REMANUFACTURING SCHEDULING AND CONTROL: WHERE ARE WE?

Shona D. Morgan, Ph.D.
Associate Professor of Operations Management
Department of Management
North Carolina A&T State University
Greensboro, North Carolina 27411
smorgan@ncat.edu

Roger J. Gagnon, Ph.D.
Associate Professor of Operations Management
Department of Management
North Carolina A&T State University
Greensboro, North Carolina 27411
gagnonr@ncat.edu

Submitted to:
SE INFORMS
45th Annual Meeting
October 2009
Track: Production and Operations Management

ABSTRACT

We examine our progress in scheduling remanufacturing operations by reviewing the literature in detail. We individually examine published research in scheduling disassembly, remanufacturing/repair, and reassembly operations and their integration. The objective functions/performance criteria, quantitative methodologies, and complexities/issues are examined. Finally, an overall assessment of our progress and continued research needs are presented.

1. INTRODUCTION

Remanufacturing allows products that are no longer functional to re-enter the manufacturing process to be refurbished or disassembled into usable modules, components, or materials or disposed. Remanufacturing in the U.S. is a $53 billion per (Giuntini and Gaudette 2003). This reprocessing can significantly reduce the amount of waste directed at landfills and conserve natural resources involved in product development. This is particularly important when manufacturers are facing increasing pressure to produce products in an environmentally supportive manner. According to Carter and Ellram (1998), over $124 billion is spent in the United States to comply with mounting environmental statues and regulations and this undoubtedly will escalate. Remanufacturing received academic attention at MIT's Center for Policy Alternatives as early as 1979 (Lund 1984) and published reports of industrial applications of remanufacturing/recycling in the automobile industry emerged in the early 1990's (e.g., Wolfe 1991, Stix 1992, Anon 1993).

There is enormous complexity involved with developing effective and efficient remanufacturing operations. They are arguably more difficult than designing and managing forward supply chains, since forecasting the timing and quality of product returns and determining the optimal disassembly sequence(s), as examples, are so problematic (Toktay 2003). Guide (2000) outlines the characteristics that significantly complicate the production planning and control activities involved in remanufacturing: (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, (7) the stochastic routings for materials for remanufacturing operations, and (8) highly variable processing times. Other researchers (e.g., Krupp, 1993; Brennan, Gupta, and Taleb, 1994; Flapper et al., 2002; and Kim et. al., 2007) have noted other significant challenges, issues, and decisions involving remanufacturing scheduling, such as the selection of order release mechanisms, lot sizes, and priority scheduling rules; capacity restrictions; part commonality among multiple products; the planning of buffer inventories; scheduling over multiple time periods; integration of forward and reverse manufacturing operations, etc. and these are listed in Table 1.

INSERT TABLE 1 ABOUT HERE

Guide (2000) describes a typical remanufacturing facility to consist of three distinct operations: (1) disassembly, (2) remanufacturing/repair, and (3) reassembly. Disassembly separates the returned item into its modules, components, or basic materials. These are evaluated and determined to be acceptable for reuse, repairable, sold for scrap, or discarded. Those modules and components needing repair or rework are inventoried for later recall or sent to the remanufacturing/repair operations. After reconditioning to a usable state the modules or parts are inventoried awaiting use or sent directly to the reassembly processes, where they are reassembled into products for resale and readied for finished goods inventory or shipment. As emphasized by the complicating characteristics, the scheduling and control of each of these operations is an extremely challenging task.

However, progress has been made in: (1) identifying the realistic complexities and issues in remanufacturing scheduling needing address, (2) reporting how industry is actually addressing these issues, and (3) developing numerous quantitative methodologies and testing various objective criteria to achieve improved, if not optimal, solutions. Numerous articles have been published and research projects completed on these subjects; the review article by Gungor and Gupta (1999) alone contains over 300 references. Review articles are needed periodically to summarize and analyze these efforts – establish where we are and the future directions needing exploration. Thus, the purpose of this research effort can be divided into three stages: (1) review the progress we have made in the scheduling and control of disassembly and remanufacturing operations; (2) assess how we have advanced our ability to address the scheduling complexities mentioned in the literature; and (3) highlight additional research needs. We know of no other research that has reviewed in detail the disassembly scheduling and remanufacturing literature and the complexities/issues that impact this environment. Figure 1 delineates the boundaries of our research effort, which includes the three remanufacturing operations and the buffer inventory considerations.

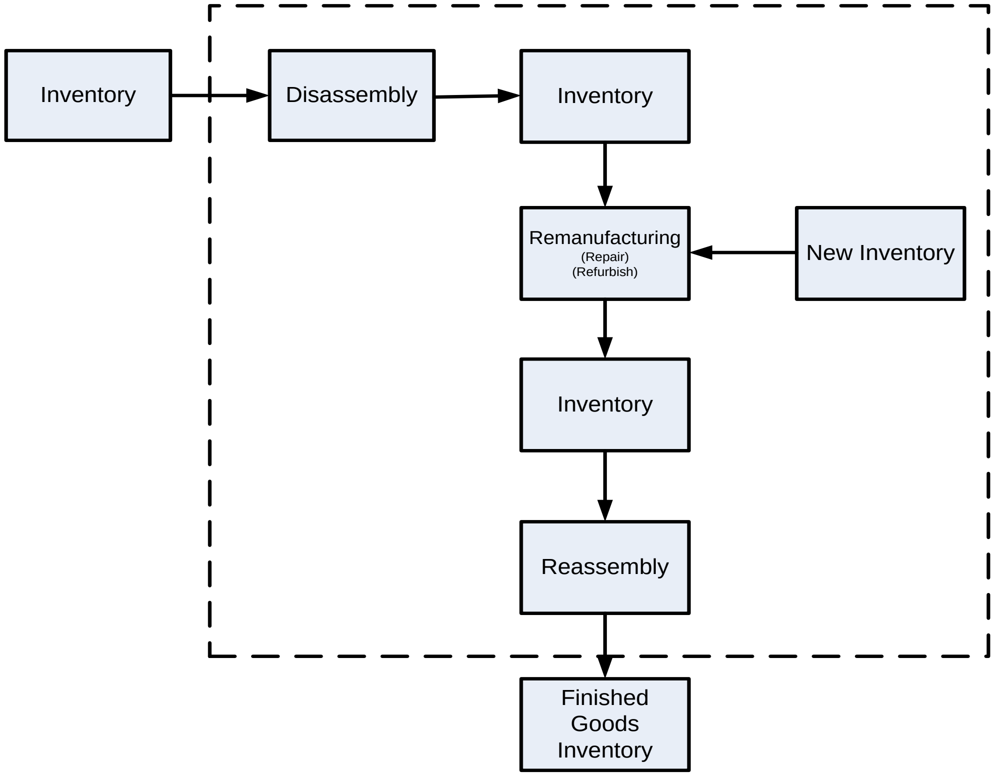

Figure 1: Remanufacturing Shop

Our literature analysis is organized in a strategic-to-tactical decision framework (product decisions before process decisions, etc.) supplemented by the necessary technological and operational progressions that need to be made in the disassembly environment. We devote section 2 to a review and analysis of the single and multiple product disassembly literature. We further subdivide this literature into infinite versus finite capacity, no parts commonality to parts commonality, and the use of deterministic versus stochastic parameters. Using the same organizational structure section 3 reviews the literature that integrates the scheduling/planning of several remanufacturing operations (aggregates disassembly, remanufacturing and/or assembly scheduling/planning). Section 4 investigates the progress on the complexities, issues and areas related to the disassembly scheduling problem. Such generalizations include capacity planning, lot sizing and inventory effects, order release priority dispatching rules, and control mechanisms. Section 5 discusses the objective criteria/functions and methodologies used in remanufacturing scheduling. Section 6 characterizes future research needs.

2. SCHEDULING DISASSEMBLY OPERATIONS

We first characterize the disassembly structure and the important nomenclature of the problem environment. The root item is the product to be disassembled. A leaf item cannot be disassembled further and are the items to satisfy demand. In Figure 2, item 1 represents the root and items 4, 5, 6, and 7 are leaf items. A child is defined as any item that has at least one parent and a parent has at least one child. Referring to Figure 2, item 3 is a parent to child items 6 and 7. Numbers in parentheses represent the item yield when the parent item is disassembled. Thus, when item 2 is disassembled it yields four units of item 5. From this, we define the basic disassembly problem as follows:

> For a given disassembly structure, determine the quantity and timing of disassembling all parent items (including the root item) while satisfying the demand of leaf items over a given planning horizon with discrete time periods (Kim 2007).

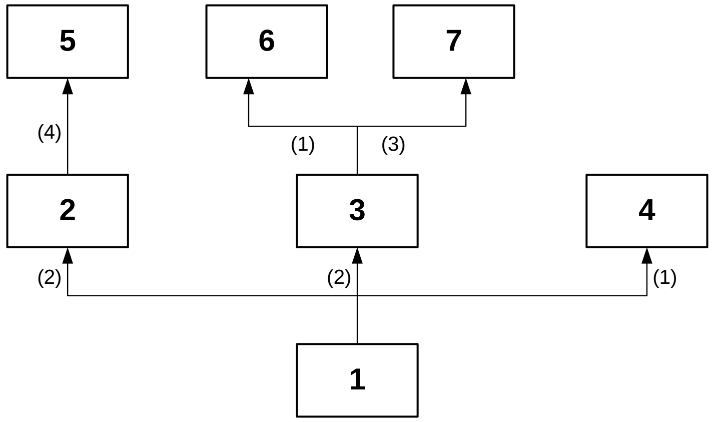

Figure 2: Disassembly Structure/ No Commonality

2.1 Disassembly Operations for Single Products

Much of the work that addresses the single product disassembly scheduling problem assumes infinite capacity. That is, no limitations on resources (e.g., setup time, storage, etc.). Articles that investigate the infinite capacity, single product environment can be further classified according to whether part commonality is considered. Commonality implies that products or subassemblies have common or shared parts and/or components. Part commonality adds considerable complexity to the disassembly scheduling problem since there are multiple procurement sources for demand items. Figure 3 summarizes the research efforts for scheduling disassembly operations for single products. We further explore the research accomplishments in the paragraphs to follow.

