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Product, process, and organizational design for remanufacture – an overview of research

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Abstract

In this paper, an overview of research aimed to improve remanufacturing is given. Compared with recycling, the research efforts in the area of remanufacture seem to be less pervasive. Specifically, descriptive work that seeks to characterize the current state or future of remanufacture, and developmental work that seeks to improve product, process, and/or organizational aspects of remanufacture are presented. The review presented is intended to provide an overview of the types of work that exists in the field of remanufacture and to provide a useful starting point for researchers interested in exploring the area of remanufacturing in greater depth.

1. Introduction

One of the environmental problems Western Europe is facing is waste management and landfill space. Under pressure by the European governments, global manufacturers are including more and more post life considerations into their product design process. Both in industry and academia, lots of attention is given to material recycling, in which the geometry of the product (and the associated value) is destroyed and only the constituent materials are led into a new cycle of usage. Arguably, a more dramatic reduction in environmental impact can be made by product *reuse and remanufacture* in which the geometrical form of the product is retained and the product is reused for the same purpose as during its original life-cycle (e.g., refillable drink bottles and reconditioned car engines) or for secondary purposes (e.g., reuse of automotive tires as mooring cushions in a harbor). With respect to material recycling, reuse and remanufacturing have the following added benefits:

- First, not only is the material waste and amount of landfill reduced, but also energy and matter consumption during manufacture is reduced because existing components are utilized.
- Second, the utilization of existing components reduces an enterprise's monetary expenditure of producing or acquiring new components. Well-known examples are automotive components, industrial machinery, and military equipment.

The purpose in this paper is to provide an overview of existing work in fields related to product remanufacture. In particular, our intent is to go beyond planning and process issues and touch upon all dimensions of remanufacturing (as much as we can do in a reasonable amount of space). We realize that many experts in the area may be familiar with the works presented. However, we feel that many more are becoming interested in the area and are not familiar with both the "classical" literature as well as new emerging work in the area of remanufacture,

In order to make sense of this broad body of work, we have classified the research in this literature review according to its intended purpose and contribution. Two main classifications are given:

1. Descriptive work that seeks to characterize the current state or future of remanufacture, and
2. Developmental work that seeks to improve product, process, and/or organizational aspects of remanufacture.

It is noted that most works make contributions in both areas by describing an aspect of or the future potential of

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remanufacture and then making some original research contribution. However, the field of remanufacture is a relatively new and unknown area, such that a significant body of work is aimed primarily at describing how product remanufacture actually works and at providing examples of existing remanufacturing operations.

This literature review is not intended to provide an exhaustive search of every article related to remanufacture. Such a literature review would likely be impossible and would certainly take up more space than would be desirable. This literature review is rather intended to provide an overview of the types of work that exists in this field and to provide a useful starting point for different areas of research that can be explored in greater depth. Thus, in performing this literature review the hope is to consider both:

- relatively well-known older literature in this area as well as some of the more current work that is being done, and
- the broad range of topics currently being explored.

2. Work describing the current state or presenting a future vision for remanufacture

Within this first category of work describing the current state of or a future vision for remanufacture, research is further categorized according to whether the work primarily

- provides an overview of the current state of remanufacturing,
- describes specific remanufacturing case studies, or
- provides further theories and motivation for the future potential of product remanufacture.

Again, it is noted that there is some overlap between these classifications, but, nonetheless, this classification is found to be useful.

2.1. Work providing a remanufacturing overview or information for remanufacturers

Much work in the field of product remanufacturing serves to give an overview of the current state of affairs and to give advice to potential remanufacturers. In many ways, the most significant of such work is that of Robert Lund in the late 1970s and early 1980s. Lund and Skeels provide a very broad overview of issues for original equipment manufacturers that are considering beginning product remanufacturing operations [1]. A discussion is provided of the benefits of remanufacture and of many issues that need to be considered including product selection, marketing strategy, remanufacturing technology, financial aspects, organizational factors, and legal considerations. Lund groups products that are currently remanufactured into the following four "general product market sectors": automotive parts, industrial equipment, commercial products, and residential products. Lund also provides a discussion of the benefits of remanufacture including energy savings, material recovery, recovery of labor and capital value added to produce parts, creation of jobs, reduction of solid waste, lower prices for goods and hence a higher standard of living, and profits for the remanufacturer. A number of advantages unique to OEM remanufactures are given including: feedback of reliability and durability information, competing in lower-priced markets, taking advantage of a manufacturer's reputation for quality, and advantages over independent remanufacturers in the form of manufacturing data, tooling, and access to suppliers.

