NPS- PM-08-020

# ACQUISITION RESEARCH SPONSORED REPORT SERIES

---

# Material Planning for Remanufacturing Defense Assets

**31 March 2008**

**by**

**Dr. Geraldo Ferrer, Associate Professor**
Graduate School of Business & Public Policy

**Naval Postgraduate School**

Prepared for: Naval Postgraduate School, Monterey, California 93943

The research presented in this report was supported by the Acquisition Chair of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

**To request Defense Acquisition Research or to become a research sponsor, please contact:**

NPS Acquisition Research Program
Attn: James B. Greene, RADM, USN, (Ret)
Acquisition Chair
Graduate School of Business and Public Policy
Naval Postgraduate School
555 Dyer Road, Room 332
Monterey, CA 93943-5103
Tel: (831) 656-2092
Fax: (831) 656-2253
e-mail: jbgreene@nps.edu

Copies of the Acquisition Sponsored Research Reports may be printed from our website www.acquisitionresearch.org

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

# Abstract

This paper develops a planning system for depots remanufacturing components of defense assets, such as helicopters, armored cars, and so forth. These depots take in used assets, disassemble them, repair, upgrade and reassemble them to supply US troops and, occasionally, foreign military services of allied nations. Uncertainty in the supply of used components, the yield of good parts, and the demand for remanufactured products makes this a difficult process to manage. This article describes a multi-period material planning system for the process. It covers everything from collection to final delivery. The system is based on material requirements planning, a method familiar to many managers. It uses linear programming to develop purchase recommendations and to schedule the disassembly of the used components. The researcher held meetings with remanufacturing practitioners to set the system parameters and to evaluate the approach.

**Keywords:** depots remanufacturing components, multi-period material planning system, linear programming

THIS PAGE INTENTIONALLY LEFT BLANK

# About the Author

**Geraldo Ferrer** is an Associate Professor of Operations Management at the Naval Postgraduate School. Prior to joining NPS, he was in the faculty of the Kenan-Flagler Business School at the University of North Carolina for seven years. His areas of expertise include global operations, supply chain management, sustainable technologies, product stewardship, reverse logistics and remanufacturing. He has also studied the reverse logistics required in recycling and remanufacturing operations, and inventory problems affecting products made in small batches for frequent deliveries.

Geraldo Ferrer
Associate Professor
Graduate School of Business and Public Policy
Naval Postgraduate School
Monterey, CA 93943-5197
Tel: (831) 656-3290
E-mail: gferrer@nps.edu

THIS PAGE INTENTIONALLY LEFT BLANK

NPS-PM-08-020

# ACQUISITION RESEARCH
# SPONSORED REPORT SERIES

---

## Material Planning for Remanufacturing Defense Assets

**31 March 2008**

**by**

**Dr. Geraldo Ferrer, Associate Professor**
Graduate School of Business & Public Policy

**Naval Postgraduate School**

THIS PAGE INTENTIONALLY LEFT BLANK

# Table of Contents

THIS PAGE INTENTIONALLY LEFT BLANK

# Introduction and Literature Review

New vehicles are assembled exclusively from new components, generally produced by a few large manufacturers. Components suppliers also produce new components in excess of assembly requirements for use as replacement items. However, much of the replacement demand is satisfied by remanufactured components. In fact, remanufacturing has been practiced in the automotive industry for quite some time. For instance, Hormozi (1997) reports that Henry Ford realized that valuable automotive components should not just be discarded, but should be rebuilt. As a result, everything from entire engines to components like alternators, turbo chargers, and starters are remanufactured today.

Reverse logistics is the set of processes associated with the product return from the user to the producer. This return can be an isolated event, usually associated with warranty claims, an incorrect order fulfillment, or it can be a recurrent event associated with remanufacturing end-of-lease or end-of-life products. Several analytical works have dealt with reverse logistics issues like those observed in a remanufacturing facility. In particular, some articles study remanufacturing processes in which the identity of the final good is not retained. In this type of process, parts released from different products are reconditioned and stocked together because there is no economic value in keeping track of individual parts. Hence, when a product is reassembled, it receives a new identity (or part number) because it contains parts from many units that were previously disassembled.

Van der Laan, Dekker, Salomon and Ridder (1996) proposed a single-product, single-echelon production and inventory system with product returns, product remanufacturing, and product disposal. They model the system with three different procurement and inventory control strategies. The control parameters in these strategies relate to the inventory position at which an outside procurement order is placed, inventory position at which returned products are disposed of, the outside procurement order quantity, and the capacity of the remanufacturing facility.

