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Trends and Research Challenges in Remanufacturing

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Remanufacturing is one of the critical elements moving our economy toward one that is circular. Today, remanufacturing is attracting growing attention worldwide. Meanwhile, despite its potential in terms of its effects on both environment and economy, remanufacturing has not yet been sufficiently exploited. This indicates that there exist both drivers for and barriers to an increase in remanufacturing in economies. Although there are both technological and non-technological requirements for remanufacturing, R&D is unavoidable for its promotion. This article outlines trends, drivers, and barriers for remanufacturing, and presents reviews of studies on selected topics in remanufacturing. The selected R&D topics in this article are product design for remanufacturing, additive manufacturing for remanufacturing, operations management in remanufacturing, and business models for remanufacturing.

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NOMENCLATURE

OEM = original equipment manufacturer
IR = independent remanufacturer
DfRem = design for remanufacturing
EOL = end of life
AM = additive manufacturing
CLSC = closed loop supply chain
PSS = product service system

1. Introduction

Remanufacturing is one of the critical elements for realizing a resource-efficient manufacturing industry and circular economy. Remanufacturing is an industrial process that turns used products into products with the same quality, functionality and warranty as new products.[1] The remanufacturing process consists of disassembling, cleaning, inspecting, repairing, replacing, and reassembling the components of a product to restore it to “as new” condition (Fig. 1).[2] Remanufacturing can also imply adding new and better functionality to a used products, such as adding a more wear resistant materials on the surface, new sensor systems, and so on. Remanufacturing has been undertaken for products such as automobile parts, machinery, photocopiers, single-use cameras, and furniture. As remanufacturing retains the geometric shape of products, it preserves the materials and added value embedded in the original products. Remanufacturing is generally superior to material recycling in terms of energy and material savings. Existing studies show that remanufacturing saves up to 90% of materials compared with new product manufacturing,[3] and that the energy required for original production versus remanufacturing can reach ratios of six to one.[4] In addition to these environmental benefits, remanufacturing has a significant potential for economic impacts. Used products, in many cases, retain a high portion of the value that was embedded in them when they were originally manufactured. However, they are usually discarded without exploiting most of the remaining value. Because remanufacturing exploits this value, it can potentially have high margins economically. In some countries, remanufacturing already holds an important position in their economies. In addition, remanufacturing is generally labor intensive, which can have positive effects on job creation. Furthermore, as remanufactured products are usually priced lower than newly manufactured products, it has the potential to improve social welfare, especially in developing countries. Due to these features, remanufacturing has affinities with the concept of sustainable production and sustainable society and has, in recent years, been attracting increasing global attention.

This article outlines the trends and research challenges related to

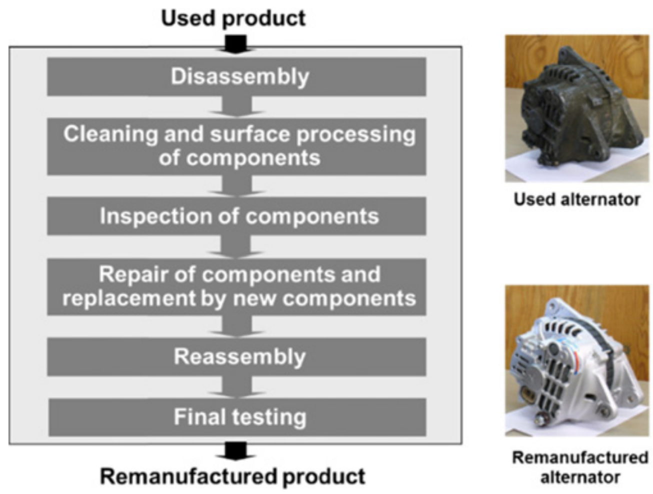

Fig. 1 Remanufacturing process

remanufacturing. Although remanufacturing has good potential for growth, this potential has not yet been exploited. This paper describes the barriers to remanufacturing and specifies the research challenges for overcoming these barriers. It then presents a review of studies on selected important research topics. The rest of the paper is organized as follows. The next section identifies some recent trends and businesses using remanufacturing. The activities of industries and governments are also summarized. Section 3 discusses the barriers to remanufacturing and shows the research needed to overcome these barriers. Sections 4 to 7 present reviews on four selected topics on the challenges for remanufacturing: product design, additive manufacturing (AM), operations management, and a business model for remanufacturing, respectively. The final section concludes the article and shows the prospects for remanufacturing.

2. Businesses Using Remanufacturing and Trends

2.1 Businesses and Markets

Remanufacturing has been conducted in various product areas. Remanufacturing has its roots in the beginning of the industrial age with steam engines, railways, power generation and electrical equipment, and machine tools.[3] The major sectors that have remanufacturing activities include automobile parts, heavy duty equipment, aerospace, machinery, medical devices, photocopiers, ink and toner cartridges, IT products, vehicle tires, office furniture, and single-use cameras (see Table 1).[3,5,6]

The automobile parts remanufacturing industry is the world's largest remanufacturing sector.[3,6] Automobile parts remanufacturing is common in many countries. In the US, for example, up to 90% of major replacement parts are remanufactured, including engines, transmissions, starters, alternators, and brakes.[7] Many other automobile parts are also remanufactured.[3] Studies on remanufacturing in this sector has also been carried out by a number of researchers.[8,9]

Remanufacturing of heavy-duty equipment parts has also been conducted for decades. Caterpillar, in the US, created its remanufacturing division in the early 1970s and has exhibited sound growth ever since.[10] Komatsu and Hitachi Construction Machinery in Japan also conduct remanufacturing. Similarly, aerospace parts, machinery, and medical devices are remanufactured mainly by the original equipment manufacturers (OEMs) of the products.

Photocopy machines is another well-known example of remanufacturing.[11,12] OEMs such as Xerox in the US and Fuji Xerox, Ricoh, and Canon in Japan conduct photocopier remanufacturing. In that sector, many products are leased to customers and need frequent maintenance and consumable supply services. Thus, the sector provides a good case for studying the possibility of incorporating remanufacturing with product service systems (PSSs).[13]

Although the market for single-use cameras has shrunk, the remanufacturing of these cameras is still a good example of consumer product remanufacturing. The remanufacturing has been done by OEMs such as FujiFilm and Konica in Japan and Kodak in the US. FujiFilm, for example, developed a fully automated remanufacturing line in 1998,[12,14] which operated for over 10 years.

There are other sectors in which remanufacturing is conducted.[6] However, in many cases, the remanufacturing of consumer products is still in the early stage of growth, and this presents a challenge. Recent market penetration products such as renewable energy generation systems and battery systems are also challenging areas for remanufacturing.

• Note that not all types of products are suitable for remanufacturing. The characteristics of remanufacturable products include the following:

• Stable product technology
• Stable process technology
• A physical lifetime of critical subparts is substantially longer than the time that the product is used
• A product that fails functionally rather than by dissolution or dissipation
• A recoverable value added to the product that is highly relative to its original cost
• A detailed guideline for identifying candidate products/ components for remanufacturing can also be found in the existing literature.[2,15-21]

2.2 Markets

The markets for remanufactured products are generally not precisely known. The US is the world's largest producer and consumer of remanufactured products,[5,6] and the US market US has been investigated in great detail. Recently the US International Trade Commission (USITC) conducted a detailed investigation into the domestic market for remanufactured products.[6] According to the report, the US production of remanufactured products in 2011 totaled at least 43.0 billion USD, and remanufacturing supported at least 180,000 fulltime jobs in that year. Table 1 shows part of the estimate.

In the UK, the Resource Recovery Forum (RRF) surveyed remanufacturing industries in the country.[22] It estimated that remanufacturing activities accounted for 2.4 billion GBP and had the effect of saving the equivalent of over 10 million tons of CO_2 per year.[22]

In most other countries, the market for remanufacturing is not precisely known. Clarifying the market impacts of remanufacturing is a critical step in developing the appropriate policies for the promotion of remanufacturing. Thus, additional investigation is needed.

Table 1 Estimate of remanufactured goods production and employment in the US in 2011[6]

Sector	Production (thousands USD)	Employment (full-time worker)
Aerospace	13,045,513	35,201
HDOR[a] equipment	7,770,586	20,870
Motor vehicle parts	6,211,838	30,653
Machinery	5,795,105	26,843
IT products	2,681,603	15,442
Medical devices	1,463,313	4,117
Retreaded tires	1,399,088	4,880
Consumer products	659,175	7,613
All other[b]	3,973,923	22,999
Wholesale	-	10,891
Total	43,000,144	179,509

[a]HDOR equipment stands for heavy-duty and off-road equipment
[b]Includes remanufactured electrical apparatus, locomotives, office furniture, restaurant equipment, etc.

