Technical Note

Production planning and control for remanufacturing: industry practice and research needs

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Abstract

Remanufacturing represents a higher form of reuse by focusing on value-added recovery, rather than materials recovery (i.e., recycling). Remanufacturing systems are widespread in the United States and are profitable. However, the management of production planning and control activities can differ greatly from management activities in traditional manufacturing. We report on managerial remanufacturing practices via a survey of production planning and control activities at remanufacturing firms in the United States. Production planning and control activities are more complex for remanufacturing firms due to uncertainties from stochastic product returns, imbalances in return and demand rates, and the unknown condition of returned products. We identify and discuss seven complicating characteristics that require significant changes in production planning and control activities. We also describe the research opportunities that exist for each of the complicating characteristics.

Keywords: Environmental issues; Production planning

1. Introduction

Remanufacturing is an environmentally and economically sound way to achieve many of the goals of sustainable development. Remanufacturing closes the materials use cycle and forms an essentially closed-loop manufacturing system. Remanufacturing focuses on value-added recovery, rather than just materials recovery, i.e., recycling. There are estimated to be in excess of 73,000 firms engaged in remanufacturing in the United States directly employing over 350,000 people (Lund, 1998). Remanufacturing operations account for total sales in excess of $53 billion per year (U.S. Environmental Protection Agency, EPA 1997). As a point of reference, consider that the US steel industry has annual sales of $56 billion per year and directly employs 241,000 (Lund, 1998). The EPA cites remanufacturing as an integral foundation of reuse activities and reports that less energy is used and less wastes are produced with these type of activities (U.S. EPA 1997). However, very few guidelines are available to the practicing manager to aid in planning, controlling and managing remanufacturing operation.

The evidence suggests that production planning and control activities are inherently more complex and difficult for remanufacturers. A recent industry-wide assessment (Nasr et al., 1998) shows that few technologies and techniques have been developed...
specifically for remanufacturing, and that the lack of these tools may limit the growth of remanufacturing as an industry.

Remanufacturing is ‘...an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent-and sometimes superior-in performance and expected lifetime to the original new product.’ (Lund, 1983). Remanufacturing is distinctly different from repair operations, since products are disassembled completely and all parts are returned to like-new condition, which may include cosmetic operations.

Remanufacturing is a form of waste avoidance since products are reused rather than being discarded. These discarded products are usually landfilled, despite any residual value. Remanufacturing also captures value-added remaining in the product in the forms of materials, energy and labor.

Firms based in Europe, or doing business in the European Union, have added incentives to engage in recoverable operations: legislative acts. The German Recycling and Waste Control Act requires that manufacturers actively seek techniques and products that avoid waste and the reuse of non-avoidable wastes (Rembert, 1997). Additionally, scrapped products must be taken back and recycled/reused at the end of their life. This act applies to firms doing business in Germany, as well as German companies. The European Union is rapidly following the German initiative with Austria, Belgium, Finland, France, Italy, The Netherlands, Spain and Sweden all passing stringent laws on reuse (Rembert, 1997). In the US, several states have passed laws, or are considering laws aimed at reducing waste. Massachusetts now prohibits the landfilling or incineration of cathode ray tubes (CRTs), Minnesota has proposed strict requirements for electronics product stewardship, and California has proposed laws mandating producer responsibility for plastics (Lindsay, 1998).

Lund (1998) has identified 75 separate product types that are routinely remanufactured, and has developed criteria for remanufacturability. The seven criteria are: (1) the product is a durable good, (2) the product fails functionally, (3) the product is standardized and the parts are interchangeable, (4) the remaining value-added is high, (5) the cost to obtain the failed product is low compared to the remaining value-added, (6) the product technology is stable, and (7) the consumer is aware that remanufactured products are available. Our research findings support these criteria and provide further support for Lund’s work. In their recent nation-wide assessment of remanufacturing, Nasr et al. (1998) report average profits margins of 20%, showing that remanufacturing is also profitable.

2. Remanufacturing literature

Previous research on remanufacturing has addressed a variety of problems, and we summarize the efforts relevant to production planning and control in Table 1. A thorough discussion of this literature is available in Guide et al. (1999), so our discussion here will be limited. While a number of topics have been covered in depth by the existing body of knowledge, significant areas have not been addressed in previous works. A very limited number of case studies exist (Thierry et al., 1995; Ferrer, 1996; Guide, 1996), and the majority of these studies are limited to a specific functional activity, such as scheduling.

