an independent IT remanufacturer of computers and smartphones. The key duties are to manage the inflow of cores, classify their quality and erase their data. Avoiding the disassembly and the following remanufacturing processes, computers that are approved for the highest quality category are sold to local end users, while computers of lesser quality are sold to resellers and remanufacturing companies throughout Europe.

**Company D** is a contracted remanufacturer of filling machines and operates in a business-to-business environment, with a throughput of one to three machines per year. The warranty period for remanufactured machines is six months and an additional performance warranty is provided. In terms of efficiency, the performance of the remanufactured machines is degraded by just 1 per cent compared to a new one of the same generation.
A brief overview of the remanufacturing companies is presented in Table 1.

Table 1: Overview of company characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Company A</th>
<th>Company B</th>
<th>Company C</th>
<th>Company D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company size</td>
<td>Large</td>
<td>Large</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Sector</td>
<td>Machines</td>
<td>Machines</td>
<td>IT equipment</td>
<td>Automotive</td>
</tr>
<tr>
<td>Product complexity</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Remanufacturing experience</td>
<td>20 years</td>
<td>10 years</td>
<td>10 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Remanufacturing business in comparison to manufacturing</td>
<td>Minor</td>
<td>Major</td>
<td>Major</td>
<td>Medium</td>
</tr>
<tr>
<td>Remanufacturing status</td>
<td>OEM</td>
<td>Contracted</td>
<td>Independent</td>
<td>Contracted</td>
</tr>
</tbody>
</table>

3. Remanufacturing challenges identified from the literature review

Many researchers agree that remanufacturing is complex and difficult to manage due to a high number of internal and external uncertainties (Hammond et al., 1996; Guide, 2000; Lundmark et al., 2009). Internal uncertainties typically originate from the remanufacturer’s internal process challenges, while external uncertainties depend on the challenges outside the companies’ borders. Based on the literature review, we developed a three-level model of remanufacturing challenges (Figure 1).

- **Industry level** refers to the challenges related to a remanufacturing industry (economic, environmental and political perspectives)
- **System level** refers to the remanufacturing system (closed product life-cycle system perspective)
- **Process level** refers to the remanufacturing process (the company’s operations perspective)

The category of the industry level was reflected in multiple sources of remanufacturing challenges on the system and process levels. It was noted that each of the industry-level challenges has a major effect on system-level challenges, while the system-level challenges mostly affect the process-level challenges. A detailed description of the classification of the challenges on the system and process levels is developed in Tables 2 and 3, respectively.

3.1 Industry-level challenges

On an industry level, the remanufacturing challenges are analysed from economic, environmental and political perspectives. The industry-level challenges can be classified as legislation and environmental regulation, customer preferences and technological change. According to Guidat et al. (2015), other researchers tend to generalize remanufacturing industry challenges into the following three categories: sceptical customer perception, variable inflow of cores (used and returned worn-out products or their parts), and labour costs versus product value.
3.2 System-level challenges

On a system level, the remanufacturing challenges were analysed from the perspective of stakeholders in a closed product life-cycle system: product designers, manufacturers, buyers/users, service/maintenance, remanufacturers and recyclers.

Challenges identified at this level often originate at or between different product life-cycle stakeholders, contributing to remanufacturing complexity and uncertainty. Table 2 presents nine categories of system-level challenges that were identified and classified from a literature review.
Table 2: Overview of key system-level remanufacturing challenges.