2.3 Worldwide Attentions on Remanufacturing

Remanufacturing is one of the enablers of a sustainable society. Two indications of this in recent years would be

- In the G7 Summit of June 2015, held in Germany, remanufacturing was for the first time stated in the summit declarations.
- The International Resource Panel (IRP) of the United Nations Environmental Program (UNEP) set up a remanufacturing working group.

Also, governments and governmental organizations have shown an increasing interest in remanufacturing in recent years. European Commission started funding an R&D project on remanufacturing. The project of European Remanufacturing Network (ERN) started in 2015 and it aims at developing a network of governments, industries, and academia on remanufacturing in the region, investigating the market and collecting the best practices for designs, processes, and business models that facilitate remanufacturing.

The Singapore government also funds R&D on remanufacturing. In 2012, it launched the Advanced Remanufacturing & Technology Centre (ARTC) to look into the R&D for developing remanufacturing technologies. The aim is to develop industry-leading capabilities in repair and restoration, surface enhancement, and product verification to enable the rapid transformation of R&D results into customer solutions. Several leading multinational corporations (MNCs) and small and medium enterprises (SMEs) such as Rolls-Royce, Siemens Industry Software, ABB, TruMarine, and JPT Electronics have signed a memorandum of understanding with the ARTC to collaborate on addressing the technological challenges of remanufacturing in the aerospace, oil & gas, marine, energy, and automotive industries. The research center has also tapped into the world-class research expertise of the Agency for Science, Technology and Research (A*STAR) as well as the strong capabilities of local universities, such as Nanyang Technological University, to rapidly create solutions and bring the technologies into industrial production applications for the benefit of all stakeholders.[23]

Governments in other countries including China, Korea, Malaysia, and a number of European countries fund R&D and investigations into remanufacturing. In China, the National Key Laboratory for Remanufacturing leads the R&D on remanufacturing in the country. The Korean Institute of Industrial Technology (KITECH) undertakes R&D and policymaking on remanufacturing in Korea and co-organized a conference on remanufacturing in recent years. The Malaysian government funded an investigation into remanufacturing markets and industries in that country.[24] All of these events show that there is growing attention on remanufacturing by governments and industries around the world.

3. Research Challenges on Remanufacturing

3.1 Barriers to Remanufacturing

Although remanufacturing has a number of driving forces, it also has numerous barriers. Many companies are still reluctant to implement remanufacturing in their company strategy and operations model due to the associated challenges and uncertainties.[25] There are at least three requirements for remanufacturing.[26,27] The remanufacturing system consists of three parts - collection, the remanufacturing process, and redistribution - each having its distinct challenges. The barriers to remanufacturing include

- Effective collection of used products
- Development of efficient remanufacturing process (including efficient disassembly process and revers logistics)
- Customer acceptance of remanufactured products
- These are the requirements for remanufacturing both in cases where remanufacturing is done by OEMs and in cases where it is done by independent remanufacturers (IRs). In addition, OEMs face a unique obstacle for remanufacturing. Thus, the fourth barrier is
- OEMs do not always have an incentive to remanufacture

Generally, OEMs have advantages over IRs in resolving the problems associated with remanufacturing because, for instance, they have feedback on product reliability and durability, a reputation for quality, and competition in lower-priced markets.[28] By contrast, OEMs face a unique obstacle: remanufacturing may reduce the sales of new products, and profits on the sales of remanufactured products may be lower than those on the sales of new products.[29] This phenomenon is called "the cannibalization of new product sales by remanufactured products."[30] When OEMs do not intend to remanufacture products themselves, they sometimes prevent their competitors (e.g., IRs) from remanufacturing them,[9] they even implement product designs that complicate remanufacturing.[8,12] These factors create additional barriers and challenges for remanufacturing.

3.2 Research Challenges for Remanufacturing

There exist both technological and non-technological challenges to mitigating the abovementioned barriers and thus promoting remanufacturing in society. The research challenges for remanufacturing include the ones in the following four categories:

- Product and process design to facilitate remanufacturing
- Remanufacturing process engineering
- Remanufacturing process optimization
- Business model to facilitate remanufacturing

Product design is a critical factor for realizing cost-effective remanufacturing processes.[2,3] In case of remanufacturing of photocopiers and single-use cameras, for example, product design plays a critical role in improving the efficiency of the remanufacturing process. Process design is also important. The selection of joining processes, for example, can hamper the later need for effective disassembly processes.

Remanufacturing process engineering includes: cleaning techniques, materials engineering for the surface processing of components, and testing and diagnosis techniques. These techniques are also critical in developing efficient remanufacturing processes. For instance, cleaning is one of the costliest processes in automobile parts remanufacturing[8] and in photocopier remanufacturing.[31] Among these techniques, additive manufacturing (AM) has been one of the hot issues in recent years. AM provides effective measures for component surface processing as well as for component manufacturing.

Remanufacturing process optimization is another important topic for developing an efficient remanufacturing process. Although production planning and control is complex in traditional new product manufacturing, it is even more complex in remanufacturing. The complexities are derived from the uncertainties in the quality, quantity, and timing of the returned products from which remanufactured products are made.[32] In addition to production planning and control, process optimization includes issues around inventory management, return and demand balancing, logistics (reverse logistics), and supply chain management.

The business model also significantly matters to remanufacturing. It matters on the collection of used products, customer acceptance of remanufactured products, and OEM motives with respect to remanufacturing. As the market becomes mature, customers increasingly seek product functions rather than the products themselves. One possible form of the business model in such a case is that the providers (e.g., OEMs) retain the ownership of products, provide the product functions, and charge for the provision of the functions. This kind of business model greatly facilitates the collection of used products, improves customer acceptance of remanufactured products, and can motivate OEMs to carry out remanufacturing.

The following sections describe the reviews of the following four topics: product design for remanufacturing, AM for remanufacturing, operations research for remanufacturing, and business models for remanufacturing. These are the topics picked out from each of the categories described above.

4. Review: Design for Remanufacturing

4.1 Definition and Motivation

Some previous studies indicate that more than 70% of the product lifecycle cost is determined by the end of the product design stage.[32] Thus, it is significant that the potential for remanufacturing is projected correctly and timely in this stage, so that an end of life (EOL) product can be remanufactured viably and economically. Meanwhile, previous research reveals that many of the barriers that occur during remanufacturing can be mitigated through proper decisions made during the design process. This further reinforces the necessity of designing the product for remanufacturing.[2,16,19,33,34]

The definition of design for remanufacturing (DfRem), as presented by Charter and Gray,[20] is “a combination of design processes whereby an item is designed to facilitate remanufacture. These design processes comprise a series of Design for X strategies, such as design for core collection, design for disassembly, design for cleaning, design for multiple lifecycles or design for upgrade, whose prioritization may vary and depend on requirements from the remanufacturing side. The underlying philosophy is to address the lack of remanufacturing knowledge in the product design stage and incorporate design features that can facilitate the EOL remanufacturing process.

Usually, remanufacturing is practiced by three types of players: (a) OEMs, who remanufacture products that own; (b) contracted remanufactures, who remanufacture products that are owned by OEMs or customers, under contract; (c) IRs, who collect, remanufacture and resell the products without any connection to the OEMs. The power to enhance the remanufacturability of a product through design is often owned by the OEM, since they have the ability to control the product design stage.

4.2 Approaches for DfRem

Understanding the motivation and necessity of DfRem, various tools and methodologies for facilitating DfRem have been proposed. Based on their approaches, these tools can be classified into three categories, which will be discussed below.

4.2.1 Guidelines for DfRem

The most straightforward and commonly used approach for DfRem is to generate a list of design guidelines that address various concerns arising from the remanufacturing process. Usually, these design guidelines are grouped and presented based on the requirements of an individual remanufacturing process, such as guidelines to facilitate disassembly, cleaning, for restoration/replacement. The details of these guidelines can be found in existing literatures.[16,17,19,20,35-37] Most of these guidelines are directional and qualitative in nature and collectively present a comprehensive and complementary insight into steering a design toward higher remanufacturability. However, this approach to DfRem, has also been criticized as being lengthy and overly-daunting, as it is impossible for designers to consider all of these criteria simultaneously, and some of the remanufacturing design requirements even intrude on traditional design.[38]

4.2.2 Assessment Metrics, Models, Tools for DfRem

Other DfRem work has focused on developing mathematical models, evaluation frameworks, or analytical tools to assess the remanufacturability of a product and providing design feedback to enhance the potential remanufacturing. An example is the remanufacturability assessment tool developed by Bras and Hammond.[39] In this tool, a series of matrices for assembly and disassembly, testing and inspection, cleaning, and part refurbishing and replacement were developed to assess the performance of the design toward a major remanufacturing process. The indices of these matrices will be further synthesized strategically into a single remanufacturability index to indicate the feasibility of the product DfRem. Other examples can also be found in “RemPro Matrix” developed by Sundin;[34] “Remanufacturable Product Profile” proposed by Zwolinski et al.,[38] “Integrated Remanufacturability Evaluation Tool” reported by Du et al.[40] In addition, some research groups have tried to develop appropriate existing design tools like quality function development (QFD), platform design, or failure mode and effects analysis (FMEA), to facilitate product DfRem.[41-44] The advantage of these widely used industrial design tools is the familiarity that designers already have with them, which, to a certain extent, can ease the product design process and facilitate the integration of DfRem within the product development process.[44] However, most of these tools, especially those of a quantitative nature, require too much technical data and either are too complex to use in the early design stage, or by the time the product specification has been defined, it is too late to make substantial changes to the design.[44] In addition, with these DfRem tools, "lifecycle thinking is often missed.