Van der Laan, Dekker, and Salomon (1999) provided numerical evidence of the effects of lead-time duration and lead-time variability on total expected costs in production/inventory systems with remanufacturing. They concluded: (1) manufacturing lead-times have a larger influence on system costs than remanufacturing lead-times; (2) a larger remanufacturing lead-time may sometimes result in a cost decrease, and (3) a larger variability in the manufacturing lead-time may sometimes result in a cost decrease.

Fleischmann, Bloemhof-Ruwaard, Dekker and Van der Laan (1997) carefully examined reverse logistics quantitative models and indicated that a general framework had yet to be suggested. They classified the research into three main areas: distribution planning, inventory control, and production planning. For each of these, the implications of the emerging reuse efforts were discussed, and the proposed mathematical models are reviewed. Other conventional inventory/production policies were also extended to remanufacturing planning. Guide, Jayaraman, Srivastava, and Benton (2000) indicated that recoverable manufacturing systems minimize the environmental impact of industry by reusing materials, reducing energy use, and reducing the need to landfill industrial products. However, the management of reverse supply-chain activities differs greatly from management activities in traditional supply chains due to its increased complexity. Other important research in reverse logistics are Mahadevan and Pyke (2001), Van der Laan, Saloman, Dekker, and Van Wassenhove (1999), Dowlatshahi (2000), Klausner and Hendrickson (2000), Richter and Sombrutzki (2000) and Ferrer (2003).

A rapidly growing stream of literature on remanufacturing has focused on the competition between the original equipment manufacturer (OEM) and independent refurbishers/remanufacturers. Majumder and Groenevelt (2001) prove the existence of Nash equilibrium quantity solutions between an OEM and an entrant contingent on the availability of used products. Debo, Toktay and VanWassenhove (2005) determine the optimal pricing and remanufacturability-level decisions of a firm competing with independent remanufacturers. They find that an increase in the competitive intensity reduces the OEM's incentive to invest in the remanufacturability of its products. Ferrer and Swaminathan (2006) identify the Nash equilibrium of the optimal pricing schemes for an OEM and a single entrant in a multiperiod setting in which consumers show a higher preference for the OEM's product over the entrant's product. They find that an OEM may forgo some of the first-period profits by making additional units to increase the number of assets available for remanufacturing in subsequent periods. Ferguson and Toktay (2006) analyze two common entry-deterrent strategies: remanufacturing and preemptive collection. For a fairly comprehensive discussion of the field, see Guide and Van Wassenhove (2003), and Dekker, R., M. Fleischmann, K. Inderfurth, L.N. Van Wassenhove (2004). These also contain extensive references to research on production, planning, and control in reverse logistics.

Managers must take actions to reduce uncertainty in the timing and quantity of returns, balance return rates with demand rates, and make material recovery more predictable. This articles focuses on facilities that remanufacture defense assets from modules retrieved from used assets. The process is characterized by batch production, repetitive tasks and fairly common routings. Uncertainty in sales, raw material supply, and the yield of good parts in the disassembled units means that managing the process is complex. The material planning system in this article helps managing the process.

First, the general process is discussed, with an emphasis on the management decisions that must be made at each stage. The emphasis is on the material flow decisions; other organizational requirements necessary to be a successful remanufacturing firm can be found in Ferrer and Whybark (2000). Next, comes the description of the material planning system. It specifies the demand for the parts needed to assemble components and plans the supply of parts required. Finally, some of the research opportunities that exist in learning more about fine-tuning and using the system in practice are described.

THIS PAGE INTENTIONALLY LEFT BLANK

## General Component Remanufacturing Process

Used defense assets are remanufactured for extended usage by several depots in the American forces.  Occasionally, these assets are extensively recovered for sales to Foreign Military Services.  The remanufacturing facility receives used assets with differing degrees of wear and tear, leading to considerable uncertainty in the recovery cost of individual modules.  Hence, each remanufacturing program demands an uncertain amount of labor and materials to accomplish its objective.  The return flow of used assets from the warfighters is also uncertain, further complicating the material flows.  Consequently, development of an integrated, closed-loop material planning system to maximize the usability of returned assets is critical.

On the surface, the remanufacturing process is straightforward.  It involves the disassembly of assets to get modules, the repair of modules and the reassembly of modules into finished components.  However, disassembling the used defense assets involves taking them apart, cleaning and inspecting the modules, and separating the scrap from the parts that are reusable.  The reusable parts are put into inventory for reassembly into components and modules.  In the assembly area, the repaired modules are inspected, reassembled, tested and inventoried for delivery.  There is no need to maintain matched sets in assembly since any component from the same pool of assets can be used in any module that needs it.  A complication in managing the process, however, is that components may be scrapped if they exceed the requirements in the reassembly line or if they are faulty.  This is shown in the process flowchart in Figure 1.