A number of characteristics that significantly complicate production planning and control activities may be inferred from the research literature. Specifically, seven complicating characteristics have been proposed in various forms by researchers. No researcher identifies more than four of the complicating characteristics, and many of the characteristics are only mentioned in passing. The seven characteristics are (1) the uncertain timing and quantity of returns, (2) the need to balance returns with demands, (3) the disassembly of returned products, (4) the uncertainty in materials recovered from returned items, (5) the requirement for a reverse logistics network, (6) the complication of material matching restrictions, and (7) the problems of stochastic routings for materials for remanufacturing operations and highly variable processing times. Table 2 shows each of the complicating characteristics investigated by
Table 1
Remanufacturing research

<table>
<thead>
<tr>
<th>Forecasting</th>
<th>Reverse logistics</th>
<th>Production planning and control</th>
<th>Inventory control and management</th>
<th>General</th>
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<tr>
<td>Reusable container returns (Kelle and Silver, 1989)</td>
<td>Problem structure (Flapper, 1995a,b, 1996; Sarkis et al., 1995; Driesch et al., 1997)</td>
<td>Disassembly economics (Johnson and Wang, 1995; Penev and de Ron 1996; Lambert 1997; Zussman et al. 1994; Veerakamilmal and Gupta, 1998)</td>
<td>Continuous review systems (Muckstadt and Isaac, 1981; van der Laan, 1997; van der Laan et al., 1996)</td>
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Table 2
Research literature identification of complicating characteristic by production planning and control activity

<table>
<thead>
<tr>
<th>Complicating characteristic</th>
<th>Production planning and control activity</th>
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<tr>
<td>Forecasting</td>
<td>Logistics</td>
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<tr>
<td>(1) The uncertain timing and quality of returns</td>
<td>✓</td>
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<td>(2) The need to balance returns with demands</td>
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<td>(3) The disassembly of returned products</td>
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<td>(5) The requirement for a reverse logistics network</td>
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research in specific production planning and control activities.

A part of the purpose of this research is to identify areas that have not been fully addressed, or that have not been investigated at all. In the research issues section, the current research needs are reconciled with previous research issues. A shortcoming of the existing literature is that no research develops integrated systems for planning and control of operational activities, and much of the research fails to consider the interactions between complicating characteristics. In Section 5, we present empirical evidence that supports each of the complicating characteristics, and show how production planning and control activities are specifically affected.

Given the high profitability, growing number of legislative initiatives and growing consumer awareness, the time is right for the formal development of systems for managing remanufacturing processes. At present, these systems exist on a number of scales, ranging from facilities remanufacturing brake shoes to facilities remanufacturing entire aircraft. However, they all lack an integrated body of knowledge of how to design, manage and control their operations.

Remanufacturing firms have a more complex shop structure to plan, control and manage (Guide and Srivastava, 1998; Guide et al., 1997b). This additional complexity is a function of stochastic product returns, disassembly operations, and highly variable material processing requirements. We discuss these and other factors in detail in the following sections. A typical remanufacturing facility consists of three distinct sub-systems: disassembly, processing, and reassembly, all of which must be carefully coordinated (see Fig. 1). Disassembly is the first step in remanufacturing operations and provides the parts and components for processing. Disassembly is also an important information gateway, as discussed in the following section. Remanufacturing operations layouts are most commonly in a job-shop form because of the use of general-purpose equipment, and the need for flexibility (Nasr et al. 1998). Less than one-fifth (17.4%) of remanufacturers report using specialized CNC equipment or manufacturing cells (Nasr et al., 1998). This may be, in part, from the diversity in products remanufactured and the low production volumes. Nasr et al. (1998) suspect that the low level of technology is because of a lack of specialized production and control systems. Reassembly is the final stage in a remanufacturing system. Because of the high variability of remanufacturing processing times and the large number of options for parts (new, remanufactured and substitutable), the task of scheduling is more complex and more likely to be done with simple rule-of-thumb techniques. Remanufacturers may carry a variety of

Fig. 1. Elements of a remanufacturing shop.
inventories: cores (products not yet remanufactured), new parts, spare parts, finished goods, and WIP, and this variety requires continuous monitoring. Additionally, remanufacturers may need to dispose of excess parts periodically, and this requires unique decision making tools.

Remanufacturing firms must be able to manage the additional variety inherent in their environment. The nature of multiple product positioning strategies to serve niche markets, and the resulting need for production planning and control systems capable of managing diverse objectives place significant demands on any Production Planning and Control (PP & C) system. The structure of the remanufacturing shop and the inventory control problem both add to the complexity of the control problem.

3. Survey design and overview

Next, we report on the survey instrument developed and used to assess production planning and control activities, and provide an overview of the production planning and control environment. The survey instrument consisted of 75 questions covering several areas: general company information, demand management, materials management, production planning and control, and miscellaneous information. A copy of the survey is available upon request from the author. Most of the questions asked managers to provide details on specific applications (e.g., disassembly operations) and required considerable time on the part of a manager. We used selected industry experts to provide feedback in a small pilot study of the survey. Their feedback led to additional questions and improved responses. The American Production and Inventory Control Society Research and Education Foundation (APICS E&R) provided funding (Grant #97-14) for the survey and access to the Remanufacturing Specific Industry Group membership list. The membership list yielded 320 firms actively engaged in remanufacturing. We excluded consulting firms, academics, and firms that were interested in remanufacturing, but not presently engaged in remanufacturing. The response rate was 15%, or 48 useable surveys. Multiple responses from the same firms were combined and counted as one response (we had 12 responses from three firms that we averaged and counted as three separate responses). The vast majority of firms responding (95%) are not original equipment manufacturers (OEMs). We believe our sample is representative of the population as our respondents were comparable on several dimensions (e.g., sales, OEM, product type) with a more general assessment of remanufacturing technology conducted by Nasr et al. (1998).