Lund and Denny discuss the benefits and problems of extending product lifecycles and the factors affecting product lifecycles (subjective consumer decisions are stressed as well as production and design aspects) [2]. In addition, the authors propose policy alternatives to both to extend product life cycles and identify appropriate product categories for life-cycle extension. Four policy classifications are given based on whether the influences on the life cycle are producer or consumer based and on whether the policy impacts are short or long term. The authors call remanufacturing the "neglected alternative" and advocate "a highly organized business of total disassembly of products, pooling interchangeable parts, and production line re-assembly with some replacement of worn parts". The authors stress a number of advantages since remanufacture is labor intensive and thus creates many jobs, reclaims a larger share of the value than recycling, provides low cost products, and provides a source of replacement parts. The authors mention a number of needs including (1) the need to establish channels for recollecting worn-out products, (2) the need to successfully redistribute and retail reprocessed products, (3) the need for product design for remanufacture, and (4) the need to identify appropriate target products. Lund describes the benefits of remanufacturing and gives a general overview of important issues [3]. For example, Lund states that unless an OEM is doing the remanufacture, there is little incentive to design products for remanufacture and that, by definition, almost every core will be defective in some way. In OEM remanufacture, Lund advocates the use of retail dealers being used as collection points where customers trade in products when purchasing new items. For independent remanufacturers, an advantage is that a low capital investment is required since the expensive equipment for component fabrication is not needed and the raw material is an inexpensive core whose cost is lower than its economic value. From an environmental perspective, Lund estimates that the energy embodied in producing a new product is four to five times as high as the energy embodied in remanufacturing a product.

In another work in this area, Thierry and associates give an overview of product recover management (PRM), a philosophy that seeks to recover as much of the economic and ecological value of products as possible [4]. The authors argue that consumers do not necessarily wish to pay extra for products designed for the life cycle and that producers produce for minimal cost and not optimal life-cycle performance. Nonetheless, the authors list a number of benefits to this strategy and important issues that companies should consider (e.g., product composition, product return information, markets for reprocessed goods, and product recovery and waste management operations). In addition, several case studies describe the experiences of various companies with PRM, and managerial implications are suggested based on the experiences of these companies that have established systems for PRM.

Paton discusses market considerations for product reuse based on experience in Hewlett–Packard's Finance and Remarketing Division [5]. Paton discusses opportunities for and problems with integrating reuse into existing business strategies. Paton notes that market requirements are just as important as technical requirements. The problems with reuse in electronics products include: (1) significant performance improvements with each product release, (2) rapidly decreasing prices, (3) rapid innovations which cause customers to upgrade quickly, (4) incomplete markets for used electronics products (not all supply is needed), and (5) no channels exist for resell ing products. Opportunities include the facts that: (1) markets are expanding rapidly in many categories creating opportunities for reuse, (2) consumers differ in requirements creating a market for lower price, lower performance goods. In order to take advantage of these opportunities, Paton lists six levels with which producers can provide value to consumers: (1) initial sale/lease (compete based on features, performance and price), (2) performance-sensitive (early) reuse (technology is still relatively current, higher price, testing and refurbishment required), (3) price-sensitive (later) reuse (older technology, lower price, not necessarily refurbished), (4) service and support (replacement parts), (5) second market reuse (other industries find another use for goods), (6) recycle materials (lowest economic value but landfill is avoided). In performance-sensitive reuse the producer can assure customers of quality with refurbishment, testing and warranty. Paton also discusses the following methods to integrate reuse into existing business strategies: (1) offer refurbished products into the existing product mix, (2) sell goods through alternate channels, and (3) use components in service and support.