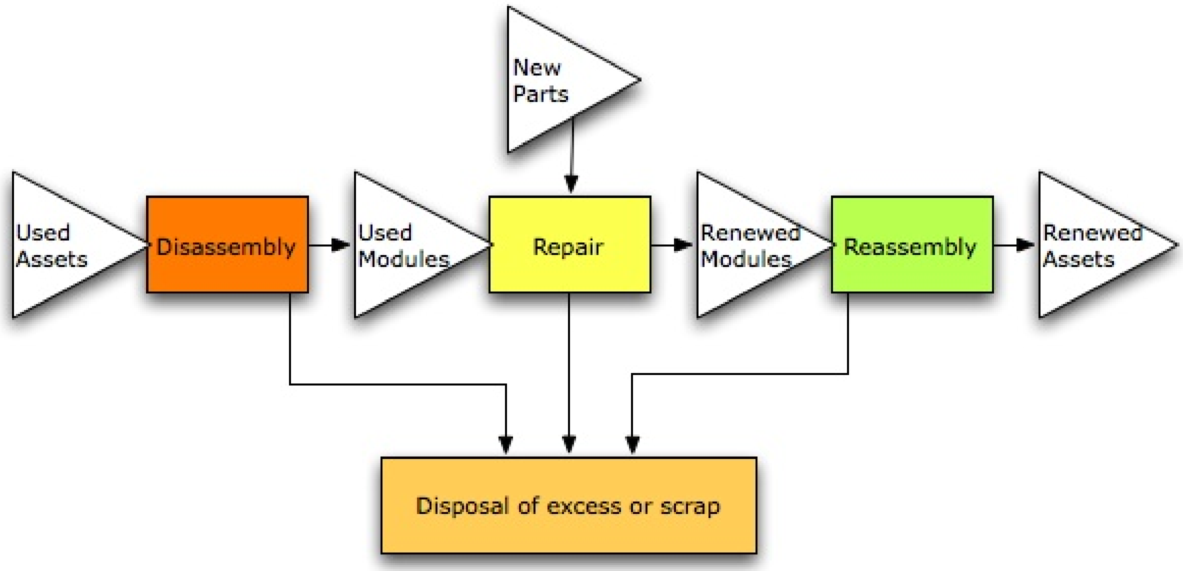

**Figure 1. Process Flowchart for Component Remanufacturing**

## Disassembly

The inventory of used assets provides the raw material for disassembly. Managing disassembly requires forecasting return volumes and deciding when to buy, sell or scrap parts. Used assets come in at an uncertain frequency, up to several weeks after the corresponding remanufactured components are released. Moreover, some portion of the assets never arrive, adding to the uncertainty. Finally, there is uncertainty regarding the quality of used assets until they are disassembled. Sometimes they are badly damaged, so recovering their parts would be too costly and/or would yield few recoverable parts.

Governing the disassembly activity is the disassembly schedule. It specifies how many of which assets to disassemble in the next few periods. Since disassembly provides most of the parts for assembling the remanufactured components, assuring an appropriate supply of assets is a primary management concern. To do so, components (or parts) may need to be purchased from the supplier. When purchasing is required, management expects to buy the minimum necessary to meet the demand over the next few periods. In making this decision, it is also necessary to analyze the trade-off between buying parts or buying completed modules. If parts are to be purchased, a linear programming model is used to determine what to purchase.

The disassembly schedule takes into consideration several factors. First, there are both unique and common modules among different assets. Therefore, several combinations of used assets could provide the number of each part type that is needed. Secondly, the yield rates are uncertain and could be different for each module. They could even differ for the same part in different assets. This means some parts might be generated in excessive numbers and need to be stored until needed or discarded. Finally, some of the assets may not be worth disassembling at all. For this reason, asset safety stock is usually not held. Instead, it is kept in parts.

Specification of the disassembly schedule, therefore, is not simply a matter of matching the components that are to be reassembled plus some factor to allow for yield losses. In fact, it could be quite different. The choice of assets to disassemble must take into account the number of parts needed, the number already in stock, the total assets in inventory, and the expected yield of each part from each asset type. Since setup costs are low, management would like to disassemble the number of assets that minimizes the residual inventory of parts. The system developed herein uses a linear programming model to determine the disassembly schedule.

## Assembly

While disassembly provides the supply of modules, the demand for them comes from the reassembly line supplying the users. The demand for remanufactured modules is characterized by uncertainties in timing, quantity and mix. Thus, management must determine how much safety stock should be carried for each component. Moreover, there is very little advance demand information on which to build a forecast. However, demand estimate lies at the heart of any attempt to develop reassembly plans to meet the warfighters’ needs.