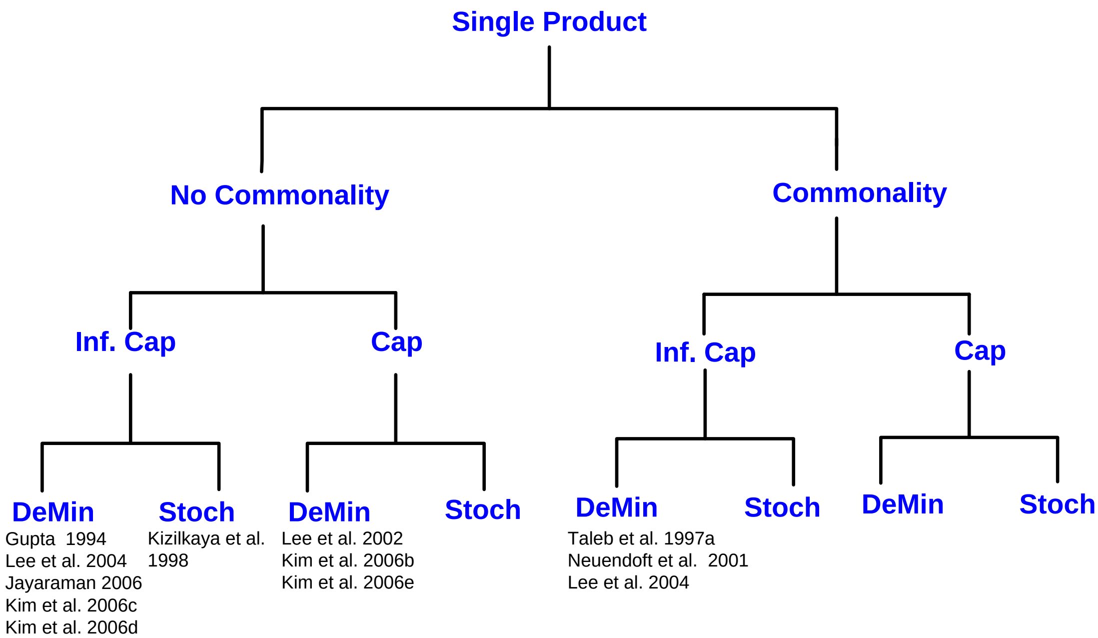

Figure 3: Summary of Disassembly Scheduling Research for Single Products

2.1.1 Infinite Capacity with No Parts Commonality

Gupta and Taleb (1994) help define the disassembly scheduling problem and reiterated that MRP cannot be applied to shop floor operations that require disassembly of some items. They present an algorithm that is essentially a reverse version of materials requirements planning. In their algorithm the demand for leaf items (parts) is converted into the required demand for parent items level-by-level up to the root item (finished good). Thus, the disassembly schedule for the root item and all other parents is determined so as to satisfy the demand for all leaf items; no other objective is addressed. The authors demonstrate the procedure for a single product assuming constant lead times and no defects. They recognize the likelihood of excess part inventories that can result. Finally, they also mention the need to address part commonality and the necessity to integrate the scheduling of disassembly and assembly operations.

Lee et al. (2004) develop integer-programming models to solve disassembly scheduling. Integer programming models are developed to solve three cases of the disassembly-scheduling problem – (1) single product without part commonality, (2) single product with part commonality, and (3) multiple product types with part commonality. The integer programming results for each problem case will be discussed in the appropriate section of this paper. The objective is to minimize the sum of the purchase, set-up, inventory holding, and disassembly operations costs. The authors do not compare their results directly to the results obtained by Gupta and Taleb (1994; single product with no part commonality), since the MRP-like algorithm of Gupta and Taleb provides the optimal solution, but utilizes a different objective. However, the authors do test the performance of their integer programming formulation on a set of 900 randomly generated test problems for each combination of three levels of the number of items (10, 20, and 30) and three levels of the number of periods (10, 15, and 20) for a total of 2700 evaluated test problems. Results show that most problems are solved optimally. The performance of the integer programming models becomes worse as the number of items increase and as the number of periods increase.

According to Kim (2007) more recent work has been done that demonstrates that the disassembly scheduling problem is NP hard (see Kim 2006d). The authors solve the problem using a branch and bound algorithm that determines the upper and lower bounds using a Lagrangean relaxation technique.

Kim et al. (2006c) consider the two-level disassembly structure. This special case of the basic disassembly scheduling problem assumes a direct link between the root item and leaf items with no intermediate non-root parent items. This special structure is exploited in the development of a polynomial optimal algorithm based on the theme of the Wagner Whitin (1958) algorithm. More specifically, the problem is formulated as a dynamic programming model by decomposing it into sub-problems.

Jayaraman (2006) presents a linear programming model that minimizes the total cost per remanufactured unit. The solution to the model provides a value for the number of unit cores with a nominal quality level that are disassembled and remanufactured in a period, the number of modules remanufactured, and the number of cores that remain in inventory at the end of a time period.

Kizilkaya and Gupta (1998) consider stochastic elements of disassembly scheduling in terms of the time to disassemble a product. They investigate the need to control the material flow from the disassembly cell to remanufacturing. The focus is on the disassembly cell, which consists of *N* workstations in series. Unlike the traditional Just-in-Time (JIT) system where demand is generated at the last station, demand in the disassembly cell can occur at any of the *N* workstations. The authors invoke a flexible Kanban system (FKS) that has the ability to adjust the number of Kanbans at each station on a daily basis according to a predetermined percentage of the demand. The simulation model developed takes into account that retrieved products may be defective, thus necessitating the need to disassemble several units of the used product. The FKS model also accounts for uncertainty in the disassembly time needed for a product. Results indicate that as the number of Kanbans increases, the work in process increases, yet the order completion times (exponentially distributed) and shortages decrease yielding better customer satisfaction.

Gupta and Taleb (1994) address the disassembly scheduling problem by developing a reverse MRP procedure with no explicit objective function – merely satisfy demand for all leaf items. More recently Lee et al. (2004), Kim et al. (2006d), Kim et al. (2006e), and Jayaraman (2006) develop deterministic, mathematical programming models that consider various cost-based objective functions and are shown to achieve optimal solutions to restricted, test problems. Kizilkaya and Gupta (1998) use a computer simulation methodology to introduce a flexible Kanban approach that incorporates stochastic processing times. Due to its ability to adjust to production uncertainties, they recommend FKS as a viable production strategy for remanufacturers. More work is needed to integrate disassembly planning and scheduling that specifically addresses the need for feasible shop schedules.

2.1.2 Infinite Capacity with Part Commonality

Disassembly scheduling that takes into account part commonality is more challenging to solve. Part commonality implies that a product or subassembly shares its parts or components. The complexity with parts commonality arises from the multiple procurement sources for each common part and the additional interdependencies between parts/components (see Figure 4).

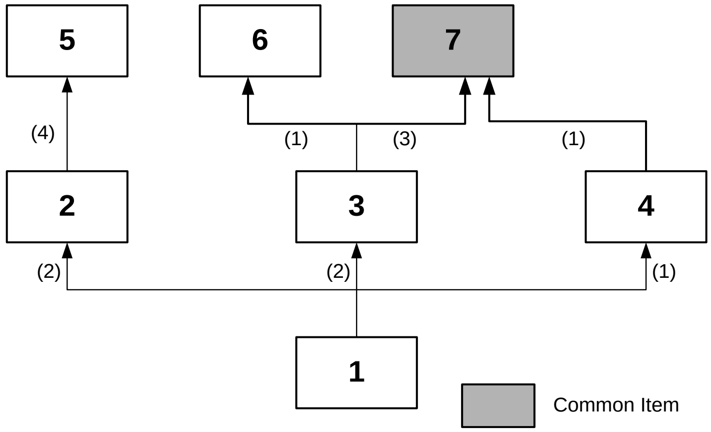

Figure 4: Single Product with Part Commonality

All open literature within this category address the disassembly scheduling problem with deterministic parameters. In 1997 Taleb, Gupta, and Brennan (TGB) offer a reverse MRP-based algorithm for a disassembly product structure that includes common parts and materials. Their objective is to minimize the total number of end items to disassemble to fulfill the demand for components. The authors assume lead times are constant and no defects.

Neuendoft et al. (2001) extend the work of TGB (1997) by presenting an algorithm based on Petri Nets. In the first step of the algorithm, the minimal number of root items to meet the total demand of all leaf items is computed. The second step details the disassembly schedule of the root item so that demand in each period can be satisfied. The authors show that their Petri Net algorithm, overcomes many of the shortcomings of the TGB algorithm. Most notably, the TGB algorithm has the assumption that parts commonality occurs at the same level within the disassembly product structure making the algorithm less extendable to a variety of product structures.

Lee et al. (2004) modify their integer programming formulation to solve single product disassembly problems with parts commonality. The cost-based objective remains the same. However, the inventory balance constraints are modified to account for the potential of multiple parents for a given item. The result of their integer programming solution are compared with TGB (1997; single product with part commonality) and Neuendorf et al. (2001) who in addition to their Petri Net algorithm, present a corrected version of TGB to overcome the round-off errors observed in the TGB original solution. Results show that the integer programming models achieve the optimal solution for the existing problems in the open literature and provide optimal or near-optimal solutions to a set of randomly generated test problems. The cost-based objective function proves to be particularly useful when compared with TGB, since the cost-based objective presented in the paper provides a method to distinguish among multiple solutions generating the same number of products to be disassembled.

A variety of solution methodologies (i.e., MRP, Petri Nets, and IP) have been applied to disassembly scheduling of single products with parts commonality. Several of these are extensions to previous work completed for the "single product - no commonality case". (For the mathematical programming models additional constraints were added to account for the multiple component sources.) As with the "no commonality case" optimal solutions have been achieved for restricted problems and near-optimal solutions to sets of larger, test problems. Additional advancements need to address the realistic, stochastic issues of defective parts and components, customer demands, and disassembly operation times.

2.1.3. Finite Capacity with No Part Commonality

The work of Lee et al. (2002) focuses on extending the efforts of Gupta and Taleb (1994) to handle capacity constraints. The authors develop an integer programming model, which is a reversed form of the capacitated multi-level lot-sizing problem. A case study on end-of-life inkjet printers is used to test the model. Results demonstrate that optimal solutions can be obtained for the set of test problems within a reasonable amount of computation time. Extensions to this work need to consider multiple products, parts commonality, and heuristic strategies to accommodate large-sized problems.

Kim et al. (2006e) extend the work of Lee et al. (2002) by tackling a shortcoming of the integer programming model's inability to handle real-sized problems due to excessive computational needs. Kim et al. (2006e) overcome this drawback by introducing an additional phase of the solution process. This second phase utilizes the initial solution obtained from the integer program. The initial solution is evaluated to determine if the capacity constraints are satisfied. If the constraints are satisfied, the optimal solution has been found. If the capacity constraints are not satisfied, a search commences for a feasible disassembly schedule that simultaneously maintains the current value of the objective function.

Additional extensions to the work of Lee et al. (2002) are made by Kim et al. (2006b). The authors develop an integer programming formulation with the objective of minimizing the sum of set-up, disassembly operation, and inventory holding costs. The extensions are manifested in two areas. First, fixed set-up costs are considered over the disassembly planning horizon. Second, a Lagrangean heuristic algorithm is suggested that allows for the problem to be decomposed into the single item, lot-sizing problem, which is easily solved with a polynomial time algorithm. Several randomly generated problems are used to test the algorithm and indicate that the heuristic provides near optimal solutions within reasonable computation time.

Clearly, from the research in this area, there has been increased focus on the capacitated problem since 2002. The initial work of Lee et al. (2002) laid the groundwork for incorporating a time limit for the disassembly operation to be performed. Improvements are made in Kim et al. (2006e) and Kim et al. (2006b) which specifically confront the limitations of the integer program presented in Lee et al. (2002) in solving practical sized problems. Additional work in this area calls for effective solution methodologies for the more general capacitated problems (i.e., parts commonality or multiple products).