The survey by Nasr et al. (1998) reports on a number of technical functions, such as cleaning operations, reverse engineering and material handling techniques. Our survey is focused exclusively on production planning and control activities and provides a more detailed view of current practice. Firms remanufactured a variety of products ranging from automotive (33% of respondents) to aerospace, machinery, office equipment, bearings, gears, pumps and other small items. The majorities of the respondents’ positions were in materials management (25.6%), and production (28.2%), but several were plant managers (12.8%), or vice presidents (12.8%).

4. An overview of PP & C for remanufacturing

Remanufacturing firms must obtain products that have failed functionally. Acquiring cores — failed products — requires reverse logistics activities, and these activities, in turn, require significant modifications to traditional production planning and control systems. Remanufacturing firms commonly serve a number of smaller niche markets, and use diverse product offerings and strategies to serve these often dissimilar markets. However, even serving smaller niche markets is profitable; 78% of the firms responding had sales in excess of $21 M per year. Firms reported remanufacturing, on average, over 1400 product types and over 50,000 part types per facility. The majority (80%) of remanufacturing firms uses a mix of make-to-stock (MTS), make-to-order (MTO), and assemble-to-order (ATO) strategies, within a single remanufacturing facility. Only one-fifth of firms surveyed reported having pure MTS, MTO or ATO strategies. Further, almost a quarter of the firms report that the mix of MTS, MTO, and ATO changes based on market conditions. In order to manage this amount of product diversity many remanufacturing firms surveyed reported using hybrid PP & C systems. These systems included customized material requirements planning (MRP) sys-
tems, combined with Just-in-Time (JIT) techniques such as Kanbans, Theory of Constraints (TOC) techniques such as drum-buffer-rope, and classic inventory control techniques (reorder point and economic order quantity); although not all remanufacturers used all techniques.

5. The complicating characteristics of remanufacturing

Nasr et al. (1998) conclude that there is a significant lack of specific technologies and techniques for remanufacturing logistics. Based on our survey results, we discuss in detail the seven major characteristics of recoverable manufacturing systems that significantly complicate the production planning and control activities. The characteristics discussed here were developed from the data from our survey, on-site facility visits, and a review of the current literature.

5.1. Uncertainty in the timing and the quantity of returns

Characteristic (1), the problem of uncertainty in timing and quantity of returns is a reflection of the uncertain nature of the life of a product. A number of factors including the life-cycle stage of a product and the rate of technological change will influence the rate of returns.

The product returns process is highly uncertain with respect to timing, when cores are available for remanufacturing; and quantity, how many cores are available. The problem of core acquisition requires that core availability be forecast for planning purposes, for both quantities available and the timing of availability. This forecast should be compared with the demand forecast to determine whether sufficient cores are available to meet demand (which we discuss in Section 5.2). Firms report activities that assist in the control of the timing or the quantity of returns, but not both. Over half (61.5%) of the firms report that they have no control over the timing or quantity of returns. Firms reporting some degree of control mainly used some form of core deposit system. Core deposit systems are intended to generate a core when a remanufactured product is sold. Most companies report requiring a trade-in, or charging a premium if no core is returned (80%). A small percentage of firms (5%) use leasing of the item to reduce timing uncertainties. However, these activities only reduce the quantity uncertainty of returns. Return policies do little to reduce the timing aspect of returns since a sale generates a return — a stochastic event itself. Leased equipment may have the lease renewed or the equipment purchased. Because of these uncertainties in returns quantities and returns timing, remanufacturing firms report core inventories account for one-third of the inventory carried (Nasr et al., 1998). Presumably, higher levels of cores are held to buffer against variation in the supply of cores and the variability in demands.

5.2. Balancing returns with demands

Characteristic (2), the problem of balancing returns with demands, is also a function of a product’s expected life and the rate of technical innovation. The goal, in order to maximize profits, is for a firm to be able to balance the returns of items from consumers with demand for remanufactured items. This need to balance return and demand rates complicates inventory management and control functions, and requires additional coordination between functional areas to effectively manage.

Remanufacturing firms seek to balance return and demand rates to avoid excessive amounts of inventory from building up (where returns exceed demands), or low levels of customer service (where demand exceeds returns). Almost half of the firms (46.1%) report that they attempt to balance returns with final demand. The remaining firms do not attempt to balance returns with demands, preferring instead to dispose of excess inventories on a periodic basis. About half the firms base core acquisition on a mix of actual and forecasted demands, but one-third of firms report using only actual demand rates. Firms using only demand-based rates to acquire cores generally use MTO or ATO strategies, and commonly use work-in-process inventory to buffer against lead-time and demand uncertainty. The MTS firms relying solely on actual demand rates reported no difficulties obtaining sufficient cores. However, one-quarter of the firms report that no excess of cores exists, and their major product acquisition management problem is identifying reliable sources of sufficient quantities of cores. The remaining firms
report several methods of dealing with excess materials, including using excess parts as spares (5%), placing the excess cores into a holding warehouse (22.7%), trading excess cores with other remanufacturing firms (10%), and selling the excess parts and cores to scrap dealers (41%).

The core acquisition problem requires coordination amongst the various functional areas to provide the proper balance of cores and purchased replacement parts, and to ensure a balance of return and demand rates. Core acquisition activities at a typical firm include identifying the potential sources for cores, and establishing preferences based on various criteria (e.g., quality, cost, etc.). We defer this discussion to Section 5.5.