The reassembly schedule specifies how many of which components are needed to meet the demand, forecasted or planned, and to provide the safety stock required. Once the reassembly schedule is determined, the parts required to fulfill the schedule can be determined. The trade-off between buying components or modules to fulfill the schedule must take into account the possibility that excess parts may eventually be discarded. To time the reassembly process, the manager must incorporate information about the delivery schedule to the user, the availability of components and modules and any need to balance workloads.

Remanufactured assets are often delivered on a weekly basis; this is a common planning increment for many firms. Consequently, this study uses a weekly planning cycle in developing the material planning system. Recognize, however, that this does not limit the generality of the approach. The objectives of the system are to determine which modules should be assembled to meet demand, what mix of assets should be disassembled, and, if need be, which components should be purchased from suppliers. The system links all aspects of the process—from forecasting to component purchasing—and provides information to manage required inventories. It follows the approach first used by Ferrer and Whybark (2001) to develop a closed-loop approach to material planning from sales and asset returns to scheduling and purchasing.

The overall structure of the information flows for the system is shown in Figure 2. The component inventory is central to the concept. Demand for modules comes from anticipated future deliveries, and the supply of components comes from disassembly of assets (or purchases). To integrate the system, the delivery forecasts provide information on future asset receipts to the asset inventory plans, and the disassembly schedule projects usage of the assets. The system is described in detail in the following section.