2.2 Scheduling Disassembly for Multiple Products

The multiple products case with no part commonality is essentially multiple, independent, single products. These are typically run in separate batches and are, thus, considered a special case under the single product category. The research pertaining to scheduling disassembly operations for multiple products is outlined in Figure 5. We summarize this literature now.

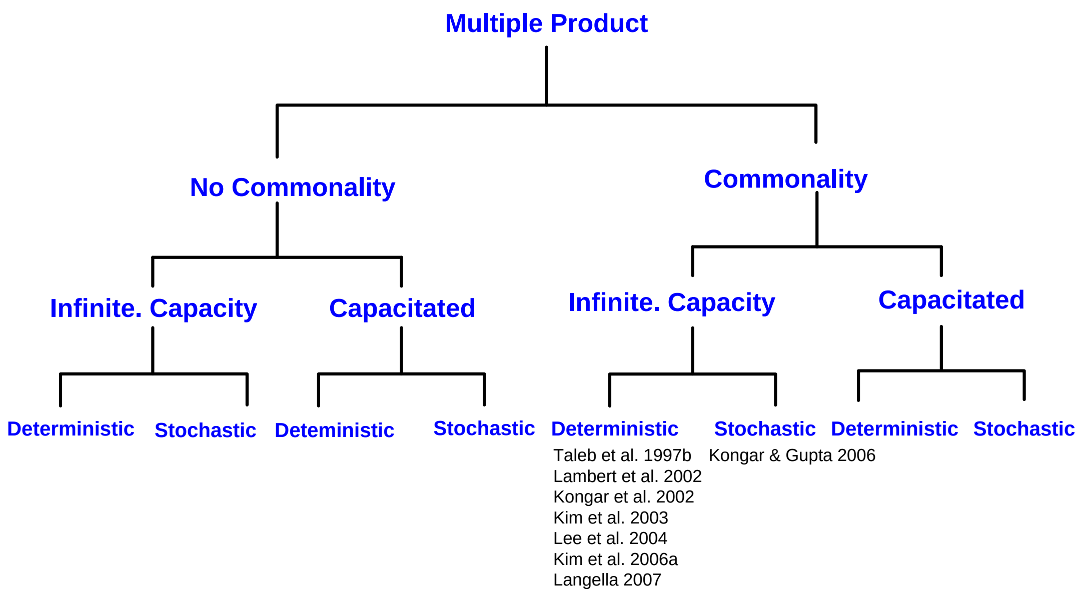

Figure 5: Summary of Disassembly Scheduling Research for Multiple Products

2.2.1 Infinite Capacity with Part Commonality and Deterministic Parameters

The case of multiple products with parts commonality adds additional complexity. In this scenario there is more than one root item and items that may have more than one parent (see Figure 6).

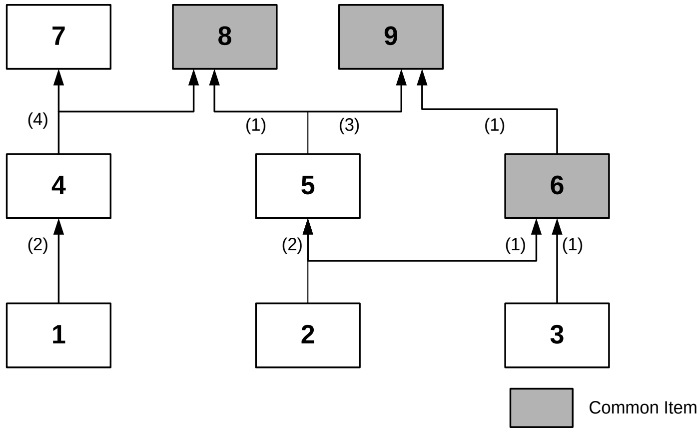

Figure 6: Multiple Products with Parts Commonality

Taleb and Gupta (1997) present a methodology, in part employing reverse MRP logic, for disassembling multiple product structures with parts and material commonality. This methodology consists of two algorithms: the Core Algorithm and the Allocation Algorithm. The first algorithm determines the total disassembly requirements of the root items over the planning horizon in order to minimize the total disassembly cost. The latter algorithm provides a schedule for disassembling the root items and subassemblies by allocating requirements over the planning horizon and implicitly minimizes the holding cost by delaying disassembly as much as possible. The methodology assumes constant and known lead times, no defects, and unrestricted capacity.

Kim et al. (2003) consider the cost-based objective of minimizing the sum of setup, disassembly operation, and inventory holding costs. A heuristic procedure rooted in the linear programming relaxation is developed that provides near optimal solution for real-sized problems. In essence the heuristic solves the LP relaxation and then rounds down the solution. The second phase of the heuristic modifies the rounded down solution such that all of the original constraints are satisfied while also factoring in cost changes. Computational results reveal that the algorithm performs the best when setup costs are small, which is a rare feature of disassembly processes.

Lee et al. (2004) modify their integer programming model once again to handle the case of the multiple product types with parts commonality. Their integer programming model is compared to the two-phase heuristic of Taleb and Gupta (1997) described above. Two objective functions are considered (i.e., minimize the number of products to be disassembled and minimize the sum of product disassembly costs) with the integer program for adequate comparison with the Taleb and Gupta (1997) two-phrase heuristic. Results indicate that the integer program outperformed the two-phrase heuristic under both objective function scenarios using the existing problems from the literature.

Kim et al. (2006a) present an integer programming model for disassembly scheduling (i.e., the quantity and timing of disassembly) such that the sum of set-up, disassembly operation, and inventory-holding costs are minimized. Multiple products with part commonality are considered. A two-phase heuristic procedure is presented which first finds an initial solution by solving the linear programming relaxation and then refines the solution using a dynamic programming algorithm. This paper extends the work of Kim (2003). Test results show that the two-phase heuristic provides near-optimal solutions in short computation time. Extensions to this work call for the elimination of several assumptions to the model. Specifically, the complicating characteristics of (1) defective part and component recovery, (2) stochastic demand and lead times, and (3) resource capacity constraints need to be incorporated into the model.

Kongar and Gupta (2002) suggest an alternative to the single criteria objective of the disassembly scheduling problem found in the open literature. The authors assert that the single criterion objective often limits full consideration of the problem environment. A goal programming model is developed that allows the decision maker to meet the demand for leaf items while satisfying a variety of physical, financial and environmental constraints and multiple goals. The six goals incorporated in the decision model are (1) maximize the total profit value, (2) maximize profit from material sales, (3) minimize the number of disposed items, (4) minimize the number of stored items, (5) minimize the cost of disposal, and (6) minimize the cost of preparation.

The model is tested via a case example comprised of three products that are made up of various combinations of 15 different items. Model results provide the number of reused, recycled, stored and disposed items as well as the values of the six aforementioned performance measures.

Lambert et al. (2002) consider demand driven disassembly. More specifically, optimal lot-sizes of end-of-life products must be determined to fulfill the demand for components from multiple products. The authors assert that traditional approaches fall in one of two categories: (1) component mining where strategies rely on applying the reverse bill of material or (2) full material mining where in addition to components, frames, castings and fasteners are mined for reuse. The later approach may be too comprehensive for industries concerned only with component recovery, yet component recovery is limited in its ability to be extended to more general problems. To overcome this, the authors present a new method that combines the advantages while simultaneously eliminating the disadvantages of both methods. The new procedure succeeds at devising a linear constraint to represent the disassembly quantity. A mixed integer program is developed and optimally solved. As the component demand increases, the LP relaxation solution provides reasonable approximations.

Finally Langella (2007) develops an integer programming model with the objective of minimizing the sum of procurement, separation, holding, and disposal costs. A heuristic procedure is developed that modifies the algorithm of Taleb and Gupta (1997) in order to alleviate the potential of infeasible solutions. Results reveal that the algorithm performs well in large majority of generated test problems that vary by product structure, cost, and demand. The performance of the algorithm declines as the problem size grows.

As researchers explore more practical-sized problems with increased (and realistic) problem complexity such as parts commonality and longer time horizons, this requires a move away from exact methods due to excessive computation time. Numerous heuristic techniques with varying objectives are shown to provide good solutions. More specifically, Taleb and Gupta (1997) look at minimizing disassembly costs, Kim et al. (2003) minimize the sum of setup disassembly operations and inventory holding costs. Integer programming models with varying objective functions were developed in Lee et al. (2004), Kim et al. (2006a), and Lambert et al. (2002). Kongar and Gupta (2002) use goal programming as a solution methodology to satisfy six objectives. Each advancement attempts to increase the industrial relevance of disassembly scheduling by considering extensions to the pioneering work of Taleb and Gupta (1997). However, additional work needs to be done to incorporate the realistic challenges of defective parts, stochastic demand and lead times, and resource capacity constraints.

2.2.2. Infinite Capacity with Part Commonality and Stochastic Parameters

Kongar and Gupta (2006) extend their earlier work (Kongar and Gupta 2002) by incorporating uncertainty in terms of the total profit goal, the number of EOL products retrieved from end users or collectors, and the sum of the number of reused and recycled components. The authors utilize fuzzy goal programming (FGP) to solve a multi-criteria decision problem. FGP allows for the goals of the problem to be characterized with intentional vagueness to better mimic the imprecise real world environment. A case example consisting of three products made up of a combination of 24 different items is used to test the model. Results provide optimal the number of products to be taken back to satisfy the demand, the number of items reused, recycled, stored, and disposed. Values of numerous other physical, financial, and environmental performance measures are also provided.

2.2.3 Finite Capacity with Part Commonality

We uncovered no articles that address multiple products with capacity restrictions *and* part commonality.

3. SCHEDULING INTEGRATED OPERATIONS

This section reviews research addressing the scheduling and control of all disassembly, remanufacturing, and reassembly processes. Scheduling integrated operations (disassembly, remanufacturing/repair, and reassembly) encompasses the full range of complexities associated with remanufacturing supply chains.

3.1. Scheduling Integrated Operations for Single Products

3.1.1. Order Release Mechanisms and Priority Dispatching Rules

Materials requirements planning (MRP) encompasses all remanufacturing operations from core returns inventory through reassembly, storage, and shipping. While the MRP planning and control methodology had been a prime choice for OEM manufacturers for years, researchers (e.g., Panisset 1988, Krupp 1993, Gupta and Taleb 1994) recognized that traditional material requirements planning (MRP II) was inadequate to address the needs of remanufacturing due to multiple demand points (leaf items), the divergence property, the uncertain rate of recovery, uncertain routings, uncertain yield from material recovery, stochastic task times, etc. However, a number of efforts were made to modify or augment elements of MRP to make it more amenable to remanufacturing scheduling. Panisset (1988) pointed out that traditional material requirements planning (MRP) logic and the supporting bills of materials do not provide sufficient guidance for repair/refurbish industries (e.g., diesel locomotives and railcars).