Secondary effects of this characteristic include materials management, and resource planning. Materials management activities are influenced by core acquisition activities since replacement lot sizing is dependent on the expected volumes and condition of cores. In the event replacement parts are not available, excess cores may be cannibalized for needed replacement parts. Inventory control and management techniques should be developed specifically for cores since many remanufacturing firms report that excess cores require costly storage space, and that disposal costs may be high. Finally, production decisions with respect to staffing and scheduling are dependent on core acquisitions and timing. When new parts production co-exists with remanufacturing using shared resources, this information becomes even more crucial since resource contention becomes more pronounced.

5.3. Disassembly

Characteristic (3), returned items must be disassembled before the product may be restored to full use. The effects of disassembly operations impact a large number of areas, including production control, scheduling, shop floor control, and materials and resource planning. The disassembly and subsequent release of parts to the remanufacturing operations requires a high degree of coordination with reassembly to avoid high inventory levels or poor customer service.

Disassembly is the first step in processing for remanufacturing and acts as a gateway for parts to the remanufacturing processes. Products are disassembled to the part level, assessed as to their remanufacturability, and acceptable parts are then routed to the necessary operations. Parts not meeting minimum remanufacturing standards may be used for spares, or sold for scrap value. Purchasing requires information from disassembly to ensure that sufficient new parts are procured. Nasr et al. (1998) report that disassembly is not simply the reverse of assembly, and that a good design for assembly is not necessarily a good design for disassembly. Two-thirds of remanufacturing firms must practice reverse engineering to generate disassembly sequences, and this set of activities is time consuming (average time 22.7 days per product) and expensive (average cost $37k per product). Our survey findings indicate that three-quarters of products remanufactured are not designed for disassembly, and this has a significant impact on operations. Products not designed for disassembly have less predictable material recovery rates (MRRs), higher disassembly times, and generate more waste. Parts may be damaged during disassembly, especially on products not designed for disassembly, and this often increases material replacement rates.

In general, disassembly operations are highly variable with respect to the time required. Our respondents reported that disassembly times ranged from minutes to weeks, with very large variances in required times to disassemble like-units. The average times reported to disassemble a typical product ranges from a low of 5.54 h to a high of 300 h. All products exhibit a wide range of average times for the disassembly of identical products. The variances associated with disassembly times may be very high, with coefficients of variance (CVs) as high as 5.0. This uncertainty makes estimating flow times difficult and setting accurate lead times almost impossible. The majority of remanufacturers stated that they were under constant pressure to reduce lead times in order to remain competitive with OEMs.

One of the decisions facing a planner is how to release parts from the disassembly area to the remanufacturing shops. Firms report using pull, push, and push/pull release mechanisms. Our experience has shown that careful coordination is required between disassembly and reassembly to provide short, responsive lead times. Disassembly activities are also labor intensive with no automated techniques reported.
This is a function of the current paradigm of design for disposal, and as design engineers become more aware of the problems associated with disassembly, presumably the outcome of disassembly operations will become more predictable.

5.4. Uncertainty in materials recovered

Characteristic 4, materials recovery uncertainty, reflects that two identical end items returned may yield a very different set of remanufacturable parts. Parts may be reused in a variety of applications, depending on their condition. For example, parts may be remanufactured, used for spares, sold to secondary markets, or recycled. This uncertainty makes inventory planning and control, and purchasing more problematic.

Material recovery uncertainty is measured as the MRR: the frequency that material recovered off a core unit is remanufacturable (Guide and Spencer, 1997). The majority (95%) of remanufacturing firms use simple averages to calculate MRR, although at least one firm responding used more sophisticated multiple regression models. Firms reported a wide range of stability for most MRRs, ranging from completely predictable to completely unpredictable. Products are equally likely to contain parts with known predictable recovery rates, as to contain parts with no known pattern of recovery.

Material recovery rates may be used in determining purchase lot sizes and remanufacturing lot sizes, and may play an important role in the use of MRP systems. Firms are almost evenly split with respect to incorporating MRRs into purchase lot sizing. Firms must purchase replacement parts and materials to use when original parts may no longer be returned to serviceable condition. Purchased replacement parts account for, on average, one-third of parts on a fully remanufactured item (Nasr et al., 1998). The average purchase lot size for remanufacturing firms is relatively small, only 334 units, and the average cost of a purchase order is $11k. Of the firms using recovery rates in calculating purchase lots, three-quarters use the historical rates and the remaining firms report that planners use subjective judgement. This is surprising, since if a fixed schedule of end items is known in advance, the required replacement materials may be calculated with certainty, given the appropriate MRRs. Many managers (32.8%) reported not being aware of material recovery rates, suggesting a lack of communication between engineers and materials managers.