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Main focus</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Business model</strong></td>
<td>- Selling channels</td>
<td>Sundin and Bras, 2005; Wang et al., 2014; Guidat et al., 2014; Kuo et al., 2010; Lindahl et al., 2014; Opresnik and Taisch, 2015; Ovchinnikov et al., 2014; Kuik et al., 2011</td>
</tr>
<tr>
<td></td>
<td>- Product-service system integration</td>
<td></td>
</tr>
<tr>
<td><strong>Company identity</strong></td>
<td>- Brand equity</td>
<td>Abbey et al., 2015; Subramanian R. and Subramanym, 2012; Agrawal et al., 2015; Pang et al., 2015</td>
</tr>
<tr>
<td></td>
<td>- Seller reputation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Remanufacturer identity</td>
<td></td>
</tr>
<tr>
<td><strong>Marketing strategy</strong></td>
<td>- Remanufactured product positioning</td>
<td>Kwak and Kim, 2013; Michaud and Llerena, 2010; Jimenez-Parra et al., 2014</td>
</tr>
<tr>
<td></td>
<td>- Willingness to pay for green products</td>
<td></td>
</tr>
<tr>
<td><strong>Supply and demand</strong></td>
<td>- Stochastic product return</td>
<td>Liang et al., 2014; Aras et al., 2004; Chen and Chang 2012; Guidat et al., 2015; Zhu et al., 2014; Alqahtani and Gupta, 2015; Asif et al., 2012; Govindan and Popiuc, 2014; Kiziboga et al., 2013; El korchi and Millet, 2011; Sundin and Dunbäck, 2013; Wen-hui et al., 2011; Xiong et al., 2013; Yan, 2012; Jayant et al., 2014; Galberth et al., 2012; Mukhopadhyay and Ma, 2015; Akçalı and Çetinkaya, 2011; Steinhilper, 1998; Östlin et al., 2009; Inmar Reverse Logistics, 2009; Clottey et al., 2012; Clottey and Benton, 2014</td>
</tr>
<tr>
<td></td>
<td>- Core forecasting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Supply chain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Network revenue sharing</td>
<td></td>
</tr>
<tr>
<td><strong>Information and knowledge</strong></td>
<td>- Information sharing</td>
<td>Kurilova-Palisaitiene et al., 2015; Jaber and El Saadany, 2011; Karvonen et al. 2015; Cao et al., 2011; Son et al. 2015; Sargiécili et al., 2013; Tan et al., 2014; Wang and Wang, 2015</td>
</tr>
<tr>
<td></td>
<td>- Learning capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Enterprise collaboration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Agent-based systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Cloud manufacturing</td>
<td></td>
</tr>
<tr>
<td><strong>Material flow</strong></td>
<td>- Hybrid manufacturing and remanufacturing system</td>
<td>Corum et al., 2014; Hsueh, 2011</td>
</tr>
<tr>
<td></td>
<td>- Inventory control and management</td>
<td></td>
</tr>
<tr>
<td><strong>Design for remanufacturing</strong></td>
<td>- Product remanufacturability</td>
<td>Prendeville and Bocken, 2016; Shi et al., 2015 a; Yang et al., 2015; Bakker et al., 2014; Fukushima et al., 2012; Hatcher et al., 2013; Hatcher et al., 2014; Hatcher et al., 2011; Ijomah et al., 2007; Kremer et al., 2016; Kwak and Kim, 2015; Ramoni and Zhang, 2012; Sakao and Mizuyama, 2014; Soh et al., 2015; Sihvonen and Ritola, 2015; Wang and Chan, 2013; Wu, 2012; Wu, 2013; Xiaoyan, 2012; Yang et al., 2015; Pigosso et al., 2010; Du et al., 2012; Pialot et al., 2012; Yang et al. 2015; Cheung et al., 2015</td>
</tr>
<tr>
<td></td>
<td>- Product life extension strategies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Product-service system design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Design for disassembly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Eco-design</td>
<td></td>
</tr>
<tr>
<td><strong>Life-cycle perspective</strong></td>
<td>- Isolated process</td>
<td>Ortegon et al., 2014; Liu et al., 2014; Marshall and Archibald, 2015; Toktay and Wei, 2011; Shi et al., 2015 b; Cerdas et al., 2015; Biswas and Rosano M, 2011; Kafuku et al., 2015; Barquet et al., 2013;</td>
</tr>
<tr>
<td></td>
<td>- System approach</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Industrial symbiosis</td>
<td></td>
</tr>
<tr>
<td><strong>Sustainable approach</strong></td>
<td>- No standard end-of-life solution</td>
<td>Bashkite et al., 2014; Bernard, 2011; Elo and Kareila, 2014; Golinska and Kuebler, 2014; Golinska et al., 2015; Seliger et al, 2006</td>
</tr>
<tr>
<td></td>
<td>- Regulation and laws to support sustainability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Intellectual property rights</td>
<td></td>
</tr>
</tbody>
</table>
Based on the categorization and references provided in Table 2, a short description of the challenges is provided below.