4.2.3 Lifecycle Thinking

Given the potential conflict that DfRem may have with other DfX methodologies such as assembly and manufacture, there is a need for design support tools that can take "lifecycle thinking into account and generate an optimized and robust design decision. In this regard, another trend of the DfRem literature is proposed to address this design issue from a holistic lifecycle perspective. With this approach, a comprehensive view of the environmental/economic performance of a product is analyzed and provided. It considers not only the manufacturing and usage stages but also the EOL stages, i.e., reuse, recycle, and remanufacture. The aim is to reduce undesirable impacts throughout the product's lifecycle.[45] For example, Shu and Flowers adopted the lifecycle cost analysis (LCCA) to select fastening and joining methods that would minimize assembly/disassembly costs throughout the product lifespan.[17] Cumulative energy analysis was adopted by Yang et al. to quantify the lifecycle environmental benefits of a remanufactured product and support the decisions for improving the product design and EOL recovery system.[46] However, one of the challenges of carrying out a lifecycle analysis is that a significant amount of product data is usually required. There is a need for building a database that gathers knowledge for a specific product process, especially a remanufacturing process, to assist designers in evaluating the lifecycle performance of their products in the early design stage.

4.3 Challenges and Future Development of DfRem

Understanding the necessity of DfRem in the early design stage, there are still some roadblocks to its successful implementation. First, compared with other design issues, such as design for manufacturing or design for usage, DfRem is usually not given priority and is viewed as less important due to a lack of DfRem awareness among designers.[19,20,44] Meanwhile, DfRem guidelines comprise considerations that present a relatively new set of challenges that designers may not be prepared to deal with, not to mention that some of the DfRem requirements intrude on existing design requirements, such as design for assembly.[17,47] Furthermore, some OEMs even deliberately play down remanufacturing through product design to suppress independent remanufacturing activities.[8,12,48] The reason is that none of the OEMs is willing to enhance the remanufacturability of their products to benefit IRs, who are viewed as strong competitors to their own products.[9,44]

Until now, most of the proposed DfRem tools remain largely in the academic field. Further research work can focus on integrating the proposed tools into the product development phase, thus facilitating DfRem in the early design stage. Meanwhile, it is desirable to have more remanufacturing case studies investigated in order to build up the remanufacturing knowledge database, validate the DfRem tools proposed by researchers and further enhance the applicability of the DfRem tools.

The LENS process, courtesy of Optomec

Fig. 2 Laser-Engineered net shape by optomec

5. Review: Additive Manufacturing and Remanufacturing

5.1 Remanufacturing Using Additive Manufacturing Technology

Additive manufacturing (AM) is a 3-dimensional layer by layer manufacturing directly from digital product data. There are a number of different processes. ASTM International Committee F42 on AM Technologies has defined seven AM principles:[49] (1) binder jetting, (2) directed energy deposition, (3) material extrusion, (4) material jetting, (5) powder bed fusion, (6) sheet lamination, and (7) vat photopolymerization. For the use in remanufacturing is perhaps Directed Energy Deposition the most useful process.

5.1.1 Remanufacturing Using Directed Energy Material Deposition

Directed energy deposition is a group of processes especially well suited for remanufacturing.[50] This group of processes are using a focused thermal energy beam to melt and fuse materials. The materials added are typically in the form of powder injected into the fusing zone with a flow of powder and inert gas through a nozzle or through mechanical feeding of wire from a spool. The nozzles and beam are typically positioned and oriented by a multi-axis control structure. This can be a robot arm or similar to a CNC 5-axis milling machine.

The thermal energy beam is usually laser,[50] but conventional arc welding deposition and other high-energy beams such as plasma and electron beam do exists. One example of such a process is the Laser-engineered Net Shape from Optomec.

The process has the advantage of easier deposition on existing

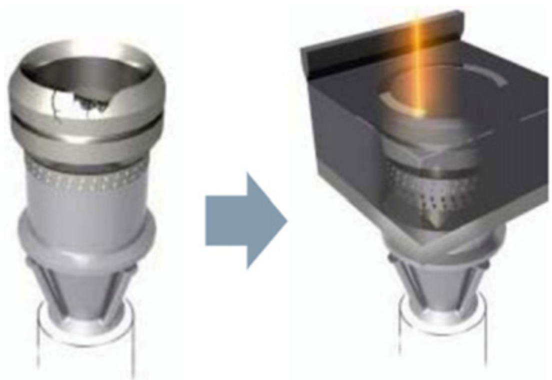

Fig. 3 Gas turbine burner tip repair, © Siemens AG 2014[56]

substrate materials of an arbitrarily shape, as a contrast to powder bed type processes.

The process allows the making of functional graded materials, by feeding different mix of materials through two or more nozzles in to the molten pool.

This allows the remanufacturing process to add improved functionality to the remanufactured part, for example adding a more wear-resistant material to the outer surface than the original material. One example could be remanufacturing of worn-out water turbines. After measuring the amount of wear, the additive machine could add Stellite directly on the worn surface, increasing the expected lifetime of the turbine. The additive manufacturing process allows also adding on additional shapes on the existing parts for extended functionality. Remanufacturing of parts such as turbine blades has been demonstrated through combining CAD data and measuring data of the damaged/ worn part can be used to generate paths for the deposition.[51-53] Remanufacturing of dies and moulds is another example.[54] It is applied not only to repair worn-out dies, but also to remanufacture the dies for new products and processes. Jhavar et al. show an example using an AM micro-plasma transferred arc wire deposition process for die remanufacturing.[55] In this study, the substrate was pre-hardened AISI P-20 tool steel, and the wire was also P20 steel.

The drawback of the directed energy deposition methods is that it would often imply a pool of molten material that would need to be horizontal to keep the material in the pool. Upside-down material deposition or similar can be challenging or impossible. When repairing larger structures, which is difficult to handle into a wanted orientation, this can typically be necessary.

5.1.2 Remanufacturing Using Powder Bed Fusion

There are numerous examples of other AM processes suitable for remanufacturing. The most widely used AM process is perhaps the powder bed process that gives the most freedom of geometry, but do have a limitation that any application of new material has to be on a planar surface, within the tolerances of the chosen powder layers. One example is SIEMENS's repair of gas turbine burner tips where damaged burner tips are machined before they are placed into the powder bed of a Selective Laser Melting machine and new tips are built onto the machined surface.[56] This is in commercial application by SIEMENS.

5.1.3 Other Benefits of AM

As mentioned, the benefit of AM is perhaps mainly the ability to add on new material on existing surfaces in order to repair and remanufacture used and worn parts. There are, however, additional advantages of AM. Gaoa et al. discuss that another benefit of AM is that it can be used for remanufacturing independent of the value chain.[57] The repair-on-demand is possible if fast repair is necessary and where normal logistics are a challenge such as for the in-the-field remanufacturing. The US army are investigating the use of AM in their "Mobile Parts Hospitals.[58]

5.1.4 AM Post Processing

One of the disadvantages of AM process is that although very near net shape, there is still a rough surface created by the layer wise adding of material. There are techniques to minimize the surface roughness through for example optimizing building paths, layer thickness and powder grain size. A better surface from AM process means in most cases a more expensive and time-effective process and post processing would in most cases be necessary anyhow. The post processing is usually a material removing process, with a material cutting or one or more abrasive processes such as polishing. There exist optimization of the combination of AM and subtractive processes, but these are mainly applied to new component manufacturing, and not to remanufacturing. Boivie et al. described an optimization system called OMOS for a hybrid additive/subtractive manufacturing cell combining powder bed fusion and machining which probably also can be applied to remanufacturing.[59]

5.2 Material Properties

The directed energy deposition can deposit a large range of materials, including: tool steels, stainless steels, titanium and titanium alloys, aluminum alloys, nickel based alloys, cobalt-chromium alloys, copper alloys, gold and silver.[49] Most AM systems melt the material and make a part with close to 100% density. In many cases the material properties exceed casted materials and are close to wrought materials. Longitudinal tests performed by Arcam and Morris technologies show evidence of sustained reliability on the material properties.[49] There is, however, still a way to go before AM parts are fully qualified for advanced use. The anisotropy caused by the layers surface texture and through-part homogeneity are some of the challenges. Materials made by can be more brittle, but local failure mechanisms are still not completely understood. This uncertainty in material properties is currently a challenge for the establishment of reliable remanufacturing processes using AM.