Brown and Davis stress the advantages of remanufacture and propose a list of product characteristics which enable remanufacture [6]. The authors also stress the need for design for remanufacture by OEMs. Hormozi describes the differences between remanufacture and repair and also provides a discussion on the automotive parts industry including a historical overview and overview of current operations and challenges [7]. Kuuva and Airila [8] discuss methods of including design for recycling and reuse into existing design processes. The authors also discuss important problems in design for recycling and reuse and propose design guidelines for these end-of-life options. Di Rodi provides a discussion on how companies can assess their environmental impacts and select a desirable and feasible course of action [9]. The authors discuss how such a plan should be implemented on an organization wide level. Klussman provides an overview of issues for independent remanufacturers including operations, political and labor considerations, and internal organization [10]. The author also discusses his experiences with engineering, sales and marketing, accounting, production and inventory control. A good overview of issues in design for reuse is provided in [11]. In the work, methods of marketing products are listed, the steps in product remanufacture and the issues that should be considered at each phase are described, and a list of rules for designers is provided. Warnecke and Steinhilper provide an overview of remanufacture in the United States and in Germany and present design recommendations to facilitate remanufacture [12]. In [13], a discussion of remanufacturing and related issues is provided to give designers a better understanding of the goals of product life extension within the context of environmentlly conscious design and manufacturing. In this work, a good description is provided of issues such as durability, adaptability, reliability, serviceability, repair, remanufacture and reuse that are important considerations in product life extension. Cooper provdies an overview of the current state of reuse in Britain [14]. The focus is on consumer durables designed for reuse, and copper describes the British government's national waste strategy, the current reuse sector in Britain, the barriers to reuse, and potential solutions to increase product reuse.

2.2. Work describing specific industries or case studies in product remanufacture

An important part of the remanufacturing literature describes the experiences of specific companies or industries with product remanufacture. A well-known example of an OEM's experience with remanufacture is described in [15–18], which describe the Xerox Corporation's experiences with remanufacturing. Berko-Boateng and associates describe Asset Recover Management, the company's strategic initiative to incorporate asset management into their product delivery process and to emphasize design for the environment in the early stages of design [15]. The stated goal is 100% reuse or recycling of their products. Seaver describes design issues encountered at Xerox in the environmentally conscious design of user interface devices [16]. Azar and associates describe the Xerox corporation's design for the environment program, the product delivery process that is used, and design tools used at Xerox [17]. Reyes and associates describe the company's five phase method to assess the reliability of recovered parts to be used in product remanufacture [18].

Hammond and associates present the results of surveys in the independent automotive remanufacturing industry and highlight critical issues and the relative importance of factors in the automotive parts remanufacturing industry [19]. The results show that the remanufacturing industry is struggling to keep up with the modern production practices of the OEMs such as parts proliferation and product design issues. Hendrickson and associates consider environmental issues related to the disposal, reuse and recycling of portable computers and propose design changes to improve to improve end-of-life options such as reusability [20]. Mizuki and associates discuss the various end-of-life options for cathode-ray tubes (reuse, refurbish, recycling and landfill are considered) and consider the role of regulation, technology and the market in deciding which option is chosen [21]. The remanufacturing operations of a company that remanufactures machinery used in the cold forming and hot forging industries are described in [22]. The company brings in 40-year-old equipment and brings the equipment up to current standards at a 40–50% cost reduction over new equipment. This example illustrates the broad use of the term remanufacture since the company rebuilds roughly 14 machines a year in processes that obviously do not resemble batch processes where product identity is lost. Herb describes a remanufacturing operation in which not just automotive components are remanufactured, but the entire automobile is remanufactured [23]. The operation handles 15–20 automobiles a month and takes 6–8 weeks to rebuild each automobile. Each automobile then comes with a 12 000 mile or 12 month guarantee, and the cost is only $6000, which is roughly half of the price of a new car at the time of the article. However, in order to limit the variety of remanufacturing processes and to ensure a remanufacturable core, only BMWs and Volvos are remanufactured. Lambert and Splinter consider reuse options for packaging materials [24]. The authors propose two methods to evaluate the routing of products and materials with respect to technical, economic, logistic, and environmental criteria. Amezquita [25] also focuses on the issue of variety. He describes a clutch remanufacture process in great detail and proposes an improved lean process to allow for increased variety and reduced set-up times, among others.

2.3. Work providing theories or motivation for the future of remanufacture

Other work in this area presents visions or motivation for where remanufacture should go in the future. One of the most important persons in this area is Walter Stahel. Stahel [26] describes the difference between an industrial economy and a service economy and argues that our economy is likely to shift more towards a service economy as the need to reuse products and accept liability for the entire product life cycle is given to the product's manufacturer. Stahel describes the potential impacts of such a shift, presents the changes in our economic concepts that would result, and proposes technological strategies that will become key issues.

Haynsworth and Lyons [27] provide a vision for how OEMs can begin to take advantage of the potential opportunity for reuse by using proper marketing, product design, and product distribution and return systems. The authors also present a good discussion on the potential of OEM remanufacture and provide a description of the problems and benefits of remanufacturing by an OEM. The problems they list include:

1. consumer prejudice against used goods,
2. difficulty in obtaining cores at a reasonable cost,
3. design changes that make new parts non-interchangeable with old parts.