**Business model challenges** - Remanufacturing keeps a strong economic and environmental competitive advantage if operated within a product-service system (PSS). PSS means that the manufacturing company provides the function or their product rather than the products itself, e.g. photocopiers instead of a photocopier. The PSS business model implies a greater servitization of manufacturing industries and would enable a smoother used products and their parts return to remanufacturers. Today, serious concerns have arisen from weak and uncompetitive selling strategies of remanufactured products, dependent on the OEM, since remanufacturers have failed to be a part of a product-service system business model.

**Company identity challenges** – Discounting has a positive effect on remanufactured products, while brand equity manipulation is less important to customers than quality aspects. Moreover, authorized factories receive a higher price for remanufactured product than third-party remanufacturers. Indeed, while seller reputation, length of warranty, proxies of demand and supply, duration, end day of product listings and availability of return policies are all important determinants of price differentials, the most important role is played by the seller’s identity.

**Marketing strategy challenges** – There is no standard market entrance for a remanufactured product, since remanufacturers often struggle to find a competitive market position compared to new products. A common concern of remanufacturers is whether customers are willing to pay for a more sustainable “green” product.

**Supply and demand challenges** – These challenges mainly originate from the stochastic nature of product returns and forecasting techniques that usually fail to incorporate knowledge from related sales, product usage, customer returns behaviour, and product life expectancy information. Additionally, a degree of focus on supply chain complexity can be emphasized, such as closed supply chain barriers for remanufacturers, complex reverse logistics network systems including geographical location of remanufacturing, and revenue-sharing contracts among supply chains. In fact, an inappropriate reverse supply chain complements the demand and supply challenge with insufficient communication and collaboration.

**Information and knowledge challenges** – Faced with negative consequences of insufficient product information sharing among the product life-cycle actors, remanufacturers fail to utilize their learning capacity; manage inventories; coordinate production, distribution and enterprise collaboration; and manage standard remanufacturing operations. The possible introduction of agent-based systems for information sharing to facilitate learning and knowledge is not effective for decision making regarding returned products either. Consequently, remanufacturing fails to join the cloud manufacturing community to overcome challenges in end-of-life processes, such as a remanufacturing system integration, data exchange and resource management.
Material flow challenges – The challenges in material flow are closely linked to the demand and supply challenges, with the main focus on integrated manufacturing and remanufacturing facilities as a hybrid system for cost efficiency, especially related to inventory control and management.

Design for remanufacturing challenges – Decisions made during the design phase have a considerable effect during the remanufacturing process. Indeed, even though product remanufacturability is greatly dependent on product design, design for remanufacturing is rarely applied in the product development process. Among the main reasons for this are unestablished routines and communication practices between multidisciplinary product development teams, and weak attempts to incorporate design for remanufacturing or disassembly, as well as design for product-service systems into the product development process. Moreover, product design typically fails to address sustainability initiatives through the maximization of environmental and economic impact savings across the product supply chain, or even the exploration of a range of product life extension strategies and other eco-design methods.

Life-cycle perspective challenges – Remanufacturing is often treated as an isolated process rather than as a system with a dynamic interface between product life-cycle stakeholders. One of the benefits of the system approach is the rise of an industrial symbiosis, transferring waste to value. In the life-cycle perspective, other remanufacturing benefits could be achieved, including reduced energy demand, reduced environmental impact, decreased global warming, and increased ozone formation.

Sustainable approach challenges – The aspects of economic, environmental and social sustainability are not actively practiced at the remanufacturing companies. Additionally, there is no standard end-of-life solution for used products across the product life-cycle system. The sustainability-supporting regulations and laws fail to impose the remanufacturing practice on society and industry. Finally, the implications of intellectual property rights on the strategic management of remanufacturing in a global perspective remain underdeveloped and unexamined.

3.3 Process-level challenges
A great amount of research has been done to identify remanufacturing challenges related to developing efficient operations (Steinhilper, 1998; Guide, 2000; Van Nunen and Zuidwijk, 2004; Seitz and Peattie, 2004; Lundmark et al., 2009, Östlin et al., 2009; Inmar Reverse Logistics, 2009). The typical operations of a remanufacturing process are illustrated in Figure 2.
The literature study revealed the following classification of process-level remanufacturing challenges (for references, see Table 3).

**Core challenges** – The most typical remanufacturing process challenges are related to the unpredictable and sometimes insufficient incoming core: quantity, quality, variability, and timing, with the main emphasis on core and spare part acquisition and management issues. An underdeveloped approach with which to estimate the remaining useful life of a core challenges the decision of when the core is most suitable for remanufacturing.

