SCHEDULING REMANUFACTURING OPERATIONS:

A LITERATURE REVIEW AND ANALYSIS

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SUBMITTED TO 2008 ANNUAL MEETING OF THE SOUTH EASTERN INSTITUTE FOR

OPERATIONS RESEARCH AND THE MANAGEMENT SCIENCES

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.

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

TABLE 1: CONTINUED

REMANUFACTURING SCHEDULING COMPLEXITIES AND ISSUES[1.]

- 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

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1. 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.

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, remanufacturing/repair, and reassembly operations; (2) assess how we have advanced our ability to address the scheduling complexities mentioned in the literature; and (3) highlight additional research. Our research is currently at stage one. We know of no other research that has reviewed in detail the scheduling literature for all three remanufacturing areas and further analyzed each stage by production strategy (make-to-stock, assemble-to-order, and make-to-order). Figure 1 delineates the boundaries of our research effort, which includes the three remanufacturing operations and the buffer inventory considerations between them. Figure 2 illustrates the three remanufacturing stages and their further analysis by production strategy.

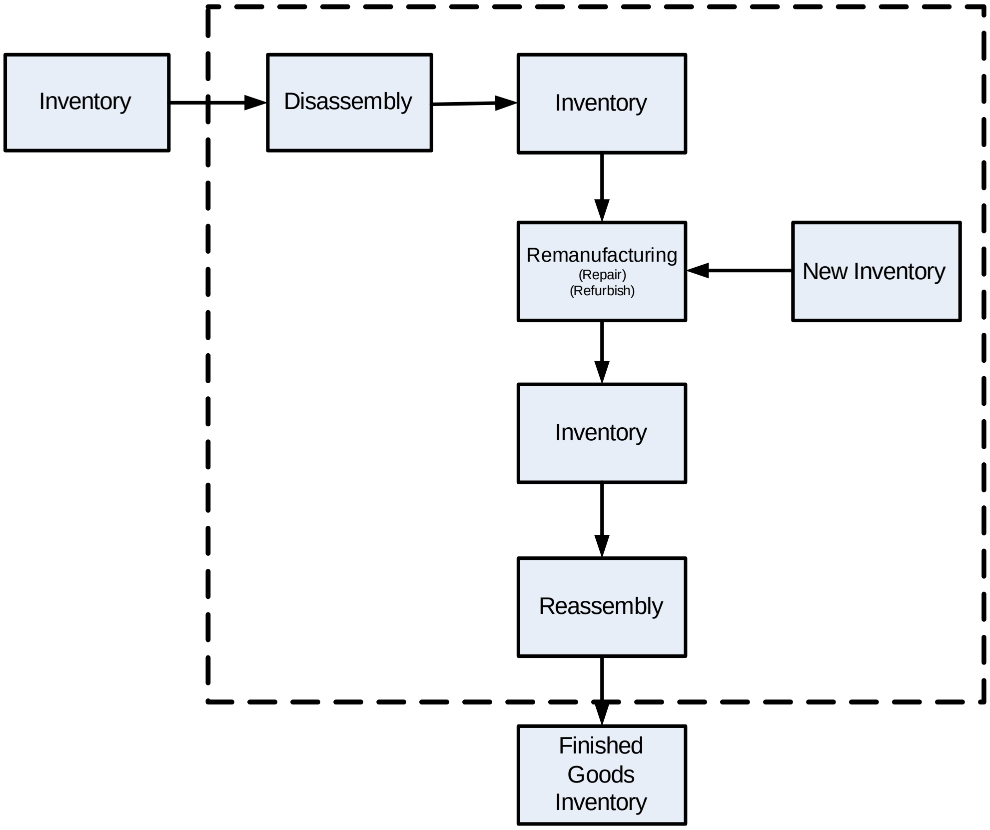

Figure 1: Remanufacturing Shop

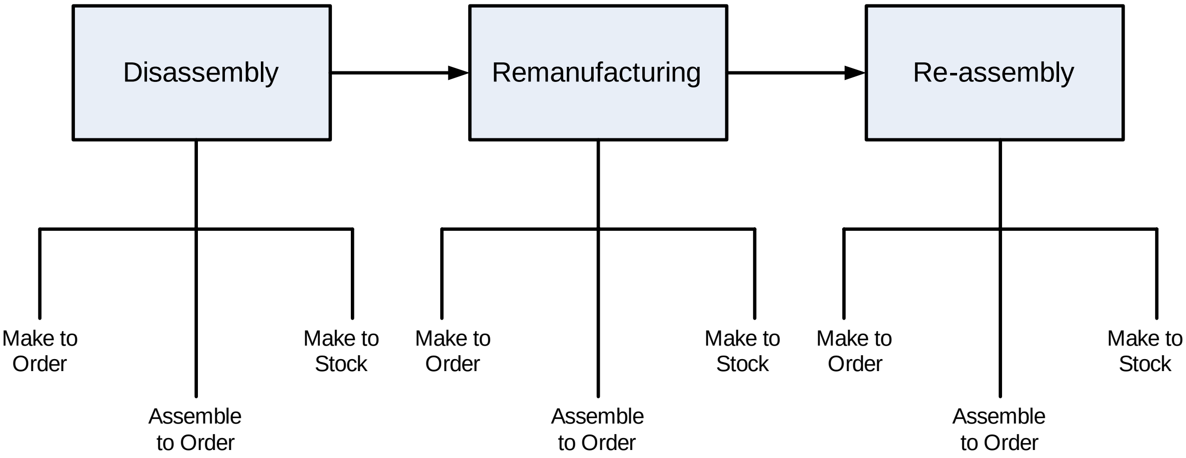

Figure 2: Remanufacturing stages and production strategy