Purchase lot sizing is done using a variety of techniques, and over one-quarter of the managers reported using multiple lot sizing techniques. The most common purchasing lot sizing techniques are dynamic lot sizing rules where historical consumption patterns, price breaks, and service level requirements may be taken into account. Lot-for-lot purchasing is also common because of the simplicity and the perception of holding lower amounts of inventory. Finally, one-fifth of firms routinely use fixed purchase lot sizing; the reason most cited being a vendor’s minimum purchase requirement. Purchase lot sizing provides a level of protection against variability in material recovery rates since orders are commonly planned to cover multiple periods. Managers cited a number of concerns with purchasing, the most common ones were: (1) long lead times (90%), (2) sole suppliers for a part or component (75%), (3) poor visibility of requirements (65%), and (4) small purchase orders and, as a result, unresponsive vendors (55%). Purchase lead times reported were highly variable; the mean time to receive an order ranged from 0.5 to 90 weeks. The variation in lead times is also very high, with coefficients of variation as high as 3.0 not uncommon. Purchased parts also cause a high percentage (~45%) of late orders.

MRRs also make lot sizing for remanufactured items more complex since uncertain recovery rates may delay release of lots until a batch of parts has accumulated from disassembly. Additionally, the problem of stochastic routings makes remanufacturing lot sizing a more complex problem than traditional manufacturing lot sizing. We defer our discussion of remanufacturing lot sizing until a later section.

A final area that merits discussion is the use of MRP in a remanufacturing environment. The use of MRP is widespread among remanufacturers and three-fourths report using some form of MRP. A high percentage (86.2%) of firms report the MRP system is customized to some extent, and the uses of MRP vary greatly in this environment. Firms commonly use MRP for planning purchase and remanu-
facturing order releases, maintaining bills of materials, and materials tracking. There was no evidence that firms using MRP systems were less likely to experience significant problems with purchase orders, inventory control, or due-date performance. Firms that incorporated MRRs into the purchase order release calculations were less likely to cite concern with poor visibility of requirements, but still cited visibility as problematic. This poor visibility is a function of the short planning lead times (average less than 4 weeks) and dependence on actual demand rather than forecasts. Few firms report being satisfied with their MRP systems, yet few report using alternative techniques.

5.5. Reverse logistics

Characteristic 5, a reverse logistics network is how products are collected from the end user and returned to a facility for repair, remanufacturing or recycling. This requirement is a very complex one in itself. It involves a number of decisions such as the number and location of take-back centers, incentives for product returns, transportation methods, third-party providers and a number of other decisions. We discuss the impact of this characteristic from the view that a successful production planning and control system must adapt to the additional supply-driven uncertainties. The management of product acquisition activities is a key research issue for this characteristic.

A large portion of reverse logistics is concerned with core acquisition management, which we discussed briefly in a previous section. This area is responsible for core acquisition and ensuring an adequate supply of cores for remanufacturing. Most firms acquire cores directly from the customer (81.8%) by requiring a trade-in when a remanufactured item is purchased. Since the majority of products remanufactured by the firms surveyed were of relatively high value ($141,000), customers were motivated to return the products themselves. This is an important distinction from reuse networks for relatively low value items (e.g., recycled goods), where the consumer may require incentives even to provide the products for collection. The design of a returns network in a value-added remanufacturing system may not be as critical for success as in material-recovery operations; further investigation is certainly needed. The other three methods to acquire cores were core brokers (9.2%), third party agencies (7.3%), and seed stock (1.7%). Core brokers act as middlemen, speculating on cores that have no formal market presently and serving as a consolidator for smaller volume core collectors. Managers reported that core brokers charged a premium for their services, and that cores obtained were often very costly to remanufacture due to poor condition. Third party agencies are information brokers that provide information about cores, arrange for a core exchange, or connect buyer and seller. These third party agencies do not exist for many remanufactured products, but are extensive in the automotive parts industry where there is a large established trade organization. Leasing is an option that more remanufacturers are taking advantage of, but it represents a relatively small portion (5%) of returned products for the firms surveyed. It may be worthwhile to note that leasing does reduce timing uncertainty, but it does not eliminate it since a lessee has the option to renew. Finally, in order to provide remanufactured products where the original products have not been in use long enough to provide sufficient returns, seed stock may be used. Seed stock is composed of products that failed OEM specifications at the manufacturing plant and is purchased by a remanufacturer to provide customers with current product designs or features. If the remanufacturing firm is an OEM subsidiary, seed stocks may be provided as part of customer service. Core acquisition management controls how products are acquired and from what sources, in order to meet customer demand. As discussed earlier, balancing return rates with demand rates is a related function.

5.6. Materials matching requirements

Characteristic 6, part matching requirements is where the customer retains ownership of the product and requires the same unit returned. This requirement may be customer-driven, e.g., when a customer turns in a unit to be remanufactured and then requests that same unit is returned to them. Xerox offers customer-driven returns as a part of customer service for copier remanufacturing. A unit may also be composed of a mix of common parts and components and serial number specific parts and compo-
ments. This characteristic complicates resource planning, shop floor control, and materials management.

The requirement for parts matching compels the firm to coordinate disassembly operations carefully with remanufacture operations and reassembly. This requirement is common for remanufacturers practicing a MTO product position strategy where the customer retains ownership and provides the product to be remanufactured. A full 15% of firms reported depending solely on customer-owned assets. This dependence on customer-owned assets has the advantage of no risky core acquisitions based on projected demands. However, the major disadvantage is a very short planning horizon with very low visibility for replacement parts. Replacement parts and components are more expensive for customer-owned assets, almost 25% on average, greater than for MTS parts. Remanufacturers report offering customer required returns as a service to customers for a variety of product types, including copiers, network equipment and avionics.