He offered a "repair bill", which had lead-time offsets for disassembly, repair, and assembly. He recognized that different repair plans and times would be needed and would often be unknown until the end item was disassembled. Thus, he created different "repair classes" which prescribed different repair operations and times. These were based on the repair class that occurred most frequently, is the most complex repair, or the most pessimistic repair time. Finally, some had only one type of repair. The planners decided the appropriate repair class. Thus, Panisset handled the uncertain nature of the work (routings, operations, times) by creating repair classes and employed the intervention of the planner to select the appropriate repair class before disassembly and modify the plan, if necessary, after disassembly operations. The production strategy here was essentially a make (or repair)-to-order job shop, since one or multiple items could be sent for repair (locomotives, box cars, electrical equipment, etc.) and similar items were sent for repair/refurbish operations allowing somewhat standardized planning.

Krupp (1991) offered suggestions and evidence of how restructuring and adding additional bills of materials (BOMs) can address some of the challenges of using MRP II systems in a remanufacturing environment. These challenges include the uncertain timing and quality of returned of cores, salvage yield, and the need to having matched sets of replaced parts.

Inderfuth et al. (2001a) consider product recovery with multiple remanufacturing options. Products entering the reverse network are not all suitable for the same reuse option. Different remanufacturing options have different cost and profits values associated with them that must be considered. The objective of this work is to select the correct quantities of product for a specific remanufacturing option such that the costs (i.e., disposal, remanufacturing, stock holding, backordering) are minimized. A periodic review system is employed with stochastic returns.

Souza et al. (2002a) investigate the impact of various dispatching rules to determine the optimal remanufacturing policy. This work considers the case where a remanufacturer can sell products "as is" to the consumer or remanufacture the product. Products returned to the remanufacturer are categorized or graded based on condition. Graded products that are not sold "as is" to the consumer are assigned to a remanufacturing station based on three different dispatching rules (*Random*, *MaxDiff*, and *Dynamic*). The objective is to maximize profit while achieving a desired service level, which is measured by the flow time (lead time) for an order. Results show that the Dynamic dispatching rule which accounts for the current workload at each remanufacturing stations outperforms the *Random* and *MaxDiff* dispatching rules.

Thus, we see efforts in a multiple product environment to modify or enhance traditional MRP II systems to allow use in remanufacturing. Additional repair bills and BOMs, augmented with planner intervention, are introduced to handle various returns timing, quality, and yield issues. Costs are addressed as Inderfuth et al. (2001) model the multiple remanufacturing options with the objective of minimizing the costs of disposal, remanufacturing, holding, and even backordering. In addition to employing multiple, internal remanufacturing "bills" Souza et al. (2002a) introduce the "sell as is" (non-remanufacturing) option, which expands the portfolio of choices for satisfying market demand.

3.1.2. Product Structure Complexity, Disassembly Release Mechanisms, Priority Scheduling/Expediting Rules, and Control Mechanisms

The vast majority of research on product structure complexity focuses on the impact of product structure on stocking decisions, such as lot sizing and safety stocks (Blackburn and Millen 1982, Collier 1982, Benton and Srivastava 1985, and Sum et al. 1993) in OEM assembly operations. Other research (Fry et al. 1989, Philipoom et al. 1989, and Russell and Taylor 1985b) examined the effect of product structure on the performance of dispatching rules in an assembly job shop.

Guide, Srivastava, and Kraus (1997) use computer simulation to test the impact of different types of product structures (simple, intermediate, and tall) on the performance of remanufacturing operations using sixteen different priority-scheduling rules. Four different performance criteria were employed. They conclude that for simple product structures the best performing priority-dispatching rules are the high level (level 0) bill of material-based rules (HLB). However, as the complexity of the product structure increases, the shortest processing time rule (SPT) and dynamic priority dispatching rules perform better than the HLB rules. When the product structure becomes very complex, due date rules outperform all others. The authors conclude that the mechanism guiding the release of materials from the disassembly operations to the remanufacturing stage is also critical.

In a related work Guide and Srivastava (1997b) use computer simulation to evaluate the performance of four order release strategies (level, local load oriented, global load oriented, and batch) and two priority scheduling rules (first come-first served (FCFS) and earliest due date (EDD)) against five performance criteria (mean tardiness, mean flow time, work-in-process, mean idle time, and mean throughput units). They determined that in this complex and highly variable environment: (1) the batch release strategy performed poorly and should not be considered, (2) the EDD rule outperformed the FCFS rule in four out of five performance measures (all but throughput), and (3) since there was no clear victor among the three remaining release strategies, managers should opt for the simplest strategy, the level order release strategy. Thus, the authors conclude that a simple level order release strategy combined with a due date priority scheduling rule provides an effective means of releasing and scheduling work in this environment.

Guide (1996) introduces the drum-buffer-rope (DBR) production philosophy as a means of planning, scheduling, and controlling remanufacturing operations. He promotes this “synchronous manufacturing” methodology as a means to cope with routing uncertainties (frequency and time) and required task sequences. In this scheme the final assembly schedule and the assembly buffer, which feeds the final assembly operation, drive the order releases. The “drum” and primary constraint is the schedule of parts arriving to the final assembly area. The final assembly inventory “buffer” acts to protect against assembly disruptions (late parts due to routing delays, scrap, rework, etc.). The “rope” pulls parts into the repair shop to ensure that all parts appear at the final assembly area at the right time. Guide uses computer simulation to test the DBR approach against an existing modified MRP system. Since the set-up and processing times were stochastic, Guide utilized beta distributions with the mean, maximum, and minimum expected times based on historical data. Material release schedules for individual parts were dictated by the buffer size per part. Parts with longer expected processing times had precedence. Each work center follows a FCFS queue discipline. The primary objective was to complete orders on schedule with secondary performance measures including the mean WIP, the mean throughput rate, and the mean flow time. He learned that the DBR approach, regardless of buffer size multiplier outperformed the MRP-based method on every performance measure. Guide concludes that the inventory buffer multipliers help the system to cope with variability in the remanufacturing environment.

Guide (1997) later employs computer simulation to examine the impact of different priority dispatching rules (FCFS, SPT, EDD, longest processing time (LPT), global SPT, and Slack) on the performance of the DBR methodology at non-constraint work centers. He assesses the mean flow time, lateness, percentage of parts expedited, and throughput at non-constraint work centers. He also tests his results over three shop load levels and incorporates one complicating characteristic – the requirement for mating specific parts. His results indicate that at low levels of utilization any of the PDRs examined performed well; the only performance measure which was sensitive to the PDR the was percentage of units expedited for which EDD and FCFS performed the best. At intermediate levels of utilization EDD or FCFS produces the best results with respect to all performance measures. The results from these levels of utilization indicate that the simpler priority rules, EDD or FCFS, outperform the more complex and that rules that perform well in a typical job shop, e.g. SPT, had poor results in this remanufacturing shop. Finally, at high levels of utilization *none* of the PDRs performed well. Guide suggests that in this situation variability and queues increase and, as a result, the part buffer sizes need to be enlarged.

Guide, Srivastava, and Kraus (1998) investigate the performance of proactive expediting policies with different product structures and disassembly release mechanisms. Using computer simulation they find that the proactive expediting systems do not significantly improve performance regardless of the level of utilization or threshold value (the percentage of a product’s parts that have arrived at the reassembly operation and which is used to initiate the expediting). In addition they report that the performance of these policies decrease with increasing product complexity. They also report that the disassembly release mechanisms (DRM) do not affect the performance of the expediting policies nor was there any difference in the performance of the various DRMs. Additionally, they note that the highest level BOM priority dispatch rule performed well for simple product complexity, but was outmatched by the earliest due date release at intermediate and high product complexity. Therefore, Guide et al. reassert the value of simple priority rules (e.g., EDD) for the remanufacturing environment.

Veerakamolmal and Gupta (1998) develop a procedure, which sequences multiple, single-product batches through disassembly, and retrieval operations in order to minimize machine idle time and makespan. The procedure requires that returned (electronic) products be grouped into like product batches. A standard process plan (and time) for disassembly is then assigned to each batch and used to determine the optimal batch sequence.

Thus, we see that product structure plays an integral role in the performance of remanufacturing operations. High-level BOM rules perform best for simple structures, with the SPT and dynamic rules the choice for intermediate structures, and EDD outperforming all for complex structures. It is also shown that, as the level of utilization of the remanufacturing system increases, the EDD rule dominates; however, at high levels of utilization none of the PDR rules perform well and part buffers must be enlarged. Research indicates that the drum-buffer-rope methodology outperforms MRP-based methods on every performance measure tested. Perhaps not surprisingly, larger inventory buffers are shown to help with system variability and performance. Finally, research shows that proactive expediting policies do not significantly improve system performance.

3.2. Scheduling Integrated Operations for Multiple Products

3.2.1. Part Commonality and Product Structure

Kim et al. (2006), present a mixed integer program to aid remanufacturers decide how many cores should be designated for remanufacturing and how many new parts to purchase from an external supplier, such that the cost savings from remanufacturing is maximized. A numerical example with multiple products and part commonality is presented to test the proposed model. Sensitivity analysis is conducted to assess how changes in the capacity of the remanufacturing facility impacts the objective function. Results indicate that an optimal remanufacturing capacity exists such that additional capacity expansion does not improve the cost savings.

3.2.2. Order Release Mechanisms, Lot Sizing, Priority Dispatching Rules, and Control Mechanisms

Guide, Kraus, and Srivastava (1997) use computer simulation to comprehensively test the performance of fifteen priority dispatching rules and four disassembly release mechanisms against four performance measures (mean flow time, mean tardiness, root means square tardiness, and mean percentage tardy) in a multiple product remanufacturing environment. They found that: (1) there were no significant performance differences among the disassembly release mechanisms and interestingly the time-phased release mechanism provided no significant advantages over the simpler mechanisms, (2) due date priority rules provided good, and in some cases the best, overall performance, and (3) the use of reassembly accelerator rules to proactively expedite parts to the assembly operation made no significant difference in any of the performance measures. They, therefore, concluded that use of the simplest disassembly release mechanisms (first off, first to shop - FOFS) is warranted. They also encouraged the use of due-date-based rules and discouraged the use of accelerator priority rules, which provided no significant benefits in performance.

Guide, Jayaraman, and Srivastava (1999) use computer simulation to assess the effect of lead time variation on the performance of disassembly release mechanisms in a multiple product environment. They tested five disassembly release mechanisms and three performance measures - mean flowtime, RMS tardy, and percentage tardy. Since the due date priority rule had worked well in previous studies for the authors (e.g., Guide, Kraus, and Srivastava, 1997), EDD was used exclusively in this analysis. Job batches were a mixture of three products with simple, intermediate, or complex structures. Five different levels of lead time variability were tested. Results indicate that the lead time variation does have an effect on the release of parts from the disassembly operation. At all levels of variation the FOFS release mechanism performed well, particularly for serial specific parts. Although at high levels of variability there is less distinction between the performance of various DRMs, the authors encourage the use of the FOFS DRM for both serial number specific and common parts over a range of lead time variances.

While there is less published research pertaining to this section, several, reported results are noted. Kim et al. (2006a) show that for multiple products with part commonality an optimal remanufacturing capacity exists that minimizes remanufacturing costs. Guide et al. (1997) reveal that there are no significant performance differences among DRMs and that reassembly accelerator rules to proactively expedite parts to the assembly operation had no impact on performance. Thus, they encourage the use of the simplest disassembly release mechanisms (FOFS) and EDD priority rules and discouraged the use of accelerator priority rules. In addition they promote the FOFS release mechanisms when lead time varies for either common or specific parts. As for single products we see that simple DRMs and priority scheduling rules (EDD) having advantages over more sophisticated variations for a wide range of several common complexities.