CIRP is currently investigating the variability of AM material properties through a round robin test.[59,60] VDI has made series of tests resulting in material standards for different materials.[61] A standard is not yet established, but there is work going on through ISO/TC261 and ASTM F42.[49]

5.3 Need for Further Research

AM is still an immature technology. There is a need to further develop geometric representation, materials and material support for the remanufacturing using AM.[57] There is a need for novel methods for optimizing the combination of AM and subtractive machining for remanufacturing. Few current application of remanufacturing using AM has been implemented on an industry scale. For a more “mass remanufacturing approach in a future circular economy, there is a need for more research on the professionalization and industrialization of AM in a remanufacturing chain.

6. Review: Operations Management in Remanufacturing

6.1 Closed-Loop Supply Chain

Within the supply chain literature, social and environmental issues appear in reverse logistics, the green supply chain, and closed-loop supply chain (CLSC). Guide and Van Wassenhove defined CLSC as design, control, and operation of a system to maximize value creation over the entire lifecycle of a product, with dynamic recovery of value from different types and volumes of return over time.[62] The introduction of CLSC into a company’s operational system is essential for meeting customer service needs and improving environmental problems associated with shorter lifecycles resulting from the recent demand for lower prices and product variety.

Remanufacturing presents great challenges for research and practice. It is because operations management in remanufacturing is more complex than those in traditional manufacturing. The complexities derive from the uncertainties in product returns in terms of their timing, quantity, and quality. Guide et al. enumerated several complicated characteristics in remanufacturing.[32] Researchers have developed methodologies to deal with various operations management issues in remanufacturing including forecasting, production planning and scheduling, capacity planning, inventory management, and effect of uncertainty.

6.2 Research Topics

6.2.1 Forecasting

Developing a reliable forecasting process is the first step to deal with complex systems. Pioneering works in forecasting product return for remanufacturing include those of Kelle and Silver,[63] and Goh and Varaprasad.[64] These researchers developed forecasting models for returns of reusable containers that are typically used in practice to sell or store liquids. Researchers have sought to expand the model. De Brito and van der Laan investigated the performance of the forecasting methods proposed by Kelle and Silver by considering the impact of imperfect information on inventory related costs.[65] A case study for building a forecast model designed for specific products in remanufacturing was presented by Toktay et al. who used actual data for returns of Kodak single-use cameras and developed a discrete-time distributed-lag model with dynamic information updates to estimate product returns.[66] Marx-Gomez et al. investigated forecasting models applicable to the remanufacturing of photocopiers.[67] The authors developed a fuzzy reasoning and neuro-fuzzy model to predict the quantity and timing of photocopier returns to the OEM. These studies, however, typically assume that the time distribution of new product sales are known, which is reasonable when the OEMs are the remanufacturers. Matsumoto and Komatsu focused on the case where no accurate information on time distribution of new product sales is available.[68] They examined the effectiveness of forecasting by time series analysis that does not need those information.

6.2.2 Production Scheduling

To cope with the uncertainty and complexity of remanufacturing systems, researchers have developed remanufacturing oriented scheduling methodologies. The most commonly used technique to test the performance of these methods is Discrete Event Simulation (DES).[69] Guide used DES modeling to compare a Material-Requirements-Planning (MRP)-based production planning and control system with a Drum-Buffer-Rope (DBR)-based proposed system for a real life remanufacturing facility.[70] He concluded that the usefulness of MRP in remanufacturing systems is questionable because remanufacturing environment lacks the stability which is one of the requirements for a successful MRP system. Guide et al. extended the study by carrying out a DES analysis to examine the performance of several priority dispatching rules for a repair shop.[71] Guide et al. analyzed the performance of static priority rules for a remanufacturing system with shared facilities.[72]

6.2.3 Capacity Planning

Researchers have developed capacity planning techniques considering the characteristics of remanufacturing environments. Guide and Spencer developed a Rough Cut Capacity Planning (RCCP) method for remanufacturing companies by considering probabilistic material replacement and probabilistic routing files.[73] Linear programming and simulation were used to develop capacity plans for remanufacturing facilities. Kim et al. developed a mathematical model to determine the capacity of remanufacturing facilities based on the maximization of the saving from the investment on remanufacturing facilities.[74] Franke et al. integrated linear programming and DES to generate capacity plans for a cell phone remanufacturing facility.[75]

6.2.3 Production Planning

A production planning system for remanufacturing supports managers to plan how much and when to disassemble, how much and when to remanufacture, how much to produce and/or order for new materials, and coordinates disassembly and reassembly.[76] Ferrer and Whybark developed a MRP-based methodology to determine how many and which cores to buy, what mix of cores to disassemble and which components should be assembled to meet demand.[77] Souza et al. considered a company that meets demand for an order with remanufactured products, new products or a mix of both.[78] There is a capacity limitation on production and a service-level constraint measured in terms of the average order lead time. They use a two-stage G1/G/1 queueing network model to find the optimal, long-run production mix that maximizes profit subject to the service-level constraint. Gupta and Veerakamolmal used an integer programming-based algorithm for the determination of the number of products to disassemble in order to fulfill the demand for various components for remanufacturing in different time periods.[79] Kiesmuller and Minner proposed a method to determine the quantities of manufacturing and remanufacturing under a newsvendor-type formula based on minimizing the total costs for a manufacturer that include the holding cost of reused parts and new parts and cost of opportunity loss.[80] Fleischmann and Minner[81] considered the importance of inventory theory to CLSC. Ferguson identified strategic issues in CLSC with remanufacturing.[82] The author focused on some direct costs and opportunity costs of manufacturing within a company's decision to remanufacture products or to support the secondary market of remanufactured products. Geyer et al. developed a strategic model of economic remanufacturing under limited component durability and finite product lifecycle.[83]

6.2.4 Inventory Management

In inventory management of remanufacturing, an uncertain element is added due to the uncertainty of product return. Moreover, there is an additional need for coordination between the remanufacturing and regular model of procurement.[84] In studies of inventory management that employ deterministic models, demand and return quantities were assumed to be known for entire planning horizon. The studies try to find an optimal balance between fixed setup costs and variable inventory holding costs. Assuming infinite production rates for manufacturing and remanufacturing, the first Economic Order Quantity (EOQ) model with item returns was developed by Schrady.[85] Dobos and Richter developed integer non-linear models for the analysis of EOQ repair and waste disposal problem with integer setup numbers.[86] They found that the pure strategy was optimal.

Teunter developed EOQ formulae by using different holding cost rates for manufactured and recovered items.[87] Tang et al. considered a hybrid remanufacturing/manufacturing system in which manufacturing and remanufacturing operations for multiple product types performed on the same production line.[88] The authors indicated that as degree of information transparency increases, the robustness of a hybrid system increases too. Teunter et al. investigated the multi product economic lot scheduling problem for hybrid manufacturing/ remanufacturing system.[89] Similarly, Kenne et al. proposed a production planning model for a hybrid manufacturing/remanufacturing system in a stochastic optimization context.[90] Kainuma developed a model for cascade reuse hybrid manufacturing/remanufacturing systems.[91]

6.3 Future Research Prospects

The shift from a producer- to a consumer-led economy requires an efficient and quick supply of products and services. Moreover, in addition to making profits, actions related to social and environmental problems are now considered to be the responsibility of companies. The introduction of CLSC into a company's operational system is essential for meeting customer service needs and improving environmental problems associated with product manufacturing. Operations management in remanufacturing is even more complex than those in traditional manufacturing. Accordingly operations management research is a critical element to enable an efficient and effective remanufacturing. Previous studies, however, sometimes consider only one specific issue on operations management such as inventory management, production planning, and so on. In order for these studies to contribute more to realize efficient and effective remanufacturing systems, further integrated approaches need to be taken.