**Operations challenges** – The issues of unpredictable and long processing and waiting times, an unknown number of required operations in the process and process sequence, and a high level of inventory originate from a complex and insufficient remanufacturing process. Production planning, together with the reliability of remanufacturing capacity, become an obstacle when the returns rate is not defined, raising a strong concern about disassembly planning and operations scheduling. Product challenges – Remanufactured product quality is the key issue to be addressed, along with the other process challenges. Product reliability and safety issues of these products, compared to new products, are repeating concerns among customers. It was noted that lower quality meant a lower willingness to pay. We identified a need to reduce the level of ambiguity associated with the remanufacturing process, increase quality, and ask for a higher price for products.

**Cost challenges** – The costs associated with the remanufacturing process remain a great challenge to many remanufacturers. Cost fluctuations are closely related to uncertainty in the processes, and especially to acquired core condition. Therefore, it is important to control the performance of the process; however, key performance indicators (KPIs) are rarely used at the remanufacturing facilities. The performance measurement system is typically undeveloped and fails to meet the required process conditions as well as business objectives.

**Upgrade challenges** – The customer’s required innovation rate effects both the remanufactured product and the remanufacturing process. Product knowledge and process information become critical, leading to
a situation where remanufacturers struggle to evaluate and apply the upgrade strategy as well as link it to business objectives and revenue generation models.

Table 3: Overview of key process-level remanufacturing challenges.

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Main focus</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>Core and spare part acquisition and management</td>
<td>Hammond et al., 1996; Aras et al., 2004; Zhou and Yu, 2011; Lin et al., 2014; Wei et al., 2015; Wei and Tang, 2015; Wu et al., 2015; Hu et al., 2014; Hu et al., 2015; Inderfurth and Mukherjee, 2008; Inderfurth and Kleber, 2013; Goodall, 2015; Zhang et al., 2014; Zhou et al., 2014</td>
</tr>
<tr>
<td></td>
<td>Remaining useful life</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optimal point for core remanufacturing</td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td>Process time and sequence</td>
<td>Hammond et al, 1996; Lundmark et al., 2009; Van Nunen and Zuidwijk, 2004; Pawlik et al., 2012; Gan and Su, 2009; Jin et al., 2013; Seliger et al., 2004; Kin et al., 2014; Morgan and Gagnon, 2013; Priyono et al., 2015; Kang and Hong, 2012; Kellenbrink et al., 2014; Kurilova-Palisaitiene and Sundin, 2015</td>
</tr>
<tr>
<td></td>
<td>Operations number</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disassembly planning and operations scheduling</td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Perceived product quality</td>
<td>Parkinson and Thompson, 2004; Wang et al., 2013; Hazen et al., 2012</td>
</tr>
<tr>
<td></td>
<td>Product reliability and safety</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>Process costs</td>
<td>Robotis et al., 2012; Graham et al., 2015; Mutingi et al., 2014</td>
</tr>
<tr>
<td></td>
<td>Performance measurement</td>
<td></td>
</tr>
<tr>
<td>Upgrade</td>
<td>Customer-required innovation rate</td>
<td>Behdad and Thurston, 2011; Galbreth et al., 2013</td>
</tr>
<tr>
<td></td>
<td>Upgrade strategy</td>
<td></td>
</tr>
</tbody>
</table>

### 4. Case Company challenges and lean-based improvements

#### 4.1. Remanufacturing challenges at case companies

Due to the many uncertainties and challenges associated with core availability, timing and quality remanufacturers tend to have longer and more variable lead times than manufacturers. *Long and variable lead times* are also observed at four case companies. In manufacturing, long and variable lead times typically cause considerable losses in companies' throughput and substantially increase the process costs. In remanufacturing, core acquisition and holding costs tend to be low, which means that long lead times are tolerated. The lead time for the Company A is between five and 354 days; such a large variation of 348 days (marked in red colour in Figure 3) originates from unnecessary activities such as inventory storing (before, during, and after the process), waiting for/collecting spare parts and waiting for information on incoming core (see Table 4). These unnecessary operations contribute for the 99 per cent of the total lead time at Company A. A similar situation was discovered at Companies B, C and D, with unnecessary activities accounting for 94 per cent, 98 per cent and 83 per cent of total lead time, respectively.
Based on Table 4, the three most time-consuming unnecessary operations at case companies are:

- **Inventory storing (before, during and after process):** Long remanufacturing lead times are mainly due to long inventory storing times at the case companies. Long inventory storing time primarily reflects process instability when the problem coping strategy is based on uncontrolled safety inventory to compensate for insufficient cores, spare parts or remanufactured product quality. The other reason for long inventory storage time is as a response to unpredictable and uneven core delivery, where the storage inventory strategy is selected due to low core acquisition costs. However, long inventory storage time contributes to the high level of uncontrolled inventory, which not only occupies considerable facility space, but also hinders the collection of necessary cores, spare parts or remanufactured products. This is observed at Company C, where long lead times and also facility capacity to store the fluctuating number of cores, work in process and finished products inventory creates operational difficulties experienced with high labour costs. The analysis of Company C’s challenges revealed that the accumulated inventory storage time was almost 50 times more than the required time for performing the equipment recovery process. Remarkably, only three days are needed to recover the high-quality core when the unnecessary operations are avoided (see Figure 3). The incorrect kind of remanufactured products in finished goods inventory was observed at Company A, and missing parts on the kitting trolley are a typical problem at

### Table 4: Unnecessary operations at case companies in days.

<table>
<thead>
<tr>
<th>Unnecessary operations [in days] caused by challenges</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory storing (before, during and after process)</td>
<td>328</td>
<td>1</td>
<td>153</td>
<td>510</td>
</tr>
<tr>
<td>Waiting for/collecting spare parts</td>
<td>15</td>
<td>62</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Waiting for information on incoming core</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>348</td>
<td>63</td>
<td>153</td>
<td>514</td>
</tr>
</tbody>
</table>

Fig. 3: Lead time at case companies, where necessary operations are marked in green and unnecessary operations caused by challenges are marked in red.
Company B. Long storage time at the external suppliers is experienced by Company C, where process capacity is limited by inadequate information while contributing to process inflexibility in relation to great variation of core inflow pushing the limits of storage space.

- *Waiting for/collecting spare parts* is another reason for long lead time. Long waiting time for material considerably prolongs the lead time and does not add value to the remanufactured product. At Company D, the remanufacturing activities maintain little or no cooperation with the other product life-cycle stakeholders. It was discovered that long waiting times originated from an insufficient connection to external suppliers as well as the absence of material requirements planning system to control the material flow. Long waiting time for special spare parts was also observed at Company B; this time accounts for more than 94 per cent of the lead time in the worst-case scenario.

- *Waiting for information on incoming core:* Company A experiences a lack of information about the core, combined with no core delivery information and usually an unknown supplier; this lack of information has caused operations to be stopped.

Long and variable lead times for the remanufacturing process are often the result of irregular material and information flows; in addition to the above-mentioned causes, other unnecessary activities observed in the four case companies include waiting for a driver, waiting to start an order, and internal logistics. The case company challenges of the incomplete and defective cores when additional time is needed to compensate for the insufficient core quality contribute to unpredictable lead time. Case company challenges, which originate mainly from the company’s inability to control the process, hinder the process improvements, contribute to weakened customer satisfaction and lead to the absence of stable process time. The absence of standard operations, a standard bill of material, a standard list of assembly steps, as well as incomplete or missing documentation/instructions for the operator to perform the assembly, are especially apparent at Company D. There, highly variable lead time causes unpredictable delivery time to the customer, which reduces customer satisfaction and loyalty. The cross-case analysis of the challenges that cause long and variable lead time at the four companies is presented in Table 5.

Table 5: Cross-case analysis of remanufacturing process-level challenges that cause long and variable lead time, identified at each company (“x” is applicable; “N/A” is not applicable).

<table>
<thead>
<tr>
<th>Companies’ remanufacturing process challenges</th>
<th>Case Company</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Lack of material requirements planning system</td>
<td>x</td>
</tr>
<tr>
<td>Poor core information</td>
<td>x</td>
</tr>
<tr>
<td>Lack of core material</td>
<td>x</td>
</tr>
<tr>
<td>Poor spare parts information</td>
<td>x</td>
</tr>
<tr>
<td>Lack of spare parts material</td>
<td>x</td>
</tr>
</tbody>
</table>
• **Lack of material requirements planning (MRP) system**: A non-existent, out of date, complex or non-flexible MRP system is a big problem at each case company. The remanufacturing process is controlled by meetings where information is shared. All of the case companies use internal computerised systems, which the employees feel are not flexible and do not satisfy the companies’ needs.