Table 2 provides a summary of the pertinent features of the remanufacturing scheduling literature.

INSERT TABLE 2 ABOUT HERE

4. GENERALIZATIONS

This section examines research results not directly focusing on remanufacturing scheduling, but can, nonetheless, impact remanufacturing scheduling.

4.1. Capacity Planning

The difficulties in planning capacity for remanufacturing operations have been cited by Fourcaud (1993). Guide and Spencer (1997) state that traditional methods of manufacturing planning and control are difficult to use because of complicating factors such as probabilistic routings, uncertain material replacement, and highly variable processing times for repair operations. To aid in planning capacity with these uncertainties they develop a modified bill of resources method. This methodology incorporates an occurrence factor (OF), the percentage of time that a particular operation is required, and a material recovery rate (MRR), the frequency that material recovered from a core unit is repairable, into the bill of resources. These modifications help to account for the variation inherent in remanufacturing.

Later Guide, Srivastava, and Spencer (1997) use computer simulation to evaluate the performance of five rough-cut capacity planning techniques in a remanufacturing environment. These are the bills of resources, capacity planning using overall factors, modified bills of resources, bill of resources with variances, and modified bills of resources with variances. The latter two techniques are modified from the original methods in order to account for the inherent variability in the remanufacturing system. This is done by adding the standard deviation of the historical utilization rates at each work center to the calculations for the required capacity. Results indicate that the modified bill of resources with variance is the best choice. A clear result of this analysis is that techniques for capacity planning which recognize and include a measure of the variability inherent in the uncertain remanufacturing environment will perform better than the standard rough-cut capacity planning models.

Lee et. al. (2001) present a review of disassembly planning and scheduling research and call for an integrated approach to disassembly planning and scheduling. They emphasize that since the disassembly plan feeds into the disassembly schedule, it is imperative that both are considered at the same time.

The difficulties in planning and controlling integrated remanufacturing systems (disassembly, remanufacturing/repair, and reassembly) have been well documented. Several studies have focused on this difficult problem area. Guide and Spencer (1997) initially promote a modified bill of resources, which incorporates an occurrence factor and a material recovery rate into the bill of resources. Testing several techniques Guide et al. (1997) later report the modified bill of materials with variance as the best selection. This technique includes a measure of the variability inherent in the uncertain remanufacturing environment and appears better adapted to the uncertainties of this environment.

4.2. Lot Sizing and Inventory Effects

Perry (1991) reports the differences in lot sizing and lead times for thirteen remanufacturers in seven industries and compares these to traditional manufacturers and concludes that the differences were due to management and control policies.

Guide and Srivastava (1997) study the impact of safety stocks in a MRP system on remanufacturing customer service and inventory levels. The computer simulation study focuses on a single product, both a homogeneous and a heterogeneous material recovery environment, smooth and lumpy product demand, short and long component lead times, and five different safety stock levels (including none). Results from the study indicate that for both types of material recovery environments safety stock does protect against uncertainty and improve customer service, but only to a certain point. Slightly more buffer inventory is required for the heterogeneous environment to achieve equivalent customer service levels. The authors conclude that, due to the high degree of uncertainty in remanufacturing, increasing buffer inventories to enhance customer service levels has limits and they suggest managers also investigate shorter lead times and demand management as alternative areas of exploring improved customer service levels.

Guide and Srivastava (1998) emphasize the importance of inventory buffer locations to connect remanufacturing operations and provide managerial flexibility and control. They study the interaction of disassembly release mechanisms (DRM) (time-phased to minimize flow time, time-phased according to due date, and disassembly flush - all parts disassembled and released to the shop floor) and the location of inventory delay buffers – after disassembly, before reassembly, or mixed (at both locations). They conduct their experiments using computer simulation based on an actual facility, allow both common and serial specific parts within a single product, and examine three levels of utilization. Results are assessed on mean flow time, mean lateness, and mean reassembly delay time. They learn that serial numbered parts should be managed distinctly from common parts with the best DRM being a flush leading to a reassembly delay buffer. This combination performs well for flow time and lateness. However, for common parts the authors encourage a time-phased, minimum flow time DRM with mixed inventory buffers. Finally, the authors note that the time-phased, due date DRM and the resulting disassembly delay buffer, predicated on MRP logic and commonly favored by managers, is an extremely poor performer regarding flow time and lateness. They emphasize the significance of this finding, given the popularity of MRP systems. They attribute this finding to the higher degree of uncertainty and unpredictable lead times in remanufacturing versus traditional operations.

Inderfurth et al. (2001) develop a stochastic, dynamic optimization model to tackle the complex problem of determining optimal or near–optimal, periodic review inventory policies necessary to support various remanufacturing options (including disposal). Both the returns and the demands for the single product are stochastic. The objective is to select quantities of returned product to be remanufactured via each option so that the total expected, discounted total costs of remanufacturing, disposal, stock holding, and backordering is minimized, while satisfying the demand over a finite or infinite horizon. The authors show the complexity of this multiple recovery option problem, particularly when returnable products are scarce and an allocation scheme must be employed. However, the authors illustrate that use of linear allocation rules allow the development of fairly simple, near-optimal control policies. The authors assume infinite remanufacturing and inventory storage capacities.

Teunter and Vlachos (2002) study a single item, stochastic, hybrid production system (manufacturing and remanufacturing). They examine a variety of demands, returns, and manufacturing/remanufacturing characteristics to determine what the cost reduction for incorporating a disposal option for returned items would be. They conclude that under the assumptions that, on average, demands exceed returns and remanufacturing is marginally profitable, a disposal option is not necessary. Exceptions are for very slow-moving items (fewer than a demand of 10 per year) for which remanufacturing is almost as expensive as manufacturing plus disposal (at least 90 %), and for which the recovery rate is large (at least 90%). As returns exceed demands a disposal option is increasingly desirable. However, such situations simplify the production system, as the manufacturing option would be increasingly unncecessary.

Barba-Gutierrez et al. (2008) extend the reverse MRP algorithm of Gupta and Taleb (1994) by incorporating the concept of lot sizing in connection with disassembly scheduling. The authors use the period order quantity (POQ) lot-sizing rule on a portion of the example from Gupta and Taleb (1994). Results indicate that the POQ turns out to be one and thus the ordering sequence has the same structure that the sequence for planning disassembly. To test the behavior of the algorithm further the authors consider nine different scenarios with different cost combinations. Four different lot-sizing rules (i.e., lot-for lot (L4L), POQ, best disassembly schedule in each subassembly (BIES), and best combination (BC)) are tested on the nine different problem scenarios. Results indicate that the BC lot-sizing rule is the best in all cases considered.

From these studies we learn that for both homogenous and heterogeneous material recovery environments safety stock does protect against uncertainty and improve customer service, but only to a certain point. Slightly more buffer inventory is required for the heterogeneous environment to achieve equivalent customer service levels. The locations of safety stock and find that serial numbered parts should be managed distinctly from common parts with the best DRM being a flush leading to a reassembly delay buffer. However, for common parts a time-phased, minimum flow time DRM with mixed inventory buffers is encouraged. Thus, the material recovery environment, the amounts of inventory buffers, and the inventory locations do make a difference in the remanufacturing environment. Also, linear allocation rules allow the development of fairly simple, near-optimal, periodic review inventory control policies. In addition, when demands exceed returns and remanufacturing is marginally profitable, a disposal option is not necessary and as returns exceed demands a disposal option is increasingly desirable. Finally, Barba-Gutierrez et al. (2008) incorporate the concept of lot sizing in connection with disassembly scheduling. They conclude that the best combination (BC), lot-sizing rule is the best in all cases considered.

4.3. Order Release, Priority Dispatching Rules, and Control Mechanisms

Kizilkaya and Gupta (1998) introduce the use of a Flexible Kanban System (FKS) to control the flow of returns to a disassembly cell, the partially disassembled products and parts among work stations within the cell, and to demand points external to the work cell. The authors report the results of a simulation study, which shows the FKS system had slightly higher WIP inventory than a traditional Kanban system (TKS), but that the amount of shortages were less.

4.4 Uncertainty and Stochasticity

Guide, Kraus, and Srivastava (1999) emphasize that remanufacturing systems face a greater degree of uncertainty and complexity than traditional manufacturing systems and thus, require planning and control systems designed to deal with the added uncertainty and complexity. A number of researchers support this position (e.g., Flapper 2002, Gupta and Taleb 1994, and Johnson and Wang 1995).

Guide (2000) insists that managers must be deliberate in their actions to reduce the uncertainty in the remanufacturing environment. Unlike the traditional forward supply chain, production planning and control in a remanufacturing environment must contend with acquiring cores. In this work, a framework for product acquisition is developed that links reverse logistics activities with production planning and control activities. A set of six managerial guidelines are presented and encouraged to be used as the starting point to reduce uncertainty in the timing and quantity of materials. This in turn provides the potential to reduce uncertainty throughout the remanufacturing system particularly in regard to inventory control and balancing returns with demand.

Kizilkaya and Gupta (1998) use computer simulation to study the material flow in a disassembly environment using the Flexible Kanban System (FKS). In their study the disassembly time at each station is modeled using an exponential distribution.

Inderfurth et al. (2001) develop a stochastic, dynamic optimization model to tackle the complex problem of determining optimal or near–optimal, periodic review inventory policies necessary to support various remanufacturing options (including disposal). Both the returns and the demands for the single product are stochastic. The objective is to select quantities of returned product to be remanufactured via each option so that the total expected, discounted total costs of remanufacturing, disposal, stock holding, and backordering is minimized, while satisfying the demand over a finite or infinite horizon.

Teunter and Vlachos (2002) use computer simulation to study a hybrid production system (manufacturing and remanufacturing). They examine for a variety of demands, returns, and manufacturing/remanufacturing characteristics what the cost reduction associated with a disposal option for returned items would be. Poisson and normal distributions are used to model demands and returns per time period.

Tang et. al. (2007) estimate planned lead times in a make-to-order remanufacturing environment. Specifically, the problem of determining when to disassemble such that component parts are available in the right quantity and condition for reassembly is modeled as a newsboy problem. The authors also use a mixture of Erlang distributions in their stochastic computations.

The high degree of uncertainty surrounding remanufacturing as well as its causes (uncertain returns and their quality, stochastic routings and processing times, disposal and scrap percentages, customer demand, etc.) have been known for some time. Several techniques have been employed to incorporate this uncertainty into remanufacturing planning and control. The most prevalent technique has been computer simulation. Guide and coauthors have relied on computer simulation for many research efforts (refer to Table 2). These include the impact of product structures on the performance of remanufacturing operations, the performance of various order release strategies and priority scheduling rules on remanufacturing performance, the use of the drum-buffer-rope philosophy (synchronous manufacturing) to cope with routing and task time uncertainties, the performance of proactive expediting policies with different product structures and disassembly release mechanisms, and the effect of lead time variation on the performance of disassembly release mechanisms. In many of these studies the set-up and processing times are stochastic, often modeled using beta distributions based on historical data. Kizilkaya and Gupta (1998) use computer simulation to study material flow in a disassembly environment using the Flexible Kanban System (FKS). In their study the disassembly time at each station is modeled using an exponential distribution. Teunter and Vlachos (2002) also employ computer simulation coupled with Poisson and normal distributions to study a hybrid production system. Thus, we see computer simulation harnessed with well-known statistical distributions to successfully study the stochastic complexities of remanufacturing.