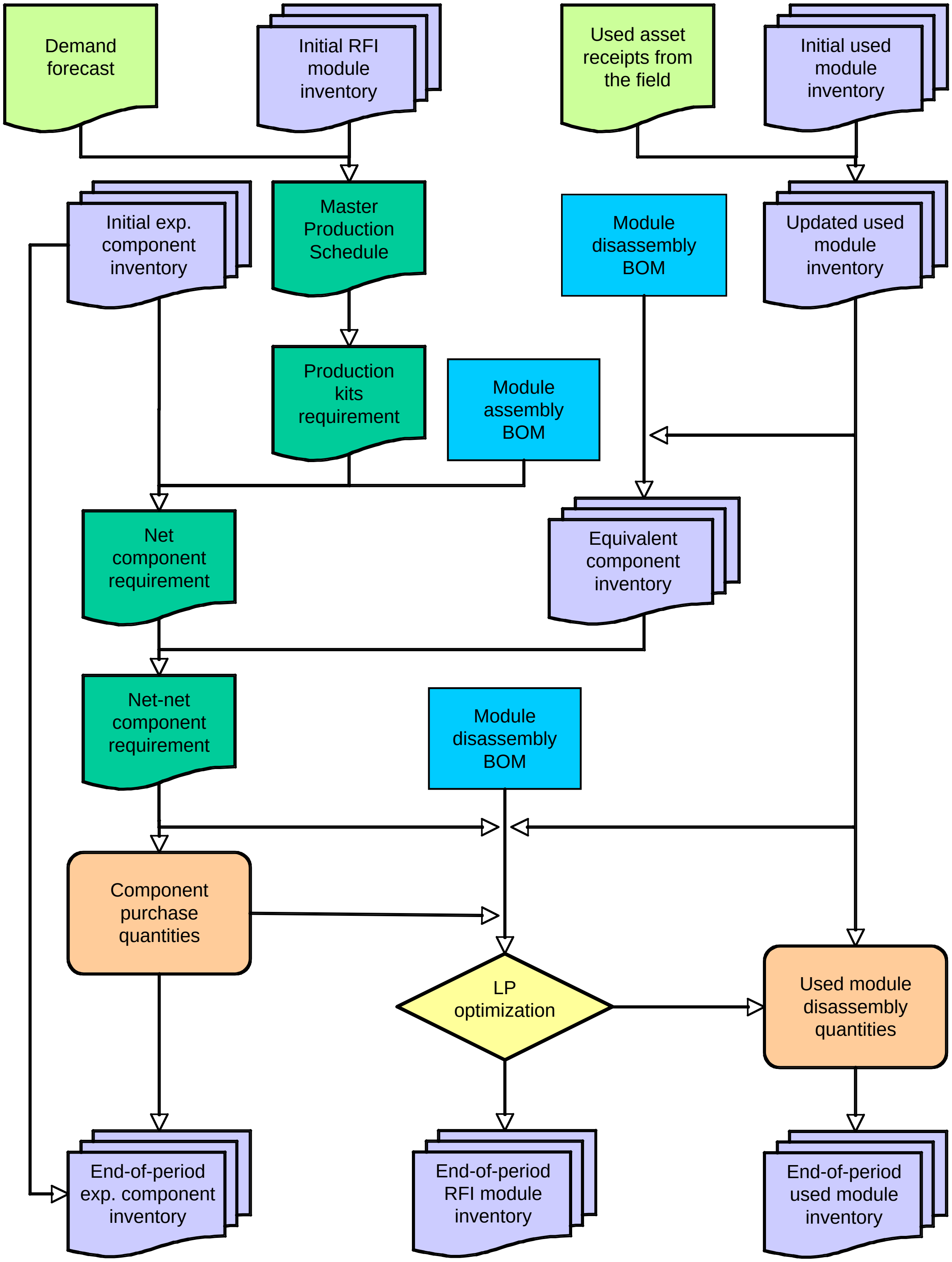

Figure 2. Information Flow Diagram for Component Remanufacturing

THIS PAGE INTENTIONALLY LEFT BLANK

## The Material Planning System

The system is based on material requirements planning (MRP). Rahman and Schroer (1998) studied MRP, Just-in-time (JIT) and Optimum Production Technique (OPT) systems to determine the conditions that would lead to preferring one over another. They found that MRP is preferred when one is using batch production in the presence of variability. MRP has the added advantage of providing a structure for treating the commonality of parts in different products. All these conditions (variability, batches and commonality) are present in defense asset remanufacturing. Moreover, many depot managers are familiar with MRP, a standard module in enterprise resource planning software.

There have already been some studies of MRP in remanufacturing facilities. For example, Krupp (1988) presented some suggestions on how to structure bills of materials for automotive component remanufacturing. His analysis recognizes the relationship between the volume of assets received and previous sales, but does not take into account disassembly yield or commonality. Panisset (1988), Szendel (1993), and McCaskey, Donald and Smith (1993) have discussed the idea of using reverse bills of material in an attempt to adapt the MRP framework to the disassembly process. None of these authors, however, integrate their work with the reassembly process. Inderfurth and Jensen (1998) conducted a mathematical analysis within the MRP framework to develop control rules for undertaking production of new components, disassembling assets, setting buffer stock levels, and disposing of excess assets in remanufacturing operations. Their model does not address yield losses in the disassembly process and is limited to a single period, with disposal of any assets left over at the end of the period.

The approach developed here extends these studies to improving remanufacturing depots in several ways. First, it links the volume of returns directly to the volume of deliveries. Secondly, it integrates the reassembly and disassembly schedules. Thirdly, component commonality and different yield factors are explicitly included. Fourth, the system derives the need for parts from forecasts and uses optimizing procedures to determine the disassembly schedule and required asset purchases to meet that need. Finally, information is provided that can be used to determine whether excess components should be discarded. The description of the system starts with the demand for modules (on the top left of Figure 2) and finishes on the disassembly.

## Component Demand Determination

The demand for parts emanates from the forecasts of remanufactured component sales. These forecasts also serve as the basis for estimating the trade-ins that will be received in the future. The demand for components is met through a finished goods inventory that is managed with a master production schedule (MPS), a separate record often controlled by sales personnel. (If they are not involved in this coordination, the inventory could be managed directly from the assembly schedule.)

### The Master Production Schedule

The master production schedule (MPS) is the part of the system that matches future supply to forecast demand by specifying the completion time for module reassembly. An example MPS record is shown in Figure 3. It projects the inventory levels of the finished Module A, given the forecast and the planning parameters, assembly lot size, lead-time and safety stock. It is a standard MPS approach, time-phased in weekly buckets, as described by Vollmann, Berry and Whybark (1997).

Master production schedule for Module A (RFI)

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Demand Forecast | | 25 | 21 | 22 | 20 | 25 | 25 | 20 | 25 |
| Expected Inventory | 16 | 33 | 12 | 32 | 12 | 29 | 46 | 26 | 43 |
| Delivery of MPS quantities | | 42 | | 42 | | 42 | 42 | | 42 |

Assembly lot size=42; lead-time=0; safety stock=5

Figure 3. Example MPS Record

The first line specifies the current week (1) and the number of weeks into the future. The next line of information is the forecast. The next line has the current ending inventory balance and the projected balances for future weeks, given the master production schedule. They are calculated by subtracting the demand in a week from the inventory balance at the end of the preceding week. Whenever the projected balance falls below the safety stock level, an MPS quantity is planned—as shown in the last line of the chart. Thus, the MPS quantities are to be completed in the week specified. The following expression explains:

$$\text{Exp. Inventory}_T = \text{Exp. Inventory}_{T-1} + \text{MPS}_T - \text{Forecast}_T$$

The planning parameters are predetermined by management and can be changed as conditions warrant. The safety stock level is set to provide the service level required for competitiveness in the industry. For the DoD, the safety level would balance cost with the need to ensure readiness and to meet the warfighter’s needs. To determine the reassembly batch size (the MPS quantity), one must trade-off any setup and holding cost and the need to keep the schedule reasonably stable. If testing, certification or some other time-consuming activity is required, the lead-time is increased, specifying earlier completion of the reassembly process.