The current state of **o**ur literature analysis is divided into three sections. In Section 2 we review the literature on disassembly scheduling. Section 3 describes our current progress in analyzing the literature regarding scheduling remanufacturing and repair operations. Section 4 reviews the literature that approaches sustainable manufacturing from an integrated approach. That is, those research efforts that provide a comprehensive approach to disassembly, remanufacturing, and reassembly. Within each section, we further subdivide the literature into single versus multiple products. The final breakdown is by topic, e.g., part commonality/ product complexity, capacity planning,, lot sizing and inventory effects, order release, priority dispatching rules and control mechanisms, and uncertainty and stochasticity. Finally, Section 5 characterizes our future work.

2. SCHEDULING DISASSEMBLY OPERATIONS

We first characterize the disassembly structure. 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 3, item 1 represents the roots 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 3, 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 4. 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.

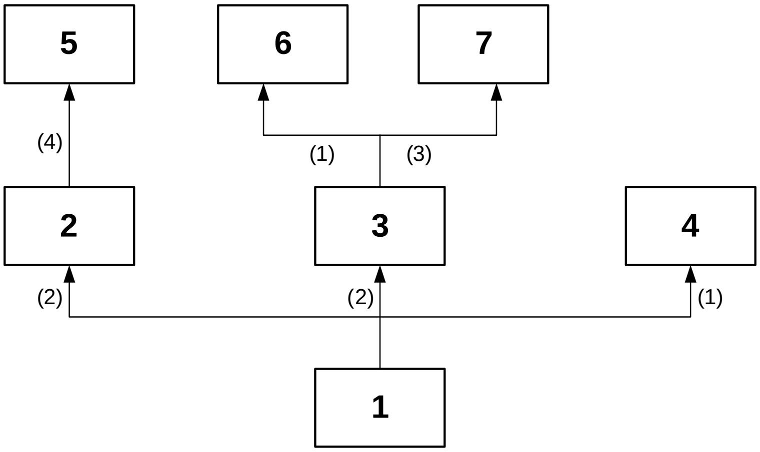

Figure 3: Disassembly Structure/ no commonality

2.1 Disassembly Operations for Single Products

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, no defects, and infinite capacity. 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 parts commonality, and (3) multiple product types with parts commonality. For ease of presentation 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. 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 optimality. The performance of the integer programming models becomes worse as the number of items increase and as the number of periods increase.

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.

Parts Commonality and Product Structure

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).