The other major impacts of this characteristic are on scheduling and information systems. In order to provide the same unit back to the customers, parts (up to 40-k parts on a relatively simple product) must be numbered, tagged and tracked, and this places an additional burden on the information systems. The reassembly of a unit composed of matched parts may be easily delayed since a specific part number, not just a specific part type, may delay the order. Remanufacturing firms relying on a MTO strategy are less likely to use an MRP system for material procurement. The majority of firms used simple re-order point systems for inexpensive parts, and ordered more expensive replacement parts as-needed. The purchase lead times for these firms were among the highest of all remanufacturers, averaging almost a full year. Make-to-order firms also reported some of the shortest planning horizons, with many firms planning materials and resources requirements only after products are returned from the customers. Order release is exclusively one-for-one and this makes set-up reduction programs popular. However, in order to provide reasonable remanufacturing lead times, firms routinely carry excess capacity for critical resources.

Firms report using a variety of methods to track materials and parts, including MRP, in-house developed database systems, and manual tagging and tracking. Remanufacturing lot sizing, when this characteristic is present, is most commonly lot-for-lot because of the unique requirements of remanufacturing operations (we discuss this fully in Section 5.7). Priority control of parts to provide a predictable arrival of parts in the reassembly area is also a common concern among remanufacturers. Firms report using a set buffer size for common parts where service levels trigger replenishments. Parts that are more expensive are pushed to the reassembly area by the use of priority dispatch rules, or pulled by a final reassembly schedule. Purchase orders are often problematic for reasons discussed earlier-low volume and visibility. These two factors are often more pronounced in an MTO environment.

5.7. Routing Uncertainty and Processing Time Uncertainty

Characteristic (7), stochastic routings and highly uncertain processing times are a primary concern at the operational level. Stochastic routings are a reflection of the uncertain condition of units returned. A part will have a maximum set of processes that should be performed to restore the part to specifications. However, these routings represent a worst-case scenario, and the majority of parts will only require a sub-set of these processing steps. Highly variable processing times are also a function of the condition of the unit being returned. These additional forms of uncertainty make resource planning, scheduling, shop floor control, and materials management more difficult than in traditional manufacturing environments.

Stochastic routings should not be confused with purely probabilistic routings common in repair shops or in the modeling of job shops. In remanufacturing operations, some tasks are known with certainty, e.g., cleaning; however, other routings may be probabilistic and highly dependent on the age and condition of the part. Routing files are a list of all possible operations, and for planning purposes, the likelihood of an operation being required is maintained. Not all parts will be required to route through the same set of operations or work centers, indeed, few of them would go through the same series of operations as a new part. This adds to the complexity of resource planning, scheduling and inventory control. Shifting
bottlenecks are common in this environment because material recovery from disassembly will vary from unit to unit (hence, remanufacturing volumes), highly variable processing times, and stochastic routings. This makes resource planning (both machines and labor) and estimating product flowtimes difficult. This characteristic is cited as the single most complicating factor for scheduling and lot sizing decisions. Order release mechanisms are limited to one-for-one core release, except for some common parts for which release may be delayed in order to provide a minimum batch size.

Remanufacturing lot sizing is complex and there is no agreement on the best method. A standard lot size of one unit was reported in over one-third of the firms because of the unique requirements of remanufacturing; that is, unique routings for identical part types. Only one-quarter of firms reported using a fixed lot size, usually based on the EOQ. Almost one-half reported using dynamic lot sizing techniques based on capacity constraints, projected demand, or service fill-rates.

Cleaning operations represent a major portion of the processing time, with an average of 20% of total processing being spent in cleaning (Nasr et al., 1998). Parts may return for multiple processing at the cleaning operation, and almost half of remanufacturing firms reported additional difficulties in cleaning due to part materials and sizes. Parts must be cleaned, tested, and evaluated before any decision is made as to remanufacturability. This late determination of a part’s suitability further complicates purchasing and capacity planning due to the short planning horizon. Firms also report that the variability in a parts’ condition creates problems in machine fixturing and set-ups. These additional sources of variability further complicate the accurate estimation of flow times.

6. Research issues

The discussion of the complicating characteristics shows that remanufacturing firms must be able to manage complex tasks that are significantly different from tasks in a traditional manufacturing environment. We find that the complicating characteristics must be considered as a whole, rather than consider-
ing the effects of each characteristic separately. Fig. 2 shows the inter-relations among key decision points, and process and information flows for a remanufacturing production planning and control system. In the following sub-sections, we discuss major research issues for each of the complicating characteristics (see Table 3). This section is based on information from the survey reported here, as well as the survey by Nasr et al. (1998), a thorough review of the existing literature (including working papers and workshop presentations), and follow-up telephone interviews with industry experts. In-depth case studies, highlighting the effects of particular characteristics would provide insights into how firms manage these complexities.