The authors also list a number of benefits to remanufacture. The benefits to the producer include:

1. an expanded share of the market if price elasticity is significant,
2. the trade-in value encourages customer loyalty and repeat business,
3. a source of data on product failures which can be used to create product improvements.
4. the existing product distribution system used by the OEM can be converted into a "two-way street" in which product used cores are returned. The marginal cost of this additional capability might be expected to be low since transportation systems already exist and are currently used only for one-way traffic.

The benefits to society include:

1. cheaper goods and hence a higher standard of living, and
2. the creation of new jobs since remanufacture is heavily labor intensive.

The authors also provide a description of a current OEM air conditioning remanufacture, which remanufactures AC motors and compressors. The units are completely disassembled so that all unit identity is lost, and parts are grouped for cleaning and refurbishing, sorted, inspected, and supplemented with new parts. The components are then used to satisfy service and replacement demand (thus, they bear the same warranty as new parts). Thus, there is no distinction between new and remanufactured components since they are functionally equivalent.

Matthews and Lave [28] present an economic and social vision and accompanying economic models describing how profit maximizing producers could set product prices for reused products based on the costs incurred during the entire expected product lifecycle (multiple uses) of a product. The result would be producers that focus more on the interaction between the producer and the customer, and producers that are strongly encouraged to determine whether products are reusable or recyclable since this strategy offers lower product prices. In this model, producers depend on reclaiming the product a given number of times to cover the previous costs of production. Therefore, in order to ensure that consumers return the product, consumers could be required to pay a deposit to cover the producer's losses if the product is not returned.

In [29], the Office of Technological Assessment (OTA) provides an overview of environmentally conscious design and manufacturing and describes the place of remanufacturing within this context. The OTA also describes the impact of government regulations and the success of companies such as AT&T and Xerox. The work also provides a description of Germany's "Product Take-Back" laws. In addition, the source gives an explanation of some of the current problems in the way transaction prices account for the life-cycle costs of products. For example, it is pointed out that the government currently gives subsidies or special tax treatment for the extraction of virgin materials but that non-hazardous industrial waste are not regulated on the federal level. Furthermore, consumers of products do not pay the full price for product disposal, which leads to economic problems. Cramer qualitatively considers the impacts of different methods of extending the useful life of products and of making them easier to return to some useful service [30]. The work is based on surveys conducted by Phillips Consumer Electronics Company. Nasr and Varel [31] discuss the phases of a product life cycle and stress the need for cost models that consider the entire life cycle of products. The goal is to determine the best options in designing for the total product life cycle. Beretta and associates discuss the benefits of remanufacture from both an environmental and an economic point of view [32]. Steinhilper gives an overview of the environmental motivation for environmentally conscious design and manufacture and provides a general method for implementing design for recycling and reuse [33]. The current and future outlook of reuse is considered and an example is provided of a US company that remanufactures vending machines to like-new condition.

3. Work seeking to improve product, process, and/or organizational aspects of remanufacturing

The second class of research focuses on improving some specific aspect of remanufacture. Many classifications can be made. We believe that improvements in remanufacture one should consider product design, process design, as well as the organizational design of the enterprise. Hence, in this paper, however, we classify and provide an overview of work according to the following aspects of remanufacturing:

1. product design,
2. process design (which includes manufacturing planning and control, and the management and logistics of reclaiming used products), and
3. organizational design and management of remanufacturing organizations.

3.1. Work seeking to improve product design for remanufacture

One area of research seeks to help designers design products that are more amenable to the processes of product remanufacture. This goal is accomplished by designing products that are able to be used and reclaimed without damage to reusable parts and then successfully pass through the processes of remanufacture as inexpensively as possible. However, this goal cannot be considered in isolation from other design goals such as assembly, function, service, and recycling. Several authors have considered issues related to this problem and these works are discussed in the following paragraphs.