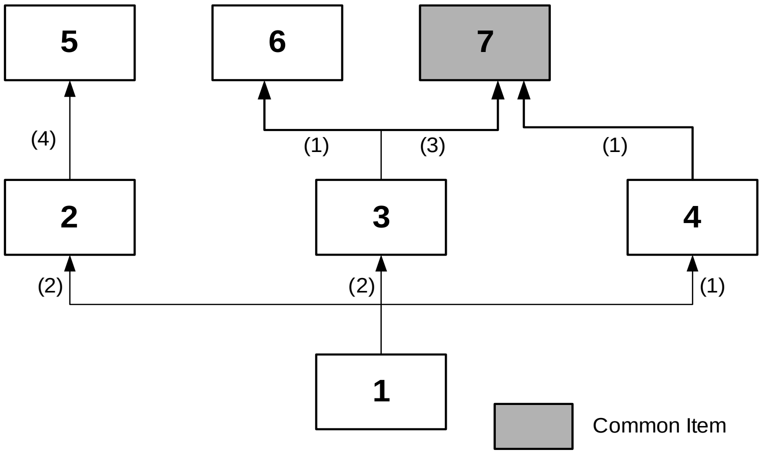

Figure 4: Single Product with part commonality

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, no defects, and unrestricted capacity.

Neuendoft et al extends 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.

In the work of Lee *et. al.* (2004) their integer programming formulation is modified 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 Taleb Gupta, and Brennan (TGB) (1997; single product with part commonality) and Neuendorf et al (2001) who in additional 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 multiple solutions exist and the cost-based objective presented in the paper provides a method to distinguish among the solutions generating the same number of products to be disassembled. Extensions to the integer programming models call for incorporation of defective parts and/ or components, stochastic demands and disassembly operation times.

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.

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 experiment 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.

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.

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.

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.

2.2 Scheduling Disassembly for Multiple Products

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 5).

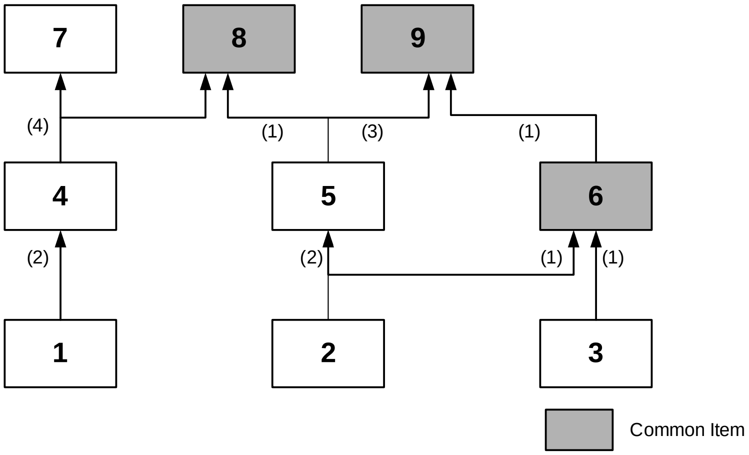

Figure 5: Multiple products with parts commonality

Part commonality and product structure

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.

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 .

Capacity planning

Kim *et al.* (2006) 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.

Additional literature analysis in the areas of order release mechanisms and priority dispatching rules, uncertainty and stochasticity and lot sizing remain for future work.

3. SCHEDULING REMANUFACTURING/REPAIR OPERATIONS

Order release, priority dispatching rules, and control mechanisms for remanufacturing operations (Single Products)

Researchers (e.g., Panisset 1988, Krupp 1993, Gupta and Talem 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. For some parts these were based on the repair class that occurred most frequently. For others, it was based on the most complex or pessimistic repair. 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 repetitive, 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 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* (2001) 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 base 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.

A second objective of Souza’s work explores the impact of inaccuracies with the sorting/ grading function on product flow time/ service level. Simulation results show significant increases in flow times as grading errors increase with the *Dynamic* dispatching rule appearing to be less sensitive to increased grading errors over the *MaxDiff* rule.

Part commonality and product structure for multiple products

Kim *et al.* (2006), present a mixed integer program to aid remanufacturers in deciding 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.

4. SCHEDULING INTEGRATED OPERATIONS

Scheduling integrated operations encompasses the full range of complexities associated with remanufacturing supply chains.