7. Review: Business Models for Remanufacturing

7.1 Remanufacturing and Business Models

Business models are another important key to fostering remanufacturing. Today, many manufacturing companies around the world are striving to provide product services to customers rather than providing only the products. The phenomenon of manufacturing companies adding services to their total offerings is called servitization.[92] The synergy between servitization and remanufacturing, or more broadly the synergy between servitization and resource-efficient manufacturing, has been argued. A product service system (PSS) is a concept that is similar to servitization. One definition of a PSS is a marketable set of products and services capable of jointly fulfilling a user's need.[93] PSS studies have focused on the benefits of a PSS in terms of sustainability and resource efficiency.[93-97] The basic idea is that since the main value to a customer comes to be the function of the product rather than the product itself, traditional material intensive ways of product utilization can be replaced by the possibility of fulfilling the customers' needs by providing a more dematerialized combination of services and products. The idea has also been argued in concepts such as functional sales,[98] performance economy,[99] service engineering,[100] and industrial product service systems (IPS2).[101]

Table 2 Types of PSS[95]

Product-Oriented services	· Product related services: Provider sells product as well as services needed during use phase (e.g., maintenance contract, financing scheme, take-back arrangement) · Advice and consultancy: provider gives advice on most efficient use of product
Use-Oriented services	· Product lease: Provider retains ownership of product and is often responsible for maintenance/repair. User pays regular fee, normally for unlimited individual access · Product renting or sharing: Provider retains ownership of product and is often responsible for maintenance/repair. User pays regular fee but does not have unlimited and individual access. Same product used sequentially by users · Product pooling: Provider retains ownership of product and is often responsible for maintenance/repair. User pays regular fee but does not have unlimited and individual access. Same product used simultaneously by users
Result-Oriented services	· Pay per service unit: Product still forms the basis of PSS. User buys output of product according to level of use · Functional result: Provider and user agree on an end result without specifying how the result is delivered · Activity management/outsourcing: Providers is outsource a part of a customer's activity

There are various types and levels of servitization. A traditional classification of product services is based on their relationship to sales. Whether the service is offered before or after the sale.[102] Kotler distinguishes two broad categories: maintenance and repair services, and business advisory services.[103] A PSS is classified in a similar way but focuses more on the forms of ownership of the products. A PSS is usually broken down into three categories: product-, use-, and result-oriented.[95] This categorization is shown in Table 1. The portion of the value based on services compared to that based on products is larger in the order of result-, use-, and result-oriented PSSs. The potential of the effects of facilitating remanufacturing as well as other forms of resource-efficient manufacturing is large in the same order.[95]

Remanufacturing can be facilitated by service business models for several reasons. First, service business models can facilitate OEMs' take-back of used products. The provision of product services strengthens the relationships between OEMs and customers. It also facilitates their take-back of used products from customers. In cases where the ownership of products is retained by OEMs such as when products are leased or rented, take-backs are more steadily guaranteed. Next, the provision of product services provides OEMs with opportunities for obtaining information about customers' product usage. This can help OEMs develop efficient remanufacturing processes.[104] Then, most importantly, in service business models, the main value to customers has more to do with the functionality of the products rather than the products themselves. As customers come to focus more on the functionality of products, they become more indifferent to the distinctions between new and remanufactured products. This can significantly improve customer acceptance of remanufactured products. Finally, remanufacturing can provide OEMs with the means to offer product functionality to customers at lower costs because remanufacturing is usually more cost-effective than new product manufacturing. If OEMs, in service business models, are paid for the services they offer rather than the products they provide, the products and consumables become cost factors for them. In this case, the companies have an incentive to conduct remanufacturing rather than fearing a conflict between new and remanufactured product sales.

7.2 Drivers and Barriers

Many manufacturing companies today are striving to add services to their total offerings. Maintaining a competitive advantage solely based on product innovation is argued to be difficult due to increasing commoditization and fierce competitive pressures. For OEMs, product-oriented services are usually the first step in servitization.[105] Advanced companies offer result-oriented services. One of the best known examples would be the services provided by aerospace engine manufacturers like GE Aviation and Rolls Royce. These companies made a major conceptual shift away from the notion of selling aircraft engines toward the idea that what the customers buy is a means of keeping aircraft in the air.[106] They now offer a complete-care package, where customers buy the capability that the engines deliver: "Power by the hour.

There are arguably a number of drivers behind the servitization movement. The three main groups of reasons for servitization are economic, customer needs, and the competitive advantage that services can provide.[105-109] Economic reasons reflect the observation that services have higher margins and provide more stable revenue than products.[105,107] Customer needs include the desire of customer companies to focus on their core businesses and outsource non-core functions such as the maintenance of products to the product-provider company.[108] Competitive reasons are as follows: services are good for relationship-building with customers,[110] services are less capital-dependent,[111] services are difficult to imitate and thus, companies can lock out competitors.[105]

Even though servitization seems reasonable from the perspectives of both manufacturing companies and customers, there exist barriers that hinder the diffusion of PSSs. There are several challenges: manufacturers may doubt the economic potential of services,[105] and differing opinions may exist within a company about the potential.[106] This can lead the companies to meet with internal resistance during their servitization path.[107] In the servitization process, the companies have to transform their organizational culture into a service-oriented one.[110] They also need to make a drastic shift of employee mindset to a service-oriented one.[106] A PSS requires a different skillset than product sales,[95] therefore, human resource management is another challenge.[13] There are also issues surrounding the costs. Due to the high labor intensity, a PSS can be more expensive than having a product operated by customers.[95] Furthermore, service provision increases an OEM's responsibility for uncertainty and risks.[101] In the case of leasing, for example, a PSS provider has to finance the capital costs and is paid back over a long time period, which increases the company's burden of financial risks. A PSS is usually provided by a group of companies, which results in more complicated contracting and revenue-sharing schemes.[97] In the case of consumer products, the added value of PSS in terms of comfort, convenience, and the experience of ownership might be lower than that of a corresponding product. Consumers simply value owning things and having control over objects.[97] These factors can hinder the manufacturing companies from implementing servitization. In fact, empirical studies indicate that many manufacturing companies have not been successful in the transfer toward services.[105,106]

Challenges also exist for companies in incorporating remanufacturing into service business models. The facilitation of remanufacturing by service business models is not automatic. In principle, in terms of the effects on product lifetimes, leasing, renting and sharing, they can achieve the same service level with the use of fewer products. However, rented, leased and shared products tend to be used less carefully than products that are owned,[112] and are usually returned earlier in comparison with the lifetime of a product sold in the traditional manner. The contract for the services is another important factor.[101] If a contract stipulates that a supplier is paid for the services it offers rather than products it provides, then the supplier has an incentive to prolong product lifetimes and remanufacture them. Otherwise, if the supplier can charge for providing products and charge more for new products, it does not change the incentive to maximize product sales, and this is often actually the case, even in advanced servitization examples such as photocopier service businesses. In addition, there exist challenges that are common to PSSs. Remanufacturing is generally labor-intensive, and cost is an issue.[12] The total costs including transportation costs can make remanufacturing economically unfeasible.[113] Remanufacturing requires initial investments by companies,[12] and strategic decision-making by companies for its inauguration. Service business models offer a great prospect of enabling remanufacturing. However, by definition, the potential is not realized. More work is necessary to develop new PSS solutions that are economically competitive and successfully incorporate remanufacturing.

7.3 Service Design Methodologies

A variety of methodologies for designing PSSs have been proposed. In the traditional approach, products and services are developed independently. Further on, services are seen as add-ons to a product thus, they are developed subsequently to the product. The concept of a PSS, on the other hand, considers the integration of products and services to fulfill customer needs. Thus, products and services need to be developed in an integrated way.[101] Aurich et al. proposed a method for considering the product, process, and information dimensions of services simultaneously.[114] They suggested the application of lifecycle engineering techniques to service design. Shimomura et al. proposed a method for designing PSSs during the early stages of product design. They provided a unified representation scheme of human and physical processes in service activities for incorporating customer value into service by extending service blueprints.[115] More recently, Martinsen and Gulbrandsen-Dahla described how everything from the business model down to the material properties needs to be revised for a circular economy to work.[116] Guidelines for PSS development have also been produced. One of the most widely disseminated is UNEP's Design for Sustainability manual, which includes a PSS module.[117] More recently, Guidat et al. proposed guidelines for creating business models, including remanufacturing and PSSs.[25] Their guidelines are organized according to business model dimensions; the method consists of a visualization tool that allows a business activity snapshot to be created by means of a collaborative brainstorming exercise. Despite the intensive work on product service design methodologies and guidelines, the area is still developing, and more work is necessary to develop new PSS solutions that are economically competitive and successfully incorporate remanufacturing.

8. Summary and Prospects

This article outlined the trends and drivers/barriers of remanufacturing and presented reviews of selected topics in R&D that will help overcoming the barriers. Remanufacturing is a critical element in moving our economy toward being more resource-efficient. Remanufacturing has the potential to positively affect the environment, economy, and society. However, this potential has not yet been sufficiently exploited. To do this, various conditions such as OEM and/or remanufacturer costs/benefits, demand side acceptance, legislation, and other relevant factors, have to be coordinated. This article highlighted four topics on R&D for remanufacturing.