• **Poor core information** presents challenges in the form of delays in incoming core information regarding type, model, year of manufacturing, condition of the core and the information of the previous user. Moreover, that information appears to be incomplete, incorrect and in some cases never reaches the remanufacturer.

• **Lack of core material** challenges are attributed to the severe defects of the core that tend to arrive at unexpected times.

• **Poor spare parts information** and **lack of spare parts material** challenges arise partly from the same challenges as described in previous two categories. In particular, non-standard or rare spare parts tend to have low priority at the suppliers, which provide little or no information to remanufacturers. Very long spare part delivery time, compared to the total remanufacturing process time, combined with little feedback, creates unnecessary operations and waiting for remanufacturers.

• **Insufficient quality management practices**: The quality challenge relates to the lack of application of quality standards to the processes, as well as the lack of employee qualification.

• **Large inventories**: The inventory challenge is attributed to the inventory storage space management, since the overloaded inventory cause problems in finding the right item. Remanufacturers tend to cope with inventory before, during and – in the worst case – after the remanufacturing operations.

• **Stochastic remanufacturing processes**: The challenge of the remanufacturing process is a long lead time with unstable and unpredictable operations. Since every single core arrives in different condition, a different number of different operations have to be performed to bring that item to “as good as new” condition.

• **Lack of supply-demand balance**: The last two challenges experienced by Company C are difficulties in maintaining the balance between arrived cores and demanded ones. Company C operates at the forefront of the remanufacturing process, where the fluctuating inflow of computers is experienced as the biggest problem.
Insufficient automation: Another challenge at Company C is an insufficient automation level that results in high operational costs due to high labour cost, since remanufacturing is highly dependent on manual work.

4.2. Suggested lean-based improvements

After the analysis of remanufacturing challenges collected at the companies (see Table 5), the development of lean-based improvements for each company was carried out. Based on the literature study on lean remanufacturing, the focus group interviews and the authors’ academic and industrial knowledge of lean production, we developed suggestions to tackle remanufacturing challenges (for a model on lean improvement tools and lean measurements, see Shah and Ward, 2007).

a) Implementing standard operations, instructions or/and checklists would develop a base for a MRP system at the remanufacturing facility. Standard operations provide remanufacturers with a stable foundation to build further improvements to enhance a company’s productivity (Bicheno and Holweg, 2009). By communicating in the standard way, the challenges related to the core and spare part information flow can be diminished. Standard operating procedures can be expressed through instructions for the standard process steps or activities needed to complete a task; thereby reducing the deviation in task performance by companies’ employees. These instructions can encompass both images and text descriptions, written briefly and simply to ensure better understanding by operators and technical personnel. According to lean, the best standards are developed by the employees who are directly involved in performing the task. Through identifying the best practice, standard operations can be designed, tested, improved and applied to remanufacturing processes. To follow standards in carrying out a given operation, a specific set of procedures has to be established. The checklist – that is, a written list of activities or tasks to be performed and/or controlled in the standard sequence – can ensure that the best performance is achieved. The introduction of the standard work procedures would help establish stable lead time that can be used to communicate internally and externally.

b) Implementing continuous flow would mostly affect the material movement at the facility; however, the information flow will be also changed dramatically. There are a broad variety of tools and practices to establish a continuous flow. The production process challenges related to stochastic remanufacturing processes can be solved by continuous flow that required great employee involvement in total production system transformation. The continuous flow focuses on linking the separate remanufacturing steps in a smooth undisrupted chain, maintaining stable and predictable cycle times; this is currently absent at the four case companies. This system attempts to reduce the cost and time of information processing and benefits with improved productivity through reduced lead time, improved product quality and an optimized inventory level (Sugimori et al., 1977).

c) Employing the Kanban ordering system is possible means to control the production process. Typically, Kanban refers to a system with triggering mechanisms to control process pace by sending a signal upstream that reflects actual customer demand. Respectively, the downstream process pulls products from upstream, creating a linked product flow. A great improvement resulting from the transformation of the ordering system to the Kanban is control of the inventory
level at the remanufacturing site. Today, the Kanban ordering system is not implemented at any of examined companies, but there is great interest and desire to transform the core and spare parts supply and demand according to the Kanban.