Kosuke Ishii and associates have developed a design strategy and an associated design representation scheme to help designers create design configurations that are beneficial to retirement processes such as disassembly as well as other life-cycle design goals. In this strategy, called "clumping", the designer defines clumps as groups of components or subassemblies that share a physical relationship as well as some common trait based on the design intent. Next, the designer uses the method to determine the compatibility of a particular clumping strategy with various design goals such as recycling, reuse, or the grouping of technologies with similar life spans. Work by Ishii and associates is presented in [34–38]. Marks and associates introduce this clumping strategy as well as their use of a semantic network representation called "Linker" to evaluate the impacts of a given clumping strategy on ownership and retirement costs [34]. Di Marco and associates further describe this clumping strategy [35]. In this work, the authors use qualitative information to assign a measure of compatibility to each "clump" of components and then an empirical function is used to predict the costs to reprocess the product based on the clumping strategy used. Ishii describes the motivation behind this method and the use of this representation scheme and applies the method to evaluate a structural layout in terms of serviceability and recyclability [36]. In the most important of these works from a remanufacturing perspective, Ishii and associates describe the impact of accelerating technological life cycles on design for product retirement [37]. The authors propose the use of the clumping strategy to group components into groups based on technological life-cycle similarities. The authors define technology life cycle as the cyclical introduction, maturation, and obsolescence of the technology embedded in a component, product or product line. Furthermore, any mature product will embody multiple technological life cycles that will be out of phase (the technologies to not become obsolete at the same time). On the other hand, product life cycle refers to the manufacturing, service, and retirement cycle that products themselves pass through. The authors argue that clumping components based on technology life cycle will improve serviceability, reliability, and the ability to easily upgrade components and thus extend material life cycles. Lee and Ishii propose a design chart and related metrics to determine sub-assemblies in a product design that have the opportunity to improve recyclability [38]. The goal is to allow the designer to determine material selection changes and configuration redesigns that can reduce retirement costs.

Bert Bras and associates have done work to allow an improved assessment of the remanufacturability of product designs. The goal is to enable designers to better design products for the processes of remanufacture. In this work, the design factors that influence remanufacturability are determined, metrics are developed to assess remanufacturability and design for remanufacturing guidelines are presented. This work is presented in [39–42]. In [39], the authors simulate an integrated disassembly and assembly process for the single use camera and investigate the impact of design for disassembly product changes on disassembly and assembly efficiency. In [41], the goal is to identify design characteristics which facilitate remanufacture. The authors describe current remanufacturing trends and remanufacturing efforts, identify the factors that drive remanufacturability, and propose design guidelines for remanufacturing. In addition, the authors use a case study involving an automobile door to assess remanufacturing feasibility and to better understand the factors that should be included in a remanufacturability metric. In another work, Amezquita and associates seek to identify efficient and effective metrics for quantifying and enhancing remanufacture [40]. The study is based on the automotive replacement part industry since this industry represents a common existing use of remanufacture. The authors propose two methods to obtain metrics. A top-down approach begins with the general (literature and technology base) and proceeds to specifics, while a bottom up approach begins with specifics (a case study) and proceeds to more general characteristics. The result is a set of measurable traits that could be implemented in a formula to return a numerical rating of remanufacture. Bras and Hammond propose a set of metrics to measure the remanufacturability of product designs and apply the metrics to various case studies [42]. Metrics are proposed to measure ease of assembly, disassembly, testing, inspection, cleaning, refurbishment, and part replacement. The authors describe a weighting scheme used to determine an overall remanufacturing index. Newcomb et al. [43] develop a method to design products with consistent modularity with respect to life-cycle viewpoints such as servicing and recycling. The authors define modularity with respect to life cycle concerns in addition to modularity just meaning a correspondence between form and function. The authors then analyze product architectures to determine the degree of life cycle modularity (i.e., the degree to which modules are independent and have similar characteristics across different life cycle concerns such as recyclability and service). It is argued that increased life cycle modularity is beneficial across all viewpoints since interested people will view the product similarly and consistently. The method of analysis that is used first partitions product architectures into ideal modules according to each life-cycle viewpoint. Next, two measures of modularity are used to analyze the resulting design. The first measure determines the correspondence of modules between several viewpoints. The second measure determines the interactions between modules within a single viewpoint.

Chen and associates present a cost benefit analysis model to assess the economics of design for reuse and recycling [44]. A first formula computes the costs of recycling and reuse as a function of the various costs of each end of life option, and a second formula computes the benefits of reuse and recycling as a function of various parameters. These results are next compared in order to determine the profitability of end-of-life options. The authors also propose design for recycling and design for disassembly guidelines that seek to improve the results of the cost benefit analysis. Lastly, the formulas are applied to a case study involving an automobile dashboard. Emblemsvåg and Bras describe how Activity-Based Costing models that include uncertainty can be developed for evaluating the cost of demanufacture operations [45]. Low et al. [46] present simple equations to compare and trade-off between end of life options. The authors express the costs of resale, remanufacture, upgrade, and recycling as fractions of manufacturing cost and then create linear models to express the profits received for the end-of-life options as functions of manufacturing costs. In another work, the authors extend this work and present revised models that separate manufacturing, disposal, and transportation costs and assume that the costs of disassembly, sorting, re-assembly, inspection, testing and packaging are all proportional to final assembly costs [47]. The authors then compare their equations to commercial data to generate empirical constants. The models are then used to explore the economic viability of different end-of-life options for mature electronics products. Richter and Dobos introduce and solve a mathematical model to address reuse and waste disposal issues [48]. The model may be used consider the economic impacts of different environmental strategies and economic pressures.