Product design, or DfRem, is critical for enabling remanufacturing. Product design determines a significant part of the remanufacturability of products, especially the costs associated with product EOL treatment. Previous studies have proposed DfRem guidelines, methods, support tools that take "lifecycle thinking into account. Further studies on these topics are necessary, and at the same time, efforts to integrate these methods into the product development phase are needed. Manufacturers' lack of awareness of DfRem and/or lack of motives with respect to remanufacturing itself constitute part of the barriers that hinder these proposed methods from penetrating into industrial practice.

A number of engineering techniques exist that must be developed to make remanufacturing processes cost-effective and the quality of remanufactured products high ("as good as new"). AM is one of the techniques that has been used in remanufacturing. It has been developed intensively in recent years, and the effective application of techniques is one of the hot issues in remanufacturing. There is, however, still a way to go before AM is fully qualified for advanced use in remanufacturing. Research on reliable materials and process parameters for AM processes is a challenge for the establishment of reliable AM in a remanufacturing chain.

Operations management is another important issue. Operations management for remanufacturing is even more complex than that it is for traditional manufacturing, which are already vastly complex. The complexity comes largely from the uncertainties of quantity, quality, and timing of returned products. Research on forecasting, product scheduling, capacity planning, production planning, inventory management, and others for remanufacturing is necessary, and further integrated methodologies are expected to be developed to make these studies contribute more to support developing efficient and effective remanufacturing systems.

Business models are critical for the promotion of remanufacturing in society. An adequate business model has the effect of increasing customer acceptance of remanufactured products, and consequently facilitates remanufacturing. Manufacturing companies adding services to their businesses (developing service business models) is one of the megatrends in industry. The trends and effective means to incorporate remanufacturing into service business models are other important topics. Although successful cases exist, such as that of photocopy machines, there are still a number of barriers to developing a successful business model that facilitates remanufacturing. Further studies on business models and the relevant legislation are necessary to promote effective business models for remanufacturing.

Remanufacturing is attracting growing attention worldwide. The promotion of remanufacturing in society requires the cooperation and coordination of various stakeholders, including OEMs, IRs, governments, customers, and researchers of various topics and disciplines in academia. Research on remanufacturing must cover aspects on macro to micro level from the "macro" business model research through "meso" aspects such as product and product-lifecycle design, and operations management, down to the "micro" aspects on remanufacturing process technologies including AM process technologies.

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REFERENCES

1. Giuntini, R. and Gaudette, K., "Remanufacturing: The Next Great Opportunity for Boosting US Productivity," Business Horizons, Vol. 46, No. 6, pp. 41-48, 2003.

2. Nasr, N. and Thurston, M., "Remanufacturing: A Key Enabler to Sustainable Product Systems," Proc. of 13th CIRP International Conference on Life-Cycle Engineering, pp.15-18, 2006.

3. Steinhilper, R., "Remanufacturing: The Ultimate Form of Recycling," Stuttgart: Fraunhofer IRB Verlag, 1998.

4. Nasr, N., "Reman for Success," Industrial Engineer, Vol. 42, No. 6, pp. 26-27, 2010.

5. Lund, R., "The Remanufacturing Industry: Hidden Giant," Boston University Press, 1996.

6. U.S. International Trade Commission, "Remanufactured Goods: An Overview of the U.S. and Global Industries, Markets, and Trade," USITC Publication 4356, Investigation No. 332-525, 2012.

7. Frost & Sullivan, "360 Degree Perspective of the North American Automotive Aftermarket," http://www.slideshare.net/soaringvjr/north-american-auto-aftermarket-frost-0211# (Accessed 14 September 2015)

8. Hammond, R., Amezquita, T., and Bras, B., "Issues in the Automotive Parts Remanufacturing Industry: A Discussion of Results from Surveys Performed among Remanufacturers," International Journal of Engineering Design and Automation, Vol. 4, No. 1, pp. 27-46, 1998.

9. Seitz, M., "A Critical Assessment of Motives for Product Recovery: the Case of Engine Remanufacturing," Journal of Cleaner Production, Vo. 15, No. 11-12, pp. 1147-1157, 2007.

10. Ellen MacArthur Foundation, "Towards the Circular Economy," http://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf (Accessed 28 December 2015)

11. Guide, V. D. R. and Van Wassenhove, L. N, "The Reverse Supply Chain: Smart Manufacturers are Designing Efficient Processes for Reusing Their Products," Harvard Business Review, Vol. 80, No. 2, pp. 25-26, 2002.

12. Matsumoto, M. and Umeda, Y., "An Analysis of Remanufacturing Practices in Japan," Journal of Remanufacturing, Vol. 1, No. 1, pp. 1-11, 2011.

13. Matsumoto, M. and Kamigaki, K., "Development and Changes in the Industrial Product Service Systems - A Case Study of the Photocopier PSS," in: The Philosopher's Stone for Sustainability, Shimomura, Y. and Kimita, K., (Eds.), Springer, pp. 167-172, 2013.

14. Duflou, J. R, Seliger, G., Kara, S., Umeda, Y., Ometto, A., et al., "Efficiency and Feasibility of Product Disassembly: A Case-Based Study," CIRP Annals-Manufacturing Technology, Vol. 57, No. 2, pp. 583-600, 2008.

15. Andreu, J., "The Remanufacturing Process," Manchester Metropolitan University, Manchester, UK, 1995.

16. Amezquita, T., Hammond, R., Salazar, M., and Bras, B., "Characterizing the Remanufacturability of Engineering Systems," Proc. of ASME Advances in Design Automation Conference, pp. 271-278, 1995.

17. Shu, L. H. and Flowers, W. C., "Application of a Design-for-Remanufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods," Vol. 15, No. 3, pp. 179-190, 1999.

18. Rose, C., Ishii, K., and Stevels, A., "ELDA and EVCA: Tools for Building Product End-of-Life Strategy," Journal of Sustainable Product Design, Vol. 1, No. 3, pp. 181-195, 2001.

19. Ijomah, W., McMahon, C., Hammond, G., and Newman, S., "Development of Robust Design-for-Remanufacturing Guidelines to Further the Aims of Sustainable Development," International Journal of Production Research, Vol. 45, No. 18-19, pp. 4513-4536, 2007.

20. Charter, M. and Gray, C., "Remanufacturing and Product Design," International Journal of Product Development, Vol. 6, No. 3-4, pp. 375-392, 2008.

21. Pigosso, D., Zanette, E., Filho, A., Ometto, A., and Rozenfeld, H., "Ecodesign Methods Focused on Remanufacturing," Journal of Cleaner Production, Vol. 18, No. 1, pp. 21-31, 2010.

22. Resource Recovery Forum (RRF), "Remanufacturing in the UK: A Snapshot of the UK Remanufacturing Industry 2009," http://www.remanufacturing.org.uk/pdf/story/1p342.pdf (Accessed 28 December 2015)

23. Advanced Remanufacturing and Technology Centre, "About ARTC," http://www.a-star.edu.sg/artc/About-ARTC.aspx (Accessed 14 July 2015)

24. Malaysia Ministry of International Trade and Industry, "Exploring Re-Manufacturing Activities in Malaysia," 2012.

25. Guidat, T., Barquet, A., Widera, H., Rozenfeld, H., and Seliger, G., "Guidelines for the Definition of Innovative Industrial Product-Service Systems (PSS) Business Models for Remanufacturing," Procedia CIRP, Vol. 16, pp. 193-198, 2014.

26. Geyer, R. and Jackson, T., "Supply Loops and Their Constraints: the Industrial Ecology of Recycling and Reuse," California Management Review, Vol. 46, No. 2, pp. 55-73, 2004.

27. Lundmark, P., Sundin, E., and Bjeorkman, M., "Industrial Challenges within the Remanufacturing System," Proc. of Swedish Production Symposium, pp. 132-139, 2009.

28. Lund, R. and Skeels, F., "Guidelines for an Original Equipment Manufacturer Starting a Remanufacturing Operation," Government Report No. DOE/CS/40192, CPA-83.8 Cambridge, Center for Policy Alternatives, 1983.

29. Linton, J., "Assessing the Economic Rationality of Remanufacturing Products," Journal of Product Innovation Management, Vol. 25, No. 3, pp. 287-302, 2008.

30. Atasu, A., Sarvary, M., and Wassenhove, L. N. V., "Remanufacturing as a Marketing Strategy," Management Science, Vol. 54, No. 10, pp. 1731-1746, 2008.

31. Chang, Y., Bae J., and Yi, H., "Ultrasonic Cleaning of Used Plastic Parts for Remanufacturing of Multifunctional Digital Copier," Int. J. Precis. Eng. Manuf., Vol. 14, No. 6, pp. 951-956, 2013.

32. Guide, V. D. R., "Production Planning and Control for Remanufacturing: Industry Practice and Research Needs," Journal of Operations Management, Vol. 18, No. 4, pp. 467-483, 2000.