Inderfurth et al. (2001) use stochastic, dynamic optimization with stochastic returns and demands to determine remanufacturing lot quantities and periodic review inventory policies in order to minimize remanufacturing, disposal, holding and backordering costs. Thus, this research couples inventory review policies with various remanufacturing options in a stochastic environment.

Tang et al. (2007) recently utilize the newsboy model with a mix of Erlang distributions to determine when to disassemble cores such that parts are available in the right quantity and condition to satisfy demand.

The sophistication of the stochastic distributions appears to have progressed with time. However, computer simulation may by the most powerful methodology to study the impact of numerous stochastic complexities simultaneously.

5. OBJECTIVE CRITERIA/FUNCTIONS AND SCHEDULING/PLANNING METHODOLIGIES USED

5.1. Objective Criteria/Functions

As shown in Table 2 the use of objective criteria seemed to span three eras. Usage of MRP-type objective criteria (satisfy demand for the time period, minimize the root items utilized to satisfy demand, and minimize the lot size and lead time) was predominant in the late 1980's and early 1990's. This was followed by more sophisticated technical, performance-based criteria such as minimize flow time, tardiness, root mean square tardiness, % of parts expedited, idle time, stockouts, safety stock, machine idle time, WIP, and makespan and maximize throughput. The third period, the economic period, gained its foothold around 2002. Published research, most involving linear, integer, or dynamic programming, now employed a variety of economic (cost-oriented) objective functions. These costs included set-up, holding, (cores and/or disassembled parts) purchase (cores), disassembly, and disposal (defective cores and parts). Even a maximize profit function (revenue - disassembly cost – disposal cost) is noted. Thus, while the economic objectives now appear dominant, the MRP-type still appear (e.g., Kim et al., 2006e; Kongar and Gupta, 2006).

5.2. Scheduling/Planning Methodologies

The study of remanufacturing scheduling, planning, and control has attracted a number of varied methodologies. As depicted in Table 2 reverse MRP was the initial methodology of choice for disassembly planning. Guide and his associates introduced the use of computer simulation to disassembly/remanufacturing scheduling, planning, and control throughout the 1990's. One benefit, of course, was that computer simulation could employ stochastic data. Much research on disassembly release mechanisms, priority dispatching rules, buffer inventory locations, the influence of product structure, and control mechanisms were conducted utilizing this methodology. Even the use of Kanban (drum-buffer-rope) has been applied with noted advantages. The mathematical programming era launched in earnest circa 2002 and research utilizing linear, integer, dynamic, and fuzzy goal programming appeared. These models addressed directly the disassembly scheduling problem and were typically coupled with economic objective functions. We noted one article (Neuendorf et al., 2001) that utilized Petri nets. While we note the occasional use of the reverse MRP approach (Barb-Guitierrez and Gupta, 2008), the mathematical programming methodologies appear to be currently prevalent.

While the mathematical programming methodologies can achieve optimal solutions for restricted, test problems, heuristics still offer the best hope for achieving useful, near optimal solutions for realistically-sized scheduling efforts.

7. AREAS FOR FUTURE RESEARCH

It can proceed without comment that the barren, end branches in Figures 3 and 5 signal research needs. The combination of finite capacity (e.g., machine, labor, storage), part commonality (within the same product and across multiple products), and stochastic parameters (core returns, processing times, processing routes, material recovery, production scrap, product demand, etc.) are complex, stand-alone issues to address and extremely formidable in combination. Yet, these are the unresolved areas for research.

We agree with the recent suggestions put forth by Kim et al. (2007), which call attention to the need to:

- Incorporate backlogging, realistic stochastic considerations, and multiple periods into disassembly scheduling.
- Integrate disassembly process planning with disassembly scheduling.
- Integrate all the remanufacturing operations (disassembly, remanufacturing/repair operations, and reassembly) into the remanufacturing scheduling decisions.

We pose several pertinent questions and offer some additional suggestions for future research:

- It is not clear what objectives, methodologies, constraints, etc. practitioners currently use in their remanufacturing scheduling operations. An industrial survey could assess what difficulties practitioners face, what they feel they need, and in what form. One hypothesis is that practitioners need more than an appropriate and computationally efficient model, they want a complete computer package - flexible, ready to run, and user-friendly.
- The simulations and models of remanufacturing scheduling and performance concern mainly technical data, operations, and decisions. However, remanufacturing design and performance can be influenced by strategic, managerial, economic, and behavioral issues and decisions. How have these issues impacted remanufacturing scheduling, operations, and performance, and how are they accommodated?
- While there has been some research involving multiple criteria (Hoshino et al., 1995; Kongar & Gupta, 2002 & 2006) most research efforts have used singular objectives. Since remanufacturing employs an economic, socio-technical system would managers desire to achieve or trade-off multiple objectives? Thus, we should support research employing technical, economic, strategic, and/or humanistic goals, which may provide a greater challenge, but result in more useful and realistic solutions.
- Twenty-eight remanufacturing scheduling complexities and issues are listed in Table 1. Are they all a concern to all remanufacturers? Are they all equally important? Conduct a survey of remanufacturers to learn which of these are important to companies by industry, by product, by process type, and by position of their product life cycle. Conduct an ABC analysis to determine the most-to-least important complexities overall and by industry group. It may then be feasible to develop models specifically tailored for each group. If longitudinal studies were conducted, it may be possible to determine how these complexities and their importance change over time.
- Assess how remanufacturers, who have employed the results of reported studies, have economically performed over time. It may be possible to assess their cradle-to-grave costs including design, construction, implementation, operation, maintenance, control, disposal, and updating.

- Kizilkaya and Gupta (1998) suggest that as customer satisfaction becomes a more differentiating factor between manufacturers, flexible Kanban systems (FKS) may give remanurfacturers the ability to reduce delivery times and shortages while keeping average WIP inventory levels at reasonable levels compared to batch manufacturing strategies. While Kizilkaya and Gupta (1998) determine the number of Kanbans to be added or removed from a FKS system based on a percentage of the (stochasitic) demand, what procedures can be developed to provide the optimal numbers of base Kanbans employed in the system and the amount to be added or removed from the base in a stochastic environment?

- It would be useful to learn what can be or has been the technical and economic impact of remanufacturing automation/robotics (which can reduce the variability of process times) on remanufacturing scheduling and operations?

- Assemble research teams involving both academic and industrial practitioners to formulate the objectives, constraints, and complexities to be examined.

Indeed, while much has been advanced, many remanufacturing industry needs yet remain for future research.

REFERENCES

Anon. The First British Plant for Dismantling Cars and Reusing Their Parts, *Al Hayat Newspaper*, January 3, 1993.

Barba-Gutierrez, Y., Adenso-Diaz, B. and Gupta, S. M. Lot Sizing in reverse MRP for Scheduling Disassembly, *International Journal of Production Economics*, 2008, Vol. 111, 741-751.

Benton, W. C. and Srivastava, R. Product Structure Complexity and Inventory Storage Capacity on the Performance of a Multi-Level Manufacturing System, *International Journal of Production Research*, 1993, 31, 2531-2545.

Blackburn J. and Millen R. The Impact of a Rolling Schedule in a MultiLevel MRP System, *Journal of Operations Management*, 1982, 2, 125-135.

Brander, P. and Forsberg, R. Cyclic Lot Scheduling with Sequence-dependent Set-ups: A Heuristic for Disassembly Processes, *International Journal of Production Research*, 2005, 295-310.

Brennan L, Gupta SM, Taleb KN. Operations Planning Issues in an Assembly/ Disassembly Environment, *International Journal of Operations and Production Management,* 1994, 14(9): 57-67.

Busher, Udo and Lindner, Gerd, Optimizing a Production System with Rework and Equal Sized Batch Shipments, *Computers and Operational Research*, 2007, Vol. 34, 515-535.

Clegg, A. J., Williams, D.J. and Uzsoy R. Production Planning and Control for Companies with Remanufacturing Capability, *Proceedings of the 1995 IEEE International Symposium on Electronics and the Environment*, 1995, 186-191.

Collier, D. A. A Product Structure Measure: The Degree of Commonality, *Proceedings of the 10th National American Institute for Decision Sciences Conference*, 1978, 313.

Dobos, I. Optimal Production –Inventory Strategies for a HMMS-type Reverse Logistics System, *International Journal of Production Economics*, 2003; 81(82): 351-360.

Flapper, Simmd Douse P., Fransoo, Jan C., Broekmeulen, Rob A.C.M., and Inderfurth, Karl. Planning and Control of Rework in the Process Industries, *Production Planning & Control*, 2002, 13(1), 26-34.

Fleischmann M, Bloemhof-Ruwaard J, M Dekker R, van der Laan E, van Nunen J, van Wassenhove L. Quantitative model for reverse logistics: a review, *European Journal of Operational Research* 1997; 103: 1-17.

Fourcard, R. Is Repair/Remanufacturing Really Different? APICS 1993 Remanufacturing Seminar Proceedings, Oklahoma City, OK (American Production and Inventory Control Society: Falls Church, 1993, 4-9.

Franke C, Basdere B, Ciupek M, Seliger S. Remanufacturing of Mobile Phones-Capacity, Program and facility Adaptation Planning, *Omega* 2006; 34: 562-570.

Fry, T.D., Oliff, M. D., Minor, E. D. and Leong, G. K. The Effects of Product Structure and Sequencing Rules on Assembly Shop Performance, *International Journal of Production Research*, 1989, 27, 671-686.

Guide, Jr. V. D. R. Scheduling using Drum-Buffer-Rope in a Remanufacturing Environment, *International Journal of Production Research*, 1996; 34(4): 1081-1091.

Guide, Jr. V. D. R. Scheduling with Priority Dispatching Rules and Drum-Buffer-Rope in a Recoverable Manufacturing System, *International Journal of Production Economics*, 1997; 53: 101-116.

Guide V. D. R. Production planning and control for remanufacturing: industry practice and research needs. *Journal of Operations Management*, 2000; 18: 467-483.

Guide, Jr. V. D. R., Souza G. C. van der Laan E. Performance of Static Priority Rules for Shared Facilities in a Remanufacturing Shop with Disassembly and Reassembly, *European Journal of Operational Research* 2005; 164: 341-353.

Guide, V. D. R., Srivastava, Rajesh, "An Evaluation of Order Release Strategies in a Remanufacturing Environment", *Computer and Operations Research*, 24(1), 37-47, 1997a.

Guide V. D. R. Srivistava R. Buffering from Material Recovery Uncertainty in a Recoverable Manufacturing Environment, *Journal of the Operational Research Society*, 1997b; 48: 519-529.