Each period, the managers responsible for remanufacturing modules review the MPS plans and make any changes necessary into future MPS quantities. Moreover, the MPS records are updated using the current actual inventory and any changes in forecast. Inventory is different than projected any time the actual demand is different from the forecast or the MPS cannot be met due the various sources of uncertainty in the remanufacturing process; at that point, the new MPS record is reviewed for accuracy. Careful management of the MPS is important since it is the major input to the demand side of the system. The use of a master production scheduling record for managing the assembled component inventory opens the system to several enhancements. For example, time fences can be implemented to provide control over how much notice is needed to make changes.

### The Component Reassembly Schedule

The master production schedule generates the need for the assembly of finished components. The component reassembly plans are developed in material requirements planning (MRP) records using the MPS quantities as the gross requirements. Using those requirements, the reassembly schedule is developed in the MRP record. An example is provided in Figure 4 for Module A.

MRP record (assembly schedule) for Module A

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Gross Requirements | | 42 | | 42 | | 42 | 42 | | 42 |
| Scheduled Completions | | 42 | | | | | | | |
| Planned Completions | | | | 42 | | 42 | 42 | | 42 |
| Assembly Start Schedule | | | 42 | | 42 | 42 | | 42 | |

Assembly lot size=Lot-for-lot (as required by MPS); lead-time=1 week, safety stock=0

**Figure 4. Example Component MRP Record**

There is no inventory planned in the MRP record shown in Figure 4, since the entire inventory for Module A, including safety stock, is accounted for in the MPS record (Figure 3). The assembly quantity has also been established in the MPS record, so reassembly can be scheduled in lots “as required” (lot-for-lot) to meet the gross requirements. A lead-time of one week is used here to allow for the parts to be withdrawn from inventory and the reassembly operation itself to be performed. Note that to meet the MPS quantity in week 1, an order had to be released last week, and a scheduled completion is indicated for the current week. The following expressions summarize the calculations, assuming a one-week lead-time:

$$\text{StartSched}_{T-1} = \text{Max}\,\{\text{GrossReq}_{T} - \text{Inventory}_{T-1}\,;\,0\}$$

$$\text{Completions}_{T} = \text{StartSched}_{T-1}$$

## The Bill of Material

The reassembly schedule defined by the MRP record in Figure 4 generates a demand for components from which the modules are assembled. Since there can be commonality in the module designs (i.e., some components can be used in more than one module), the demand must be summarized to get a complete statement of component needs. A bill of materials (BOM) translates the modules in the assembly schedule into the components required. An example BOM is shown in Figure 5.

Number of parts, by type, contained in each component

|  | Comp. 1 | Comp. 2 | Comp. 3 | Comp. 4 | Comp. 5 | Comp. 6 | Comp. 7 | Comp. 8 | Comp. 9 |
|---|---|---|---|---|---|---|---|---|---|
| Module A | 1 |  |  | 1 |  |  | 1 |  |  |
| Module B |  | 1 |  | 1 |  |  |  | 1 |  |
| Module C | 1 |  |  |  | 1 |  |  | 1 |  |
| Module D |  | 1 |  |  |  | 1 |  |  | 1 |
| Module E |  |  | 1 |  |  | 1 | 1 |  |  |

**Figure 5. Example Bill of Material**

The BOM shows which parts are needed to complete each component. For our example here, Module A uses a Component 1, a Component 4, a Component 7, and perhaps others. If multiple parts of a particular type were needed, the number required would appear in the BOM.

## Determining Part Requirements

The MRP records for the assembly of modules indicate how many units are needed each period. These are translated into component requirements using the bill of materials to sum the requirements for components in each module. For example, the requirements for Component 1 come from both Module A and Module C (as seen in the first column of the bill of material in Figure 5). Figure 6 is an example requirement record for Component 1 showing how many units are needed for each of the next 10 weeks, taking into account the number of Modules A and C scheduled for assembly. The following expressions summarize the calculations:

$$\textsc{GrossReq}_{T,\ \textsc{Comp }1} = \textsc{StartSched}_{T,\ \textsc{Mod }A} + \textsc{StartSched}_{T,\ \textsc{Mod }C}$$

$$\textsc{NetReq}_{T,\ \textsc{Comp }1} = \textsc{Max}\ \{\textsc{GrossReq}_{T,\ \textsc{Comp }1} - \textsc{Inventory}_{T\text{-}1,\ \textsc{Comp }1} + \textsc{SafetyStock}_{\textsc{Comp }1}\ ;\ 0\}$$

$$\textsc{Inventory}_{T,\ \textsc{Comp }1} = \textsc{Inventory}_{T\text{-}1,\ \textsc{Comp }1} - \textsc{GrossReq}_{T,\ \textsc{Comp }1} + \textsc{NetReq}_{T,\ \textsc{Comp }1}$$