6.1. Uncertainty in the timing and the quantity of returns

Essential research issues in this area include a need to develop strategies that create tools and techniques to manage both quantity and timing uncer-

Table 3
Research issues by complicating characteristic

<table>
<thead>
<tr>
<th>Complicating characteristic</th>
<th>Major research issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in timing and quantity of returns</td>
<td>(1) The effectiveness of methods (e.g., leasing, deposits) in reducing uncertainty in the timing and quantity of returns.</td>
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<tr>
<td></td>
<td>(2) Forecasting models to predict return rates and volumes.</td>
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<td></td>
<td>(3) Reliability models to better predict product life-cycles for products with multiple lives.</td>
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<td></td>
<td>(4) Inventory control models that explicitly consider batch arrivals of returned products.</td>
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<td></td>
<td>(5) Joint inventory/production models considering dependent return rates.</td>
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<tr>
<td></td>
<td>(6) Studies that track rate of technological advances that will influence product returns.</td>
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<tr>
<td>Balancing returns with demands</td>
<td>(1) Methods to examine the benefits of synchronizing returns with demands.</td>
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<tr>
<td></td>
<td>(2) Product positioning strategies to serve multiple markets.</td>
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<tr>
<td></td>
<td>(3) Aggregate production planning models that consider returned products.</td>
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<tr>
<td></td>
<td>(4) Coordinated efforts by purchasing and inventory managers to plan, manage, and control return rates.</td>
</tr>
<tr>
<td>Disassembly of returned products</td>
<td>(1) Models to aid in planning what parts and components to recover in disassembly.</td>
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<td></td>
<td>(2) Models and methods that examine the effectiveness of coordinating disassembly release with reassembly.</td>
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<td></td>
<td>(3) Models for the design, layout and staffing of disassembly facilities.</td>
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<tr>
<td>Materials recovery uncertainty</td>
<td>(1) Models that support material recovery planning and prediction, including reliability models.</td>
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<td></td>
<td>(2) Studies examining the key differences between traditional purchasing activities and purchasing for remanufacturing (including purchasing lot sizing).</td>
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<td></td>
<td>(3) Models that can predict amount of recovered materials based on age of product and usage rate.</td>
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<td></td>
<td>(4) Studies examining the use of MRP, including modifications/suitability.</td>
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<tr>
<td>Reverse logistics</td>
<td>(1) Studies highlighting the differences between material reuse logistics and product reuse logistics.</td>
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<td></td>
<td>(2) Models and systems for core acquisition management and strategies.</td>
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<td></td>
<td>(3) Studies that can establish product recall strategies and minimize product breakdown.</td>
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<td></td>
<td>(4) Optimal channel choice for remanufacturers (retailers, direct from the remanufacturer, or third party).</td>
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<tr>
<td>Materials matching</td>
<td>(1) Information systems to aid in materials tracking.</td>
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<td></td>
<td>(2) Models and systems that provide visibility for materials requirements.</td>
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<tr>
<td></td>
<td>(3) Models and systems for shop floor control coordination.</td>
</tr>
<tr>
<td>Stochastic routings and highly variable</td>
<td>(1) Remanufacturing lot sizing models that consider the trade-off between set-up delays and unnecessary processing delays.</td>
</tr>
<tr>
<td>processing time</td>
<td>(2) Models that provide for scheduling coordination between disassembly and reassembly.</td>
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<tr>
<td></td>
<td>(3) Order release methods that consider the rapidly changing workloads in remanufacturing work centers.</td>
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<tr>
<td></td>
<td>(4) Bottleneck scheduling heuristics based on cleaning operations.</td>
</tr>
</tbody>
</table>
Forecasting models designed to predict the availability of returns are needed to reduce some of the uncertainty. Works by Kelle and Silver (1989), and Goh and Varaprasad (1986) develop forecasting models for returns of reusable containers. However, these products have very little in common with remanufacturable goods, and a careful evaluation is needed. Reusable containers are also referred to as refillable containers (e.g., bottled gas), and these types of products are simply re-circulated until the container may not be safely re-used. The unsuitable products are discarded, and replacement units purchased. There is a body of reliability literature addressing repairable products (Ascher and Feingold, 1984), and the development of models considering multiple product life cycles could provide reliability-based models for returns.

The research literature in this characteristic has focused mainly on inventory models that assume that returns are exogenous variables, and that there is no correlation between sales and returns of products (see van der Laan, 1997 for a complete discussion of inventory models in remanufacturing). More research is needed on systems for inventory control and management since much of the previous research has assumed individual, rather than batch arrivals. Additionally, models and managerial systems that link inventory systems with reverse logistics are needed.

6.2. Balancing returns with demands

Critical research issues for this characteristic involve better methods to balance return rates with demand rates. There are also very few reports of systems designed to handle the complexity of multiple sources and uses for parts in a dynamic environment. Research regarding the most effective product positioning strategies, and corresponding PP and C systems to serve such diverse markets would also be welcome. Aggregate production planning models detailing alternatives between core acquisition, parts disposal, and purchased parts would be of benefit to practicing managers. This characteristic has mainly been addressed by inventory theory models (see van der Laan, 1997), but little has been done to integrate these models formally into a production planning and control system.