d) Improving teamwork by introducing product teams or work groups to manage shop floor tasks is desired by case companies. At Company C, only managerial staff work in a team. The production manager explains that, first of all, the remanufacturer must create conditions in which the employees are empowered to know what customers are buying and are able to talk to the suppliers. Once this is clear, often through involving shop floor employees, the company can start to approach the remanufacturing process by ordering the project according to the product team’s specification. Creating teamwork through the factory is helpful in managing spare parts, but also cores material flow and information, since improved information sharing would make it possible to order spare parts and plan the consequent operations to suit the standard lead time. Teams would be responsible for the product from the start through to the delivery to the customer, enabling quick feedback. This would facilitate a greater reduction in variation in lead time by providing what is needed when it is needed.

e) Organizing employee cross-training and learning through problem solving is necessary due to companies’ insufficient information sharing. Employee cross-training would benefit all case companies through investments in employee skills. Employee training is a dynamic, hands-on learning activity that involves knowledge sharing and teaching essential skills by the area expert or leader. It is an essential element of the continuous improvement philosophy that leads to the establishment and maintenance of standardized work tasks, the development of a platform for efficient and effective problem solving, the creation of a safe workplace, and the generation of partnering relations with suppliers (Bicheno and Holweg, 2009). Training in order to exchange experience, gain knowledge in the related area, or establish networking to generate the lacking data is vital for all four remanufacturing companies, since remanufacturers are currently very dependent on manual work.

f) Designing factory layout for continuous flow is beneficial in terms of solving inventory management challenges and, together with the continuous flow and Kanban ordering system, has the greatest effect on the lead time reduction. Moreover, an appropriate layout design contributes to process improvements and factory capacity utilization (Bouzon et al., 2012; The Productivity Development Team, 1999). Cellular manufacturing is usually considered as a method for achieving the objectives of a lean layout. Cell equipment is arranged in sequential order and is shaped in arches like a ‘U’ or a ‘C’, allowing products to flow through the process, either piece by piece or in small batch sizes. Therefore, the walking and transport required decreases. By introducing a lean layout, companies are able to create a continuous material and information flow and improve the control of inventory. Furthermore, the mentioned layout improvements facilitate communication between employees working in the cell (McLaughlin and Durazo-Cardenas, 2013). Achieving a lean layout is a challenging but realistic task for remanufacturers working with product disassembly-assembly tasks. Additionally, similar products can be divided into product families that require
similar operations, where processing can be executed in the same cell (The Productivity Development Team, 1999).

g) Developing supplier partnership is vital for every remanufacturing company and the effect of this improvement can be observed through the entire remanufacturing process in the improved supply of cores and spare parts with the feedback provided. An anticipated intention to include the customer and supplier in the remanufacturing process was revealed during the data collection interviews. Lean has established practices that companies utilize in order to successfully bring the necessary cooperation elements to form reliable and trustworthy partnering relationships (Liker and Choi, 2004).

Lean is known as a philosophy of continuous improvement that eliminates unnecessary process operations and has a significant effect on lead time improvements. The essential reductions in lead times are projected after the implementation of the seven suggested lean-based improvements. The projected lead time reduction is based on the elimination of unnecessary operations (see Table 4), which account for 99 per cent, 94 per cent, 98 per cent and 83 per cent of the total process lead time at Companies A, B, C, and D, respectively (see section 4.1), and could be perceived as an ideal lead time. The ideal lead time is a long-term goal and must be compensated by keeping the safety inventory. The suggested safety inventory is a case to change depending on the improved cooperation with suppliers and has to be estimated and adjusted to each company; however, further analysis is needed for that purpose. The suggested lean improvements can be applied to other remanufacturing companies with the similar challenges, as well as work as a compliment to the other improvements developed by remanufacturing researchers and practitioners.

Table 6 shows the interdependency of the identified remanufacturing challenges at the four case companies and the suggested lean-based improvements. To reduce the complexity of the relations, the connection of the greatest effect are demonstrated with a capital ‘X’, while the moderate effect is marked with small ‘x’.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Improvement</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core return</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spare part supply</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process efficiency</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Customer satisfaction</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

17
5. Discussion

The scepticism regarding lean’s suitability for remanufacturing contexts has been expressed since the beginning of the lean remanufacturing research (Seitz and Peattie, 2004). At the same time, some researchers have discussed the potential for applying lean to remanufacturing in order to gain efficiency through reducing process lead time, lowering the high level of inventories and improving material
movements, product flow and use of space (Sundin, 2006; Östlin and Ekholm, 2007; Hunter and Black, 2007; Kucner, 2008; and Pawlik et al., 2012).