Product Structure Complexity, Disassembly Release Mechanisms, Priority Scheduling Rules, and Control Mechanisms for single products

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 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. Again using the assembly operation as the "drum" and the various priority dispatching rules (PDR) to release parts from the disassembly area, he assesses the mean flow time, mean lateness, mean percentage of parts expedited, and mean 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 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 the performance measures, 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, these research efforts link the overall remanufacturing system performance to the release of materials from the disassembly stage to the remanufacturing operations and the means of scheduling from the remanufacturing operations to the reassembly area.

Order release mechanisms, lot sizing, priority dispatching rules, and control mechanisms (Multiple Products)

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 was 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) 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 of 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.

Table 2 is in the beginning stage of providing a summary of the pertinent features of the remanufacturing scheduling literature and aiding in its analysis.

TABLE 2

AN ANALYSIS OF REMANUFACTURING SCHEDULING RESEARCH

References	Year	Operation 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							
Fourcard	1993							
Gupta and Taleb	1994	DS	MTS	S, NC	IC, KS	MP, D	MRP	RMRP
Johnson and Wang	1995							
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, S	MC(1)	SIM, DBR
Guide	1997	I	MTO	S, NC	FC, US	MP, S	MC(2)	SIM, PDR, DBR
Guide & Srivistava	1997a	I	MTO	S, NC	FC, US	MP, S	MC(3)	SIM, MMRP, PDR, ORS
Guide & Srivistava	1997b	I		S, NC		MP, S	MC(4)	SIM, MMRP
Guide, Kraus & Srivastava	1997	I		S, NC	US	MP, S	MC(5)	SIM, PDR, DRM
Guide, Srivastava & Kraus	1997	I		S^1, NC	US	MP, S	MC(5)	SIM, PDR
Guide & Spencer	1997	I	MTO	S, NC	FC, US	MP, D*	MRP	RCCP, MBOM, MBOR
Guide, Srivastava & Spencer	1997	I	MTO	S, NC	FC, US	MP, D*	MINΔCAP	SIM, RCCP
Guide & Srivastava	1998	I	MTO	S, NC	FC, US	MP, S	MC(6)	SIM, DRM
Guide, Srivastava & Kraus	1998	I	MTO	S^1, NC	FC,US	MP, S	MC(5)	SIM, PDR
Kizilkaya & Gutpa	1998							
Veerakamolmal & Gupta	1998	I	MTS	MP, PC	AS	SP, D	MC(8)	HR
Taleb, Gupta and Brennan	1997	DS	MTS	M, PC	IC, KS	MP, D	Min #, MRP	RMRP
Taleb and Gupta	1997	DS	MTS	MP, PC	IC, KS	MP, D	MRP, Min H	RMRP, HR
Guide, Jayaraman & Srivastava	1999	I	MTO	MP, NC	FC, US	MP, S	MC(7)	SIM, DRM

TABLE 2: CONTINUED
AN ANALYSIS OF REMANUFACTURING SCHEDULING RESEARCH

Key:

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

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

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

Product Commonality = PC
No Product Commonality = NC

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

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

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

Deterministic Task Times =
Stochastic Task Times = S

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

QUANTITATIVE METHODOLOGY:
Modified Materials Requirements Planning = MMRP
Reverse Materials Requirements Planning = RMRP
Heuristic = HR
Linear programming = LP
Integer Programming = IP
Brand and Bound = B&B
Nonlinear Programming = NLP
Goal Programming = GP
Queuing Theory = Q
Computer Simulation = SIM
Petri Nets = PNets
Drum-Buffer-Rope = DBR
Priority Dispatching Rule = PDR
ORS = Order Release Strategy
Dispatching Release Mechanism = DRM
Modified Bill of Resources = MBOR
Modified Bill of Materials = MBOM

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[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.

5. FUTURE WORK

Our future work will analyze the quantitative methodologies used to aid scheduling remanufacturing operations and the performance measurement/objective criteria used to guide or assess their performance. In addition, we will discuss the other issues and complexities, quantitative and qualitative, pertinent to the effectiveness of remanufacturing operations; these will include strategic, economic, behavioral, and implementation issues and the complexities highlighted in Table 1. Finally, we will assess, in detail, our progress in scheduling remanufacturing operations, both theoretical and applied. Remanufacturing industry needs will be discussed and the avenues yet remaining for future research.

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