Guide, V. D. R., Jayaraman, V., Srivastava, R., " Production Planning and Control for Remanufacturing" A State-of-the-Art-Survey", *Robotics and Computer Integrated Manufacturing*, 15, 221-230, 1999.

Guide V. D. R. Jayaraman V. Linton J. C. Building Contingency Planning for Closed-Loop Supply Chains with Product Recovery, *Journal of Operations Management*, 2003; 21: 259-279.

Guide V. D. R. Srivastava R. Inventory Buffers in Recoverable Manufacturing, *Journal of Operations Management* 1998; 16: 551-568.

Guide V. D. R. Spencer M. S. Rough-Cut Capacity Planning for Remanufacturing Firms, *Production Planning & Control*, 1997; 8(3): 237-244.

Guide V. D. R. Kraus M E. Srivastava R. Scheduling policies for Remanufacturing, *International Journal Production Economics*, 1997; 48: 187-204.

Guide V. D. R, Jayaraman V. Product acquisition management: current industry practice and proposed framework, *International Journal of Production Research*, 2000; 38(16): 3779-3800.

Guide VDR, Srivastava R, Kraus. R. E. Product structure complexity and scheduling of operations in recoverable manufacturing, *International Journal of Production Research*, 1997; 35(11): 3179-3199.

Guide VDR, Srivastava R, Spencer M S. An evaluation of capacity planning techniques in a remanufacturing environment, *International Journal of Production Research*, 1997b; 35(1): 67-82.

Guide, Jr.VDR, Jayaraman V, Srivastava, R. The effect of lead time variation on the performance of disassembly release mechanisms, *Computers and Industrial Engineering*, 1999; 36: 759-779.

Guide, Jr., V. Daniel and Spencer, Michael S. Are Production Systems Ready for the Green Revolution, *Production and Inventory Management Journal*, 1996, 37(4), 70-76.

Guide, Jr., V. Daniel and Ghiselli, Gerald A. Implementation of Drum-Buffer-Rope at a Military Rework Depot Engine Works, *Production and Inventory Management Journal*, 1995, 36(3), 79-83.

Guide, Jr., VDR, Srivastava R, and Kraus. R. E. Proactive Expediting Policies for Recoverable Manufacturing, *The Journal of the Operational Research Society*, 1998, 49(5), 479-491.

Gungor A, Gupta S M. Issues in environmentally, conscious manufacturing and product recovery: a survey, *Computers and Industrial Engineering*, 1999; 36: 811-853.

Gungor A, and Gupta, S M. Disassembly sequence planning for products with defective parts in product recovery. *Computers and Industrial Engineering* 1998; 35(1-2): 161-164.

Gupta, S. M. and Taleb, K. N. Scheduling Disassembly, *International Journal of Production Research*, 1994, vol. 32, No. 8, 1857-1866.

Gupta, Surendra M. and McLean, Charles R. Disassembly of Products, *Computers and Industrial Engineering*. 1996, Vol. 31, No. 1/2, 225-228.

Hoshino, T. , Yura, K. and Hitomi, K. Optimization Analysis for Recycle-Oriented Manufacturing Systems. *International Journal of Production Research*. 33 (8): 2069-2078, 1995.

Inderfurth K, de Kok A, Flapper S D P. Product recovery in stochastic remanufacturing systems with multiple reuse options, *European Journal of Operational Research*, 2001a; 133: 130-152.

Inderfurth, Karl and van der Lann, Erwin. Leadtime Effects and Policy Improvement for Stochastic Inventory Control with Manufacturing, 2001b, 71, 381-390.

Inderfurth K, and Langella I M. Heuristics for Solving Disassemble-to-Order Problems with Stochastic Yields; *OR Spectrum*, 2006; 28: 73-99.

Jayaraman V. Production Planning for Closed-Loop Supply Chains with Production Recovery and Reuse: An Analytical Approach, *International Journal of Production Research*, March 2006; 44(5): 981-998.

Kiesmuller, G. P., “A New Approach for Controlling a Hybrid Stochastic Manufacturing/Remanufacturing System with Inventories and Different Leadtimes”, *European Journal of Operational Research*, 2003, Vol. 147, Issue 1, 62-71.

Kim, H-J, Lee, D-H, Xirouchakis, P., and Zust, R., “Disassembly Scheduling with Multiple Product Types”, *CIRP Annals-Manufacturing Technology*, 2003, **52**, 403-406.

Kim, H.–J., Lee, D.-H. and Xirouchakis, P. Two-Phase Heuristic for Disassembly Scheduling with Multiple Product Types and Parts Commonality, *International Journal of Production Research*, Vol. 44, No. 1, 2006a, 195-212.

Kim, H. –J., Lee, D. –H., and Xirouchakis, P., A Lagrangean Heuristic Algorithm for Disassembly Scheduling with Capacity Constraints, *Journal of the Operational Research Society*, 57 (10), 2006b, 1231-1240.

Kim, H.-J., Lee, D.-H. Xirouchakis, P. A Branch and Bound Algorithm for Disassembly Scheduling with Assembly Product Structure, *Technical Report, Institute of Production And Robotics, Swiss Federal Institute of Technology*, Lausanne (EPFL), 2006c.

Kim, H.-J., D. –H. and Xirouchakis, P., A Branch and Bound Algorithm for Disassembly Scheduling with Assembly Product Structure, *Technical Report, Institute of Production and Robotics, Swiss Federal Institute of Technology*, Lausanne (EPFL), 2006d.

Kim, H. –J., Lee, D. –H. and Xirouchakis, P. Disassembly Scheduling: Literature Review and Furure Research Directions, *International Journal of Production Research*, 2007, Vol. 45, No. 18-19, 4465-4484.

Kim, J. G., Jeon, H. B., Kim, H-J., Lee, D. H, and Xirouchakis, P., “Disassembly Scheduling with Capacity Constraints: Minimizing the Number of Products Disassembled”, *Proc. Inst. Mech, Eng.: J. Eng. Manuf. – Part B*, 2006e, 220, 1473-1481.

Kim, Kibum Iksoo, Song; Kim, Juyong and Jeong, Bongju. Supply Planning Model for Remanufacturing System in a Reverse Logistics Environment, *Computer & Industrial Engineering*, 51, 2006b, 279-287.

Kizilkaya, Elif and Surendra M. Gupta, Material flow Control and Scheduling in a Disassembly Environment, *Computers and industrial Engineering*, 1998, Vol. 35, Nos. 1-2, 93-96.

Kongar E. and Gupta, S. M., Disassembly to Order System under Uncertainty. Omega 2006; 34: 550-561.

Krupp, James A.G., Structuring Bills of Material for Automotive Remanufacturing", *Production and Inventory Management Journal*, 1993, Fourth Quarter, 46-52.

Lee, D-H. Kim, H-J, Choi, G. and Xirouchakis, P. Disassembly Scheduling: Integer Programming Models, *Proceedings of the Institution of Mechanical Engineers, Vol. 218, Part B: Journal of Engineering Manufacture,* 2004, 1357-1372.

Lee, D-H. Kang, J-G and Xirouchakis, P. Disassembly Planning and Scheduling: Review and Further Research, *Proceedings of the Institution of Mechanical Engineers, Vol. 215, Part B: Journal of Engineering Manufacture,* 2001, 695-709.

Lund, Robert T. Remanufacturing, *Technology Review*, 1984, 87, 18-26.

Manufacturing Systems, Decision Support Scheduling at Motorola, 1995, 13(4), 13-17.
Panisset, Brian D. MRP II for Repair/Refurbish Industries, *Production and Inventory Management*, 1988, Vol. 29, No. 4, 12-15.

Perry, James H. The Impact of Lot Size and Production Scheduling on Inventory Investment in a Remanufacturing Environment, *Production and Inventory Management Journal*, 1991, Vol. 32, No. 3, 41-45.

Philipoom, P. R. and Markland, R. E., and Fry, T. D. Sequencing Rules, Progress Milestones and Product Structure in a Multistage Job Shop, 1989, *Journal of Operations Management*, 8, 209-229.

Richter, K. Sombruzki M. Remanufacturing Planning for the Reverse Wagner/Whitin Models. *European Journal of Operational Research,* 2000; 121: 304-315.

Richter, Knut and Weber, Jens, "The Reverse Wagner/Whitin Model with Variable Manufacturing and Remanufacturing Cost", *International Journal of Production Economics*, 2001, 71, 447-456,

Russell, R. S. and Taylor B. W. An Evaluation of Sequencing Rules for an Assembly Shop, *Decision Sciences*, 1985, 17, 219-2332.

Souza, G. C. Ketzenberg M. E. Guide, Jr. V.D.R. Capacitated Remanufacturing with Service Level Constraint,. *Production and Operations Management* 2002; 11: 231-248.

Souza, G. C., and Ketzenberg, M. E., "Two Stage Make-to-Order Remanufacturing with Service Level Constraints", *International Journal of Production Research*, 40(2), 477-493, 2002.

Stanfield, Paul M., King, Russell E. and Hodgson, Thom J., "Determining Sequence and Ready Times in a Remanufacturing System", *IIE Transactions*, 2006, 38, 597-607

Stanfield, Paul M., Wilson, J.R. and R. E. King, Flexible Modeling of Correlated Operations Times with Applications in Product-Reuse, 2004, Volume, 42, No. 11, 2179-2196.

Stix, G. Green Machine: Volkswagen Gears Up to Recycle Autos, *Scientific American*, 266, 1992, 140-141.

Sum, Chee-Choung, Png, Daniel Oon-Sen, and Yang, Kum-Khiong, Effects of Product Structure Complexity on Multi-level Lot Sizing, *Decision Sciences*, 1993, vol. 24, No. 6, 1135-1155.

Taleb, K N, Gupta S M, Brennan. L. Disassembly of complex product structures with parts and materials commonality, *Production Planning and Control* 1997a; 8(3): 255-269.

Taleb, K N, Gupta S. M. Disassembly of Multiple Product Structures, *Computers and Industrial Engineering* 1997b; 32(4): 949-961.

Tang, Ou., Grubbstrom, R.W., Zanoni, S., "Planned lead time determination in a make-to-order remanufacturing system", *International Journal of Production Economics*, 2007, 108, 426-435.

Tang, Ou, Teunter, Ruud. Economics Lot Scheduling Problem with Returns, *Production and Operations Management*, 2006, Vol. 15, No. 4, 488-497.

Teunter R H, Vlachos D. On the necessity of a disposal option for returned items that can be remanufactured. *International Journal of Production Economics,* 2002; 75: 257-266.

Torres, F., Gil, P. and Puente, S. T. Automatic PC Disassembly for Component Recovery, *International Journal of Manufacturing Technology*, 2004, Vol. 23, 39-46.

van der Laan E. Salomon M. Production planning and inventory control with remanufacturing and disposal, *European Journal of Operational Research* 1997; 102: 264-278.

van der Laan E. Dekker R. Salomon M. Product Remanufacturing and Disposal: A Numerical Comparison of Alternative Control Strategies, *International Journal of Production Economics* 1996; 45: 489-498.

van der Laan E. Salomon M. Dekker R. Van Wassenhove L. Inventory Control in Hybrid Systems with Remanufacturing, *Management Science* 1999; 45(5): 733-747.

van der Laan E. Salomon M. Dekker R. An Investigation of Lead-Time Effects in Manufacturing/Remanufacturing Systems under Simple PUSH and PULL Control Strategies, 1999; 115: 195-214.