Ten challenges from the case study research highlight the long and variable remanufacturing process lead time. Lean production is useful for reducing process lead time. Therefore, lean improvements have been suggested to tackle remanufacturing process challenges with a focus on reducing lead times. Only three categories of system-level challenges collected from the literature review were reflected in the four case companies: information and knowledge, material flow, and demand and supply (see Figure 1 and Table 2 for more detail). Process-level challenges are observed to a greater extent than system-level ones, aligning four of five identified process challenges from Table 3: core, product, operations and costs. Therefore lean solutions developed for the case companies do not cover all of the challenges collected in the theory, which means that lean-based improvement focus is on process-level challenges.

Previous studies have actively discussed lean-based improvements in continuous flow (Fargher, 2006; and Jacobs and Chase, 2001), Kanban ordering system (Guide, 2000; Kanikula and Koch, 2011) and cellular factory layout. With this paper, four additional lean-based improvements have been identified at the case companies: (1) standard operations, instructions or/and checklists; (2) teamwork; (3) employee cross-training, and (4) supplier partnership. Thus, the study has identified a need to study other possible lean-based improvements.

At the same time as developing possible lean-based improvements to remanufacturing, it is important to remember that remanufacturing is different from manufacturing. For example, in remanufacturing, inventory is not burdened by high capital investments due to low core acquisition costs. This means that remanufacturing keeps a great amount of cheap material on site. However, large inventories contribute to long and variable remanufacturing process lead times. So, why is it important to reduce remanufacturing process lead when there are no significant inventory acquisition and holding costs? To answer this question, it is necessary to take a holistic perspective on the process lead time in a circular economy. The current remanufacturing process lead time causes unnecessary investments in raw material extraction, greater consumption of scarce raw materials, delays in hazardous material treatment, and dramatically prolongs the time it takes to return the core to the next user for a useful life. As a result, in order to bring a product to useful life, remanufacturing must make between 83 per cent -99 per cent of unnecessary activities (based on case company lead time). Consequently, remanufacturing lead times become an urgent problem in the circular economy.

6. Conclusions

In this paper challenges in remanufacturing were studied through a literature review and case studies in four companies. The literature review identified challenges at industry-, system- and process-levels. The case studies focused on process-level challenges related to core, product, operations and costs. The results show that ten identified remanufacturing process challenges contribute to long and variable remanufacturing process lead times, where 83 per cent to 99 per cent of total time is consumed by three unnecessary operations: inventory storing (before, during and after process), waiting for/collection spare parts and waiting for information on incoming core.
Theoretical implications
This paper contributes to a better understanding of remanufacturing process-level challenges and how they can be tackled using lean. The major problem of remanufacturing process is a long and variable lead time. One of the main goals of lean is elimination of unnecessary operations and reduction of lead time. The paper discusses how the identified remanufacturing challenges can be solved by tools and methods used in lean and thereby contributes to the knowledge on how lean could be applied in the remanufacturing context.

Practical implications
In this paper four remanufacturing companies with diverse products and different relations to the OEM were studied. All case companies experienced the problem of a long and variable lead time and the results point to very similar process challenges. The paper suggests concrete lean-based improvements to tackle remanufacturing process challenges and improve lead times. The paper is of interest to different remanufacturing companies facing similar challenges and a source of information for managers who are interested in the application of lean to remanufacturing.

Acknowledgement
The authors would like to thank the Swedish Governmental Agency for Innovation Systems (VINNOVA) for financing the research for this paper.

References


Centre for Remanufacturing and Reuse (CRR), 2007. An Introduction to Remanufacturing.


Fargher, J.S.W., 2006. Lean Manufacturing and Remanufacturing implementation tools, Missouri Enterprise, University of Missouri, Rolla, MO.


25


Rother, M. and Shook, J., 2003. Learning to see: Value Stream Mapping to Create Value and Eliminate Muda, The Lean Enterprise Institute, Brookline, Massachusetts, USA.