Shu and Flowers [49, 82] have also done considerable work in the area of design for remanufacture. Shu and Flowers developed a method for product and process planning for remanufacture using a design structure matrix and axiomatic design. In another work, the authors examine the effects of joining and fastening methods on remanufacturing [50]. Three case studies demonstrate product designs that facilitate assembly and recycling but which impede remanufacture due to choices made in fastening or joining methods. In addition, a computer tool is presented which is used to compute life cycle costs (manufacturing, assembly, maintenance, remanufacturing and recycling costs are considered) based on fastener choices. Scheidt and Zong describe the importance of having accurate historical information when assessing the reuse of electronic modules in electronic devices [51]. An approach is proposed where data storage units could be used for each module to store historical data for use upon product disposal to help determine the feasibility of reuse.

Within the goal of product design for remanufacture, the goal of design for disassembly is especially important since disassembly is a crucial determinant in both remanufacturing feasibility and cost. As a result, much work has been done in this area alone. Navin-Chandra [52] presents an analysis tool called ReStar, which generates disassembly plans and determines when it is both economically and environmentally beneficial to recycle or remanufacture a product. The tool takes as input a description of a product and generates a proposed disassembly plan. This analysis essentially works by keeping track of disassembly times, costs, and revenues and using an optimization algorithm to determine the best sequence for disassembly. Li and associates present a model that uses a simulated annealing algorithm to generate an optimal disassembly sequence and to determine the cost of disassembly [53]. The analysis uses a product assembly model to represent product configurations, and the user establishes disassembly precedence among the components by requiring that some joints be broken before other joints. A cost is associated with breaking each joint, and each component has an associated reclaim value or disposal cost. (Note that the model does not distinguish whether this value comes from remanufacture or recycling.) An objective function is then created by summing up the disassembly costs, reclaimed component values, and disposal costs for each component. An important point to note about this work is that it is not only concerned with a binary yes or no disassembly decision but also the order in which parts are removed. As a result, the optimization problem is not easily solved (by using a linear programming method, for example) and a stochastic optimization method is implemented.

Yan and Gu use a graph-based heuristic approach to generate assembly and disassembly sequences for assessing service and recycling costs [54]. Using the approach, first an "assembly liaison graph" of a product is generated. Second, the graph is decomposed into subgroups using graph theory, and then a disassembly sequence is generated for each subgroup. Lastly, the disassembly sequences for each subgroup are merged and reversed in order to determine an assembly sequence. The motivation behind using a method such as these that take into account the sequence of disassembly is that some methods of disassembly and assembly may require more fixtures, tool changes, and re-orientations of components and sub assemblies. Therefore, it is desirable to find the disassembly sequence that minimizes the number of fixtures, tool changes, and re-orientations necessary. This method also has the advantage that the direction of part removal can be taken into account. Gupta and Taleb describe a two-part algorithm for disassembling products with multiple part occurrences [55]. The algorithm first determines the disassembly requirements over the planning horizon and then provides a disassembly schedule. Some researchers favor a less automated and more "human-in-the-loop" approach. For example, in [56], the use of virtual reality and prototyping for disassembly planning is described.

In our opinion, it would go beyond the scope of this paper to review all work done in disassembly planning and design for disassembly. Furthermore, most disassembly work tends to be focused on recycling rather than remanufacture. Many good reviews exist on ongoing work in the area of disassembly improvements, e.g., [57,58]. It is important to note that disassembly for remanufacture has to be non-destructive, in general, whereas destructive disassembly is arguably most suitable for material recycling, see, e.g., [59,60]. The choice of using destructive vs. non-destructive disassembly processes will result in different product designs. In contrast to manual disassembly, fastener choice and disassembly sequences are irrelevant for most, if not all, mechanical destructive separation approaches (such as shredding). Selecting materials with different properties (such as magnetic versus non-magnetic, light versus heavy, etc.), however, is crucial when pursuing mechanical separation. In [59] more information on the technical and economical feasibility of destructive vs. non-destructive disassembly is given.