Veerakamolmal, Pitiopong and Gupta, Surendra M. High-mix/low-volume Batch of Electronic equipment Disassembly, *Computers and Industrial Engineering*, 1998, Vol. 35, Nos. 1-2, 65-68.

Wolfe, P.R. BMW Takes Leadership Role in Automotive Recycling, *Recycling Today*, 29, September 1991, 48.

Zhou L. Naim M. M. Tang O. Towill D. R. Dynamic a Performance of a Hybrid Inventory System with a Kanban Policy in Remanufacturing Process, *Omega* 2006; 34: 585-598.

TABLE 1
REMANUFACTURING SCHEDULING COMPLEXITIES AND ISSUES[1.]

- Mission or objective/objective function
- Need for a reverse, rather than forward, logistics network and operations
- Facility location decisions (location decisions now must consider recovery, transport, and remanufacturing considerations)
- Stochastic demands
- Balancing returns with demand
- Remanufacture or sell product as is
- Single vs. multiple stage operations
- In line vs. off-line rework
- Buffer stock location decisions
- Resource availability and allocation (particularly for facilities that produce new products and remanufacture returned items)
- One versus multiple products
- Product structure considerations (e.g., material or part commonality)
- Focused versus integrated (scheduling one or more than one operation simultaneously)
- Sourcing decisions (number of cores needed from returns, brokers, and new production and when)
- Uncertain timing and quantity of core returns
- Capacity restrictions per operation and for inventories
- Uncertainty in recovery materials or parts quality (material recovery rate or yield)
- Inaccuracies in grading returned product/component quality
- Uncertain routing for materials and parts in the remanufacturing operations
- Highly variable and uncertain processing (disassembly, reprocessing, and/or assembly) times
- Lot sizing
- Order release mechanisms
- Priority scheduling rules
- Scheduling for single vs. multiple time periods
- Complication of material or parts matching restrictions
- Accumulation of excess inventories for certain kinds of materials or parts
- Scheduling methodology employed (RMRP, mathematical programming, heuristic, queuing theory, computer simulation, etc.)
- Allowing backlogging

List compiled from Krupp 1993; Brennan, Gupta and Taleb 1994; Guide 1997(a); Guide 2000; Flapper, Fansoo, Broekmueulen and Inderfurth 2002; Sousa, Ketzenberg, and Guide 2002; Lee, Kim, Choi, and Xirouchakis 2004; and Kim, Lee, and Xirouchakis 2007.

TABLE 2
AN ANALYSIS OF REMANUFACTURING SCHEDULING RESEARCH

Reference	Year	Operations Focus	Production Strategy	Product-Related	Process-Related	Work Schedule Related	Performance Measurement/ Objective Criteria	Quantitative Methodology
Panisset	1988	I	MTO	S, NC	IC, US	PO, D	MRP	MMRP
Krupp	1991	I	MTS	M	US	MP, D	MRP	MMRP
Perry	1991	I	MTO	M	FC	MP	MLL	
Krupp	1993	I	MTS	M, NC	IC, US	D*	MRP	MMRP
Gupta and Taleb	1994	DS	MTS	S, NC	IC, KS	MP, D	MRP	RMRP
Clegg, Williams, Uzsoy	1995	I		S, NC	IC, KS	D		LP
Hoshino, Yura and Hitomi	1995	I	MTS	S, NC	IC, KS	MP, D	MC	GP
Guide	1996	I	MTO	S, NC	FC, US	MP, ST	MC(1)	SIM, DBR
Guide	1997	I	MTO	S, NC	FC, US	MP, ST	MC(2)	SIM, PDR, DBR
Guide and Srivastava	1997a	I	MTO	S, NC	FC, US	MP, ST	MC(3)	SIM, MMRP, PDR, ORS
Guide and Srivastava	1997b	I		S, NC		MP, ST	MC(4)	SIM, MMRP
Guide, Kraus, Srivastava	1997	I		S, NC	US	MP, ST	MC(5)	SIM, PDR, DRM
Guide, Srivastava, Kraus	1997	I		S, NC	US	MP, ST	MC(5)	SIM, PDR
Guide and Spencer	1997	I	MTO	S, NC	FC, US	MP, D*	MRP	RCCP, MBOM, MBOR
Guide, Srivastava, Spencer	1997	I	MTO	S, NC	FC, US		MIN Δ CAP	SIM, RCCP
Taleb, Gupta, and Brennan	1997a	DS	MTS	M, PC	IC, KS	MP, D	MIN #, MRP	RMRP
Taleb and Gupta	1997b	DS	MTS	M, PC	IC, KS	MP, D	MRP, Min H	RMRP, HR
Guide and Srivastava	1998	I	MTO	S, NC	FC, US	MP, ST	MC(6)	SIM, DRM
Guide, Srivastava, Kraus	1998	I	MTO	S, NC	FC, US	MP, ST	MC(5)	SIM, PDR
Kizilkaya and Gupta	1998	I	MTS	M, NC	IC	ST	MC(9)	SIM, DBR(FKS)

Reference	**Year**	**Operations Focus**	**Production Strategy**	**Product-Related**	**Process-Related**	**Work Schedule Related**	**Performance Measurement/ Objective Criteria**	**Quantitative Methodology**
Veerakamolmal and Gupta	1998	I	MTS	M, PC	AS	SP, D	MC(8)	HR
Guide, Jayaraman and Srivastava	1999	I	MTO	M, NC	FC, US	MP, ST	MC(7)	SIM, DRM
Neuendorf, Lee, Kiritsis, Xirouchakis	2001	DS		S, PC	IC, KS	MP, D	Min. #	PNets
Kongar and Gupta	2002	DS	DTO	M, PC	IC, KS	SP,D	Min. S+H, Max. M, Min. CD, Min NDIS, Max. Profit, Min CAP	IGP
Lambert and Gupta	2002	DS	DTO	M, PC	IC, KS	MP, D	Max. Profit	MIP
Lee, Xirouchakis, Zust	2002	DS		S, NC	FC, KS	MP, D	Min. P+H+D	IP
Kim, Kee, Xirouchakis, Zust	2003	DS		M, PC	IC, KS	D, MP	Min. S+D+H	HR, IP, LPR
Lee, Kim, Choi, Xirouchakis	2004	DS		S, M, PC, NC	IC, KS	D, MP	Min. P+S+D+H	IP
Kim, Lee, Xirouchakis	2006a	DS		M, PC	IC, KS	MP	Min. S+D+H	HR,LP,DP
Kim, Lee, Xirouchakis	2006b	DS		S, NC	FC, KS		Min S+D+H	LHR, LP
Kim, Jeon, Kim, Xirouchakis	2006e	DS		S, NC	FC, KS	D, MP	Min #	IP
Kongar and Gupta	2006	DS	DTO	M, PC	IC, KS	SP, S	Min. S+H, Max. M, Min. CD, Min NDIS, Max. Profit, Min CAP	FGP
Langella	2007	DS		M, PC	IC, KS	MP, D	Min P+S+H+D	HR
Barb-Guitierrez and Gupta	2008	DS		M, NC	IC, KS	D, MP	Min. S+O	RMRP

Table 2: Continued
AN ANALYSIS OF REMANUFACTURING SCHEDULING RESEARCH

Key:

Operation Focus:
DS = Disassembly
RE = Remanufacturing/Repair
RA = Reassembly
I = Integrated

Production Strategy:
MTS = Make-to-Stock
MTO = Make-to-Order
ATO = Assembly-to-Order
DTO = Disassembly-to-Order

Product-Related:
S = Single Product
M = Multiple Products

PC = Product Commonality
NC = No Product Commonality

Process- Related:
IC = Infinite Capacity
FC = Finite Capacity

KS = Known sequence
AS = Adaptive sequence
US = Uncertain Sequence

Work Schedule-Related:
PO = Project Oriented
SP = Single Period
MP = Multiple Periods

D = Deterministic Task Times
D* = Task times are deterministic, but multiple BOMs are developed to account for varied component recovery and usage rates
ST = Stochastic Task Times

OBJECTIVE FUNCTIONS:
MRP = Right quantity – right time
Min # = Min. number of root items used to satisfy demand
Min H = Min holding cost = Min H
Min. S+H = Min. costs (set-up + holding cost)
Min. D = Min. disassembly costs
Min. D+H = Min. costs (disassembly + holding)
Min. S+D+H = Min. costs (set-up + disassembly. + holding)
Min. P+S+D+H = Min. costs (purchase + set-up + disassembly + holding)
Min. P+S+H+D = Min (purchase + separation + holding + disposal)
Min. E(P+D+DI) = Min. expected costs (purchase + disassembly + disposal)
Max. Profit = Max profit (revenue – disassembly – disposal)
MLL = Min lot sizes and lead times
CS = Completion to schedule
WIP = Min WIP
Max = Max throughput
Min. FT = Min flowtime =
Min. ΔCap = Min. actual – estimated capacity level deviation
MC = Multiple criteria
MC(1) = Minimize CS, Min. WIP, Max throughput, Min. FT
MC(2) = Min. (FT, Min. lateness,. % of parts expedited, % tardy), Max throughput
MC(3) = Min. WIP, tardiness, FT, Idle time, Max throughput
MC(4) = Min. (% stockout, safety stock level)
MC(5) = Min. (FT, tardiness, % tardy, root mean square tardiness)
MC(6) = Min. (FT, lateness, reassembly delay)
MC(7) = Min. (FT, root mean square tardiness, % tardy)
MC(8) = Min. (Machine idle time, makespan)
MC(9) = Min. (Completion time, shortages, and WIP)

OBJECTIVE FUNCTIONS CONT'D
Max. M = Max material sales
Min. NDIS = Min number of disposed items
Min. H = Min number of stored items
Min. CD = Min cost of disposal
Min. CAP = Min cost of preparation

Table 2: Continued
AN ANALYSIS OF REMANUFACTURING SCHEDULING RESEARCH

QUANTITATIVE METHODOLOGY:

MMRP = Modified Materials Requirements Planning
RMRP = Reverse Materials Requirements Planning
HR = Heuristic
LHR = Lagrangean Heuristic
LP = Linear programming
IP = Integer Programming
MIP = Mixed Integer Programming
B&B = Brand and Bound
NLP = Nonlinear Programming
GP = Goal Programming
Q = Queuing Theory
SIM = Computer Simulation
PNets = Petri Nets
DBR = Drum-Buffer-Rope
DBR(FKS) = Drum-Buffer-Rope with Flexible Kanban System
PDR = Priority Dispatching Rule
ORS = Order Release Strategy
DRM = Dispatching Release Mechanism
MBOR = Modified Bill of Resources
MBOM = Modified Bill of Materials
DP = Dynamic Programming
LPR = Linear Programming Relaxation
FGP = Fuzzy Goal Programming

]

[1] Three series of runs were made each for a single, but increasingly complex, product structure.
[2] The process sequence is established for each new product before the disassembly operation begins.