Component requirements for Component 1

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Gross Requirements | | 14 | 42 | 14 | 42 | 56 | 0 | 42 | 14 |
| Component Inventory (RFI) | 15 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Net Requirements | | 9 | 42 | 14 | 42 | 56 | 0 | 42 | 14 |

Safety stock=10

**Figure 6. Example Component Requirement Record**

The gross requirements in the component requirement record show the total number of Component 1 needed for all modules in which it is used (A and C in our example). The net requirement in any period is determined by comparing the gross requirement with the inventory from the previous week. If the difference between the two is less than the safety stock, there is a net requirement that needs to be filled through asset disassembly or component purchase. For example, the inventory for Component 1 at end of last week was 15, and the gross requirement for the current week is 14. Consequently, the record indicates a net requirement of 9 units for Component 1 in week 1 to bring the safety stock up 10 units. The safety stock helps cover uncertainties in the disassembly process.

## Component Supply Determination

The primary source of components to meet the net requirements for the reassembly schedule is the used-asset inventory. If current asset inventory plus anticipated returns are insufficient, more components will need to be purchased, or safety stock (and maybe sales) will be breached. The following sections describe the approach to managing asset inventory and to constructing a disassembly schedule to provide components.

### Determination of Component Supply from Asset Receipts

A remanufacturing depot obtains most of its modules from used-asset returns. There are three aspects of this return flow that must be considered by those managing used-asset inventory. First, the users return assets that don't exactly match their future needs. Second, the quality of the assets coming in is uncertain, and some of the assets are so worn out that they are not worth sending through disassembly. Finally, forecasts of future returns need to be adjusted for differences between forecast and actual returns. All these factors are accounted for in the system.

To determine if there is a need to purchase additional components, it is necessary to estimate the number of usable components in the current inventory of used modules and to forecast asset receipts. These estimates are produced using the disassembly bill of material. An example is shown in Figure 7. The matrix contains the expected yield of good components from each module, including the effect of assets that are too bad to completely disassemble. The matrix is very general and can contain different yields of the same component from different assets or other anomalies that occur during disassembly.

Expected yield of usable components from module disassembly

| | Comp. 1 | Comp. 2 | Comp. 3 | Comp. 4 | Comp. 5 | Comp. 6 | Comp. 7 | Comp. 8 | Comp. 9 |
|---|---|---|---|---|---|---|---|---|---|
| Module A | 0.80 | | | 0.72 | | | 0.83 | | |
| Module B | | 0.90 | | 0.77 | | | | 0.65 | |
| Module C | 1.00 | | | | 0.88 | | | 0.94 | |
| Module D | | 0.86 | | | | 1.00 | | | 0.81 |
| Module E | | | 0.9 | | | 0.73 | 0.88 | | |

**Figure 7. Example of Disassembly Bill of Material**

The yield data from Figure 7 are combined with the asset receipt data (both Module A and Module C) to calculate the expected number of components in the current asset inventory and the expected asset receipts. These are summarized in

Figure 8. If safety stock is to be covered for selected components, the current inventory can be reduced by the safety stock amount before calculating component availability. The need to purchase additional components is determined by comparing these expected receipts with the net requirements in Figure 6. In this way, component requirements are first satisfied with components already in inventory and second, from asset disassembly. If these sources are insufficient, additional components are purchased from the supplier. Figure 8 shows the corresponding MRP record.