33. David, M. and Anderson, P. E., "Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low-Cost," High-Quality Products for Lean Production, CRC Press, 2014.

34. Sundin, E., "Product and Process Design for Successful Remanufacturing," Linköping Studies in Science and Technology Dissertation, No. 906, 2004.

35. Ijomah, W., McMahon, C., Hammond, G., and Newman, S., "Development of Design for Remanufacturing Guidelines to Support Sustainable Manufacturing, Robotics and Computer-Integrated Manufacturing, Vol. 23, No. 6, pp. 712-719, 2007.

36. Mabee, D., Bommer, M., and Keat, W., "Design Charts for Remanufacturing Assessment," Journal of Manufacturing Systems, Vol. 18, No. 5, pp. 358-366, 1999.

37. McGlothlin, S. and Kroll, E., "Systematic Estimation of Disassembly Difficulties: Application to Computer Monitors," Proc. of the IEEE International Symposium on Electronics and the Environment, pp. 83-88, 1995.

38. Zwolinski, P., Lopez-Ontiveros, M., and Brissaud, D., "Integrated Design of Remanufacturable Products Based on Product Profiles," Journal of Cleaner Production, Vol. 14, No. 15, pp. 1333-1345, 2006.

39. Bras, B. and Hammond, R., "Towards Remanufacturing: Metrics for Assessing Remanufacturability," Proc. of 1st International Workshop on Reuse, pp. 35-52, 1996.

40. Du, Y., Cao, H., Liu, F., Li, C., and Chen, X., "An Integrated Method for Evaluating the Remanufacturability of Used Machine Tool," Journal of Cleaner Production, Vol. 20, No. 1, pp. 82-91, 2012.

41. Sherwood, A. and Shu, L., "FMEA-Based Design for Remanufacture Using Automotive-Remanufacturer Data," Society of Automotive Engineers, Paper No. 2001-01-0308, 2000.

42. King, A. and Burgess, S., "The Development of a Remanufacturing Platform Design: A Strategic Response to the Directive on Waste Electrical and Electronic Equipment," Journal of Engineering Manufacture, Vol. 219, No. 8, pp. 623-631, 2005.

43. Yang, S. S., Ong, S. K., and Nee, A. Y. C., "Design for Remanufacturing: A Fuzzy-QFD Approach," Proc. of 20th CIRP International Conference on Life Cycle Engineering, pp. 633-638, 2013.

44. Hatcher, G., Ijomah, W., and Windmill, J., "Design for Remanufacture: A Literature Review and Future Research Needs," Journal of Cleaner Production, Vol. 19, No. 17, pp. 2004-2014, 2011.

45. Fava, J. A., "Life Cycle Thinking: Application to Product Design," Proc. of the IEEE International Symposium on Electronics and the Environment, pp. 69-73,1993.

46. Yang, S., Ngiam, H., Ong, S., and Nee, A., "The Impact of Automotive Product Remanufacturing on Environmental Performance," Procedia CIRP, Vol. 29, pp. 774-779, 2015.

47. Bras, B. and McIntosh, M. W., "Product, Process, and Organizational Design for Remanufacture: An Overview of Research," Robotics and Computer-Integrated Manufacturing, Vol. 15, No. 3, pp. 167-178, 1999.

48. Matsumoto, M., Nakamura, N., and Takenaka, T., "Business Constraints in Reuse Practices," IEEE Technology and Society Magazine, pp. 55-63, 2010.

49. ASTM No. F2792-12a, (Withdrawn 2015), "Standard Terminology for Additive Manufacturing Technologies," 2012.

50. Wholers Associates, "Wohlers Report 2015," http://www.wohlersassociates.com/2015report.htm (Accessed 28 December 2015)

51. Wilson, M., Piya, P., Shin, Y., Zhao, F., and Ramani, K., "Remanufacturing of Turbine Blades by Laser Direct Deposition with Its Energy and Environmental Impact Analysis," Journal of Cleaner Production, Vol. 80, pp. 170-178, 2014.

52. Zhang, Y., Yang, Z., He, G., Qin, Y., and Zhang, H., "Remanufacturing-Oriented Geometric Modelling for the Damaged Region of Components," Procedia CIRP, Vol. 29, pp. 798-803, 2015.

53. Paulic, M., Irgolic, T., Balic, J., Cus, F., Cupar, A., et al., "Reverse Engineering of Parts with Optical Scanning and Additive Manufacturing," Procedia Engineering, Vol. 69, pp. 795-803, 2014.

54. Chen, C., Wang, Y., Ou, H., He, Y., and Tan, Z., "A Review on Remanufacture of Dies and Moulds," Journal of Cleaner Production, Vol. 64, pp. 13-23, 2014.

55. Jhavar, S., Jain, N., and Paul, C., "Development of Micro-Plasma Transferred arc (μ-PTA) Wire Deposition Process for Additive Layer Manufacturing Application," Journal of Materials Processing Technology, Vol. 214, No. 5, pp. 1102-1110, 2014.

56. Navrotsky, V., "3D Printing at Siemens Power Service," Siemens, 2014.

57. Gaoa, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., et al., "The Status, Challenges, and Future of Additive Manufacturing in Engineering," Computer-Aided Design, Vol. 69, pp. 65-89, 2015.

58. Deolitte University Press, "3D Opportunity for the Department of Defense," http://dupress.com/articles/additive-manufacturing-defense-3d-printing/ (Accessed November 22 2015)

59. Boivie, K., Dolinsek, S., and Homar, D., "Hybrid Manufacturing; Integration of Additive Technologies for Competitive Production of Complex Tools and Products," 15th International Research/Expert Conference, 2011.

60. CIRP, "CIRP STC DN - 2014 Annual Report," www.cirp.net/scientific-groups/stc-dn-design/828-stc-dn-2014-annual-report.html (Accessed November 22 2015)

61. VDI-Standard: VDI 3405, "Additive Manufacturing Processes, Rapid Manufacturing - Basics, Definitions, Processes," 2014.

62. Guide, D. and Van Wassenhove, L., "Closed-Loop Supply Chain: An Introduction to the Feature Issue (Part 1)," Production and Operations Management, Vol. 15, No. 3, pp. 345-350, 2006.

63. Kelle, P. and Silver, E., "Forecasting the Returns of Reusable Containers," Journal of Operations Management, Vol. 8, No. 1, pp. 17-35, 1989.

64. Goh, T. and Varaprasad, N., "A Statistical Methodology for the Analysis of the Life-Cycle of Reusable Containers," IIE Transactions, Vol. 18, No. 1, pp. 42-47, 1986.

65. De Brito, M. P. and Van der Laan, E. A., "Inventory Control with Product Returns: The Impact of Imperfect Information," European Journal of Operational Research, Vol. 194, No. 1, pp. 85-101, 2009.

66. Toktay, L. B., Wein, L. M., and Zenios, S. A., "Inventory Management of Remanufacturable Products," Management Science, Vol. 46, No. 11, pp.1412-1426, 2000.

67. Marx-Gomez, J., Rautenstrauch, C., Nurnberger, A., and Kruse, R., "Neuro-Fuzzy Approach to Forecast Returns of Scrapped Products to Recycling and Remanufacturing," Knowledge-Based Systems, Vol. 15, No. 1, pp. 119-128, 2002.

68. Matsumoto, M. and Komatsu, S., "Demand Forecasting for Production Planning in Remanufacturing," International Journal of Advanced Manufacturing Technology, Vol. 79, No. 1-4, pp. 161-175, 2015.

69. Ilgin, M. and Gupta, S., "Environmentally Conscious Manufacturing and Product recovery (ECMPRO): A Review of the State of the Art," Journal of environmental management, Vol. 91, No. 3, pp. 563-591, 2010.

70. Guide, V. D. R., "Scheduling Using Drum-Buffer-Rope in a Remanufacturing Environment," International Journal of Production Research, Vol. 34, No. 4, pp. 1081-1091, 1996.

71. Guide, V. D. R., Srivastava, R., and Kraus, M. E., "Priority Scheduling Policies for Repair Shops," International Journal of Production Research, Vol. 38, No. 4, pp. 929-950, 2000.

72. Guide, V. D. R., Souza, G., and Van der Laan, E., "Performance of Static Priority Rules for Shared Facilities in a Remanufacturing Shop with Disassembly and Reassembly," European Journal of Operational Research, Vol. 164, No. 2, pp. 341-353, 2005.

73. Guide, V. D. R. and Spencer, M. S., "Rough-Cut Capacity Planning for Remanufacturing Firms," Production Planning & Control, Vol. 8, No. 3, pp. 237-244, 1997.

74. Kim, K., Jeong, B., and Jeong, S., "Optimization Model for Remanufacturing System at Strategic and Operational Level," Proc. of International Conference on Computational Science and Its Applications, pp. 566-576, 2005.