3.2. Work seeking to improve the process of remanufacturing

Remanufacturing presents a number of special problems compared to a manufacturing system due to high levels of uncertainty. Specific problems presented include material recovery uncertainty and probabilistic routings, lead times and process times. These differences make remanufacturing sufficiently different from manufacturing to warrant many new analyses. An overview of work in production planning with reuse of parts and materials can be found in [61] and we refer the reader to that work. Notable, however, is the work of Guide and Srivastava who have done a great deal of work in production planning and control techniques toward this end (see, [62–65]).

Interesting to note is that the increasing variety of products and parts due to mass customization practices [19,66,67] as well as the need for more rapid response to customer demands are causing third-party remanufacturers to search for more flexible process approaches than the conventionally used batch approaches. In this context, Amezquita and Bras study the current batch oriented remanufacturing processes for an automobile clutch and propose a lean remanufacturing process that is more robust and has lower costs [25,68]. Martel and Anger describe a remanufacturing environment in the Air Force Logistics Command, the problems encountered, and the implementation of an MRP II project [69].

Coupled to addressing the issues of process planning and control is the work done on managing and designing systems for the recollection of used products. For example, Boyer describes a technique that integrates sales, materials, production, and accounting to manage core control [70]. Krupp describes policies governing the right of return of used products and presents models to determine when new products are required to supplement returns, to identify excess purchases, and to forecast and value reclaimed obsolete products at the end of a product's life cycle [71]. The field of reverse logistics has become a body of research in its own right. A detailed overview of ongoing work in reverse logistics (which will not be repeated in this paper) can be found in [72] in which a number of different models for reverse logistics are presented. Other examples of reverse logistic network designs and implementation can be found in [73].

3.3. Work seeking to improve remanufacturing organizations

Arguably, the remanufacturing efforts that will have the largest economic and environmental impact will be those that have been carefully planned by both process and product design. This implies a crucial importance of original equipment manufacturers (OEMs) since, unlike independent remanufacturers, OEM remanufacturers do not simply capitalize on remanufacture given the current market conditions, but can *design-in remanufacture* and determine these conditions. However, most OEMs do not include remanufacture as part of their (core) business practices, or even consider it an opportunity. Hence, in addition to work seeking to improve individual aspects of remanufacturing operations such as product design, remanufacturing processes, and product retrieval systems, work has been done to improve the overall operations and management of remanufacturing organizations.

Discussions on the opportunities, barriers, and steps needed for increasing the roles of OEMs in remanufacture are given in, e.g., [1,26,27,74,75], see also Section 2.3. McIntosh and Bras [75] argue that in order to expand the role of reuse in society, it is necessary to:

- correct the product disposal externality so that producers bear the full incentives to remanufacture products,
- gain a better understanding of which industries are potential candidates for remanufacture and what design and development strategies enable product reuse, and
- provide producers with the ability to assess their organization's capability to sustain product remanufacture as well as the impact of their decisions on product remanufacture.

A crucial issue for any organization considering remanufacture is the economic incentive. A number of authors, therefore, have provided tools such as cost models to consider issues such as determining the costs and benefits of different end-of-life options for products and determining which products to remanufacture and which products to make in new production. One example of such work is that of Clegg, Uzsoy and associates who have developed linear programming models of production systems with remanufacturing capabilities to determine the impacts of various costs on long-term remanufacturing viability and on short-term operations management issues. Clegg and associates develop a linear programming model of production systems with remanufacturing capabilities [76]. The argument is that producers need to be able to determine how to recollect products from the user and reprocess them; therefore, simple models are needed to determine the combination of remanufacturing and new production that should be used. This model seeks to determine how different costs (such as the costs of production, disposal, inventory holding) effect long term remanufacturing viability and short term operations management issues. Thus, the model can be used to

1. explore the effects of different demand patterns, different production and disposal costs, and different government actions on remanufacture and
2. determine which costs (disassembly, remanufacture, disposal, assembly) are the most important.

The decision variables that are used are the amount of products and components used in each end-of-life option and the inventory levels of intermediate items. Thus, the model determines the amount of product to disassemble, the amount of each component to reuse and dispose of and how much of the product to remanufacture and how much to produce from raw materials in order to maximize profit. Product returns and demand are taken as input parameters.