6.3. Disassembly

There are a number of interesting research questions dealing with disassembly operations. First, disassembly acts as an information gateway, and this information is used in a number of decision areas including, purchasing, resource planning, final assembly, scheduling, and product design. Our research indicates that much of this information is not being exploited to the fullest extent possible. Disassembly operations provide data on material recovery from individual units, and there are often lengthy delays in data entry into a tracking system. Nasr et al. (1998) report that although specifications may be changed substantially because of information from disassembly, few of these changes are communicated to engineering. Formal models of information systems could help understand the cross-functional information requirements and the potential benefits of such information systems. For example, information on a product’s performance obtained at disassembly should be fed back to design engineers to provide improved designs.

Scheduling systems that enable closer coordination between disassembly and reassembly are also needed to provide more predictable lead times and provide better customer service, while minimizing the investment in unnecessary inventory (see Guide and Srivastava, 1998). The research on the release policies for materials is inconclusive and better models are needed to fully understand the gating of materials from disassembly operations. The disassembly process itself is an uninvestigated area; no models or guidelines exist for disassembly center design or staffing. Alternative structures require investigation, including disassembly line design and flexible worker allocation schemes.

6.4. Uncertainty in materials recovered

No research has used reliability models to aid in predicting material recovery rates. The development of decision models for determining material recovery options would also be of benefit, especially models focusing on the expected residual value remaining in the part (see Penev and de Ron, 1996; Lambert, 1997). There is a body of reliability literature spe-
specific to repairable products (Ascher and Feingold, 1984) and efforts are needed to incorporate these results into improved predictive models of materials recovery. MRRs provide the foundation for other decision-making activities, and more accurate predictive techniques are of great interest.

There are no models that take into account the added protection from purchase lot sizing, although preliminary research by the author has shown that some purchase lot sizing techniques may help provide more predictable remanufacturing schedules. The use of purchase lot sizing techniques that provide for several periods of coverage buffer against the likelihood that recovery rates will often be lower than expected. However, techniques that allow managers to examine the trade-off between inventory holding costs and customer service must be developed. Certainly, the complications reported by managers (i.e., low visibility of requirements, long lead times) contribute to lower levels of customer service, and all of these areas deserve further investigation.

The use of MRP in this environment, with high amounts of variation and the extensive modifications necessary requires considerable research. A number of schemes for MRP design and use are reported in the literature (Driesch et al., 1997; Flapper 1994; Inderfurth and Jensen 1998), but evaluations of these systems with real data are needed. The use of MRP combined with other forms of materials planning was reported by many firms, but no clear guidelines exist for inventory planners in this environment. Other resource planning activities, such as flexible worker assignment policies, capacity planning and machine scheduling should be documented and modeled.

6.5. Reverse logistics

Nasr et al. (1998) report that slightly less than half of remanufacturers report using the same distribution channels as new products providers. However, there are no details available as to what channels are used. This requires further investigation as to what channels are used, and how these may differ from traditional manufacturing distribution. Remanufacturing executives expressed an interest in decision-making tools that help evaluate choices among sources for cores and to aid the core buying process itself. A clear model of how core acquisition management activities coordinate between purchasing, production, and other functional areas would be of benefit to streamlining operations. Information systems using electronic commerce (i.e., the Internet) could be beneficial in bringing buyers and sellers of cores together. The development of value-added reuse reverse logistics networks requires special attention since previous reverse logistics network models reported have focused mainly on material recovery (recycling) returns. A complete discussion of reverse logistics models is available in Fleischmann et al. (1997).

6.6. Materials matching requirements

Fundamental research issues include providing remanufacturers with greater visibility in requirements for very expensive materials, and developing cooperative relationships with suppliers. Hybrid inventory control models are commonly used in this environment, and there is no research investigating the effectiveness of these tools. The unique requirements for materials tracking and control place a strain on current shop floor control systems because of the additional need for tight coordination between disassembly and reassembly. Models investigating the benefits of lot sizing techniques and guidelines for managerial use are also needed. Customer-driven returns may be a successful tool for green marketing, and help to encourage reconsumption by consumers. Cooperative research with marketing would provide hard evidence of the potential of this option.

6.7. Routing uncertainty and processing time uncertainty

There are no decision-making tools to assist a manager in deciding whether the set-up savings from remanufacturing lot sizing are greater than the added processing delays from parts not requiring particular operations. Other shop floor level decision models could address scheduling coordination between disassembly and reassembly activities, order release mechanisms, and priority control techniques. Bottleneck scheduling heuristics may be able to exploit the
high amount of time spent in cleaning operations, but detailed cases of cleaning operations are first needed.

7. Conclusions

Remanufacturing executives were asked to identify the greatest threats to industry growth over the next 10 years. The majority (60%) cited the increased pressure to reduce remanufacturing lead times continuously, and many (38%) others cited the lack of formal systems (e.g., operations, accounting, logistics) for managing their businesses. Other threats identified included lack of cores (50%), products designed for disposal (34%), and rapid technological changes (28%). The need for academics to develop new systems and evaluate the applicability of present systems is clear.

We have identified and described seven complicating characteristics of production planning and control activities for remanufacturing firms. The characteristics give focus to efforts in developing new systems for remanufacturing production planning and control. Firms use hybrid production planning and control systems to control operations catering to diverse markets. Most firms use a variety of product positioning strategies and this further complicates the problems of planning, controlling and managing operations. We also note that remanufacturing represents a much larger industrial segment than previously thought, and is deserving of full attention by academics from all areas.

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