75. Franke, C., Basdere, B., Ciupek, M., and Seliger, S., "Remanufacturing of Mobile Phones - Capacity, Program and Facility Adaptation Planning," Omega, Vol. 34, No. 6, pp. 562-570, 2006.

76. Guide, V. D. R., Jayaraman, V., and Srivastava, R., "Production Planning and Control for Remanufacturing: A State-of-the-Art Survey," Robotics and Computer-Integrated Manufacturing, Vol. 15, No. 3, pp. 221-230, 1999.

77. Ferrer, G. and Whybark, D. C., "Material Planning for a Remanufacturing Facility," Production & Operations Management, Vol. 10, No. 2, pp. 112-124, 2001.

78. Souza, G., Ketzenberg, M., and Guide, V. D. R., "Capacitated Remanufacturing with Service Level Constraints," Production and Operations Management, Vol. 11, No. 2, pp. 231-248, 2002.

79. Gupta, S. and Veerakamolmal, P., "Aggregate Planning for End-of-Life Products," in: Greener Manufacturing and Operations: From Design to Delivery and Back, Sarkis, J., (Ed.), Greenleaf Publishing Ltd., pp. 205-222, 2001.

80. Kiesmueller, G. and Minner, S., "Simple Expression for Finding Recovery System Inventory Control Parameter Values," Journal of the Operational Research Society, Vol. 54, No. 1, pp. 83-88, 2003.

81. Fleischmann, M. and Minner, S., "Inventory Management in Closed-Loop Supply Chains," in: Supply Chain Management and Reverse Logistics, Dyckhoff, H., Lacker, R., and Reese, J., (Eds.), Springer, Heidelberg, pp. 115-138, 2004.

82. Ferguson, M., "Strategic Issue in Closed-Loop Supply Chains with Remanufacturing," Auerbach Publications, 2010.

83. Geyer, R., Van Wassenhove, L. N., and Atasu, A., "The Economics of Remanufacturing under Limited Component Durability and Finite Product Lifecycle," Management Science, Vol. 53, No. 1, pp. 88-100, 2007.

84. Inderfurth, K. and Van der Laan, E., "Leadtime Effects and Policy Improvement for Stochastic Inventory Control with Remanufacturing," International Journal of Production Economics, Vol. 71, No. 1, pp. 381-390, 2001.

85. Schrady, D. A., "A Deterministic Inventory Model for Repairable Items," Naval Research Logistics Quarterly, Vol. 14, No. 3, pp. 391-398, 1967.

86. Dobos, I. and Richter, K., "The Integer EOQ Repair and Waste Disposal Model - Further Analysis," Central European Journal of Operations Research, Vol. 8, No. 2, pp. 173-195, 2000.

87. Teunter, R. H., "Economic Ordering Quantities for Recoverable Item Inventory Systems," Naval Research Logistics (NRL), Vol. 48, No. 6, pp. 484-495, 2001.

88. Tang, O. and Naim, M. M., "The Impact of Information Transparency on the Dynamic Behavior of a Hybrid Manufacturing/Remanufacturing System," International Journal of Production Research, Vol. 42, No. 19, pp. 4135-4152, 2004.

89. Teunter, R., Kaparis, K., and Tang, O., "Multi-Product Economic Lot Scheduling Problem with Separate Production Lines for Manufacturing and Remanufacturing," European Journal of Operational Research, Vol. 191, No. 3, pp. 1241-1253, 2008.

90. Kenne, J. P., Dejax, P., and Gharbi, A., "Production Planning of a Hybrid Manufacturing-Remanufacturing System under Uncertainty within a Closed-Loop Supply Chain," International Journal of Production Economics, Vol. 135, No. 1, pp. 81-93, 2012.

91. Kainuma, Y., "Sustainable Operations and Closed-Loop Supply Chain," Journal of Japan Industrial Administration Association, Vol. 64, No. 2E, pp. 348-355, 2013.

92. Vandermerwe. S. and Rada, J., “Servitization of Business: Adding Value by Adding Services,” Eur Manage Journal, Vol. 6, No. 4, pp. 314-324, 1989.

93. Goedkoop, M. J., Van Halen C. J. G., Te Riele, H. R. M., and Rommens, P. J. M., “Product Service Systems, Ecological and Economic Basis,” VROM: Hague, 1999.

94. Stahel, W. R., “The Product Life Factor,” http://infohouse.p2ric.org/ref/33/32217.pdf (Accessed on September 14 2015)

95. Tukker, A., “Eight Types of Product-Service System: Eight Ways to Sustainability? Experiences from SusProNet,” Business Strategy and the Environment, Vol. 13, No. 4, pp. 246-260, 2004.

96. Mont, O., “Product-Service Systems - Panacea or Myth?” VDM Verlag, 2008.

97. Tukker, A., “Product Services for a Resource-Efficient and Circular Economy: A Review,” Journal of Cleaner Production, Vol. 97, pp. 76-91, 2015.

98. Sundin, E. and Bras, B., “Making Functional Sales Environmentally and Economically Beneficial through Product Remanufacturing,” Journal of Cleaner Production, Vol. 13 No. 9, pp. 913-25, 2005.

99. Stahel, W. R., “The Performance Economy,” Palgrave Macmillan, 2006.

100. Sakao, T. and Shimomura, Y., “Service Engineering: A Novel Engineering Discipline for Producers to Increase Value Combing Service and Product,” Journal of Cleaner Production, Vol. 15, No. 6, pp. 590-604, 2007.

101. Meier, H., Roy, R., and Seliger, G., “Industrial Product-Service Systems - IPS2,” CIRP Annals - Manufacturing Technology, Vol. 59, No. 2, pp. 607-627, 2010.

102. Londe, B. J. L., “Customer Service: Meaning and Measurement,” National Council of Physical Distribution Management, 1976.

103. Kotler, P., “Marketing Management: Analysis, Planning, Implementation, and Control,” Prentice Hall, 1997.

104. Um, J. Y. and Suh, S. H., “Design Method for Developing a Product Recovery Management System Based on Life Cycle Information,” Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 2, No. 2, pp. 173-187, 2015.

105. Oliva, R. and Kallenberg, R., “Managing the Transition from Products to Services,” International Journal of Service Industry Management, Vol. 14, No. 2, pp. 160-172, 2003.

106. Neely, A., “Exploring the Financial Consequences of the Servitization of Manufacturing,” Operations Management Research, Vol. 1, No. 2, pp. 103-118, 2008.

107. Baines, T. S., Lightfoot, H. W., Benedettini, O., and Kay, J. M., “The Servitization of Manufacturing: A Review of Literature and Reflection on Future Challenges,” Journal of Manufacturing Technology Management, Vol. 20, No. 5, pp. 547-567, 2009.

108. Turunen, T. and Toivonen, M., “Organizing Customer-Oriented Service Business in Manufacturing,” Operations Management Research, Vol. 4, No. 1-2, pp. 74-84, 2011.

109. Quinn, J. B., Doorley, T. L., and Paquette, P. C., “Beyond Products: Services-Based Strategy,” Harvard Business Review, Vol. 68, No. 2, pp. 58-67, 1990.

110. Brax, S., “A Manufacturer Becoming Service Provider - Challenges and a Paradox,” Managing Service Quality: An International Journal, Vol. 15, No. 2, pp. 142-155, 2005.

111. Wise, R. and Baumgartner, P., “Go Downstream: The New Profit Imperative in Manufacturing,” Harvard Business Review, Vol. 77, No. 5, pp. 133-141, 1999.

112. Kuo, T. C., “Simulation of Purchase or Rental Decision-Making Based on Product Service System,” International Journal of Advanced Manufacturing Technology, Vol. 52, No. 9-12, pp. 1239-1249, 2011.

113. Besch, K., “Product-Service Systems for Office Furniture: Barriers and Opportunities on the European Market,” Journal of Cleaner Production, Vol. 13, No. 10, pp. 1083-1094, 2005.

114. Aurich, J., Fuchs, C., and DeVries, M. F., “An Approach to Life Cycle Oriented Technical Service Design,” CIRP Annals - Manufacturing Technology, Vol. 53, No. 1, pp. 151-154. 2004.

115. Shimomura, Y., Hara, T., and Arai, T., “A Unified Representation Scheme for Effective PSS Development,” CIRP Annals - Manufacturing Technology, Vol. 58, No. 1, pp. 379-382, 2009.

116. Martinsen, K. and Gulbrandsen-Dahla, S., “Use of Post-Consumer Scrap in Aluminium Wrought Alloy Structural Components for the Transportation Sector,” Procedia CIRP, Vol. 29, pp. 686-691, 2015.

117. Crul, M., Diehl, J. C., and Ryan, C., “Design for Sustainability - A Step by Step Approach,” http://www.d4s-sbs.org/ (Accessed September 14 2015)