Uzsoy extends this work and presents a set of models to both determine profitable disassembly configurations and consider a multi-plant, multi-location supply chain design [77]. The supply chain design model is given as input the supply chain configuration (the location and capacity of product recovery, disassembly, remanufacturing, new production and assembly facilities) and product demand and return volumes. In short term analyses, the model then determines the best mix of new and remanufactured products and subassemblies. In the longer term, the model may be used to determine the best supply chain design given a specific scenario. Using the second model, a bill of materials tree representation is used to represent product configurations and a cost and a value is assigned to each component (a node on the tree). An optimization algorithm is then used to determine the best set of components to remove (sequence is not considered). Again, product returns are considered as inputs. Several of the resulting candidate disassembly configurations are then provided to the supply chain model such that the model can pick the best option given the supply chain scenario.

MacIntosh and Bras describe a model for assessing how product design characteristics, product development strategies, and different business conditions impact remanufacturing viability in terms of Net Present Value for an OEM interested in integrated manufacture–remanufacture [74,75]. The model is not focused on the analysis of a single-period and/or single product, but focuses on the interplay between multiple products over multiple time periods. The authors argue the benefits of designing and remanufacturing a family of products with shared components and use a family of single-use cameras as a case study.

Arguably, in the current socio-economic framework, financial costs and profits are key decision factors for OEMs and other organizations interested in remanufacture. At first glance, remanufacture is also advantageous from an environmental point of view because resources (in terms of energy and material) used in the original manufacture are saved and reused. However, Life-Cycle Assessment (LCA) studies are showing that for a number of consumer products (e.g., cars) the use-phase is much more critical from an environmental impact perspective than the manufacturing phase. Hence, organizations must be careful not to remanufacture products with obsolete and/or polluting technologies, but strive for "open" products that allow for the upgrading of embedded technologies. Also, remanufacturing processes are by no means "clean". Cleaning and degreasing, for example, can clearly have severe environmental impact. Clearly, understanding the true environmental benefits and impact of remanufacture is an area in need of research. Unfortunately, current LCA approaches (e.g., as documented in the ISO 14000 environmental management standards) are struggling with how to include multiple product life cycles in the assessment. Furthermore, a lack of LCA standards makes comparisons virtually impossible. A good overview of LCA problems is given in [78]. Nevertheless, work on developing practical Life-Cycle Assessment methods and tools, as well as integrated economic and environmental assessment frameworks (e.g., [79]) are relevant and important to support the decision-making process in remanufacturing organizations and stake-holders.

The largest reduction in environmental impact can arguably only be reached through a holistic approach that includes cooperation between organizations (e.g., suppliers, manufacturers, and distributors). In this context, the relevance of research in what is termed "industrial ecology" is worthwhile mentioning. Industrial ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems analogous to the metabolism (use and transformation) of materials and energy in biological ecosystems, see, e.g., [80]. In industrial ecology, companies, organizations and communities work together to minimize environmental impact and use each others waste in an intelligent manner for creating new products. For example, a carpet manufacturer's production waste can be used by car companies to make sound-deadening materials. On the other hand, polyurethane seat foam taken from recycled cars can be processed into carpet underlayer. In this example, carpet manufacturer, car company, and seat recycling company have a symbiotic relationship like found in a biological ecosystems and form what is termed an industrial ecosystem. Research in understanding and "designing" such industrial eco-systems is only just emerging (see, e.g., [81]), but does have relevance to fundamental understanding and decision-support for remanufacture.

4. Closure

In this paper, an overview of research in remanufacture has been given. The intent was to show the variety and diversity, as well as an indication of the quantity of work directly focused on improving remanufacturing. Clearly, an expanding body of work exists and the review presented here is by no means exhaustive. As illustrated in this paper, the majority of research related to remanufacture seeks to

- describe existing remanufacturing organizations or industries,
- provide theories or motivations for how the role of reuse should change,
- provide improved product and process design for remanufacture,
- allow manufacturing processes to be used in a remanufacturing environment, and
- provide improved methods to reclaim used products.

Much of the existing research provides manufacturers the tools to design remanufacturable products, reclaim used products, and change (re)manufacturing processes. It is our observation that there seems to be little work on providing decision support for Original Equipment Manufacturers who seek to make a transition from traditional manufacture to an integrated manufacture-remanufacture organization, such as exemplified by Kodak and Xerox. We believe that an integrated product, process, and organizational/enterprise design approach should be taken when pursuing such an integrated approach. Furthermore, decisions should not be made based on economic assessments alone, but also include environmental aspects in an objective manner. Clearly many open research questions and opportunities exist in the field of remanufacture!

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