Expected component 1 inventory in asset receipts

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Exp. comp. receipts (in assets) | | 23 | 23 | 24 | 25 | 24 | 24 | 24 | 23 |
| Net component requirements | | 9 | 42 | 14 | 42 | 56 | 0 | 42 | 14 |
| Exp. comp. inventory (in assets) | 18 | 32 | 13 | 23 | 6 | -26 | 24 | 6 | 15 |
| Net-net component requirements | | | | | | 26 | | | |

Safety stock=10

**Figure 8. Example Record for Determining Additional Component Requirements**

The net component requirements, shown in Figure 8 for Component 1, are taken from Figure 6. Therefore, the component safety stock is included. To meet these requirements, there are the components in the current asset inventory plus the expected asset receipts. The current Component 1 inventory of 18 (shown in Figure 8) comes from 16 Module A assets (with an 80% yield) and 5 Module C assets currently on hand. To determine if any component needs to be purchased, the net requirements in each week are compared to the expected number of components available from inventory and the disassembly of assets. Whenever the component inventory is expected to be insufficient, a purchase quantity is suggested. This happens in our example in Week 5, when there is a 26-unit shortfall. These extra requirements are called "net-net" component requirements (net of component inventory and net of expected receipts). The "net-net" requirements row indicates when and how many components should be purchased. Since there is no "net-net" requirement in Week 1, any decision based on component 1 alone can be postponed for at least another week. It is possible, however, that other components will be needed, triggering a purchase decision. The following expressions summarize the calculations:

$$\textsc{ExpRec}_{\textsc{T, comp1}} = \textsc{ExpRec}_{\textsc{T, modA}} * \textsc{Yield}_{A,1} + \textsc{ExpRec}_{\textsc{T, modC}} * \textsc{Yield}_{C,1}$$

$$\textsc{ExpInv}_{\textsc{T, comp1}} = \textsc{ExpInv}_{\textsc{T-1, comp1}} + \textsc{ExpRec}_{\textsc{T, comp1}} - \textsc{NetReq}_{\textsc{T}},\ _{\textsc{comp1}}$$

$$\textsc{NetNetReq}_{\textsc{T, comp1}} = \textsc{Max}\ \{-\textsc{ExpInv}_{\textsc{T, comp1}}\ ;\ 0\}$$

Notice that the forecast and the master production schedule must extend far enough into the future to accommodate the planning horizon. Even though the decision is needed only for Week 1, the additional time periods can be used to increase the purchase alternatives for management (such as purchasing more than a one-week supply) and to provide planning information on future purchases. Alternative inventory policies (such as fixed-period ordering systems, fixed quantities, base stock policies, just-in-time or kanban), or other financial criteria (such as minimum inventory value, maximum or minimum number of useful excess components) may be used as well.

## Constructing the Disassembly Schedule

After the component purchase decision has been made, it is clear that enough assets are available to cover all the requirements but need to determine which specific assets to schedule for disassembly. There may be many combinations of assets that can be used to meet the component requirements, so a systematic decision process is required. In addition, each asset that is disassembled will provide all the usable components that are in it, whether they are needed or not. Thus, there is the possibility of generating unneeded components that will stay in inventory for a significant period of time.

Our approach to constructing a disassembly schedule is to formulate a linear program to find the minimum number of assets that meets all component requirements for each period within the planning horizon. The model takes into account component commonality, different component yields and the combinations of components in assets. Other criteria—like minimum cost of assets, minimum inventory cost, minimum residual component inventory, most useful residual component inventory, and so forth—could be used here as well. The linear programming model (LP) is formulated in Appendix A.

## Inventory Management

With the completion of the module reassembly and disassembly schedules, all aspects of the system that produce and consume components internally are in place. This means that all the information for managing the inventories of assets, modules, and components is now available. The inventory managers need to be concerned not only with meeting the components requirements, but also with preventing undue inventory build up. Excess modules containing components that have fallen from favor need to be disposed of. The unneeded components remaining from asset disassembly may be stocked or scrapped. Managers must keep finished module inventory from growing excessively while they still maintain adequate safety stock. The records that support managing these inventories are described next.

### Finished Module Inventory Management

The remanufactured modules requirements are described with the master production schedule seen in Figure 3. These inventories are controlled by managers scheduling the delivery of MPS quantities so as to maintain the safety stock without building up excess inventory. This means monitoring the forecast, establishing the MPS quantities and adjusting safety stock levels. The MPS, of course, establishes the reassembly schedule that drives the remainder of the system.

## Asset Inventory Management

The record for managing asset inventory is shown in Figure 9. The planned disassembly is dictated by the disassembly numbers recommended by the linear program to fulfill the needs for Components 1, 4 and 7. The planned inventory is what remains after used modules have been removed for disassembly. If the planned inventory is growing to unacceptable levels, then some of the assets may be scrapped. The following expression shows the calculation:

$$\mathrm{EXPINV}_{T,\ MODA} = \mathrm{EXPINV}_{T-1,\ MODA} + \mathrm{FORREC}_{T,\ MODA} - \mathrm{DISASS}_{T,\ MODA}$$

Inventory record for used Module A

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Receipts Forecast | | 21 | 21 | 23 | 24 | 22 | 22 | 22 | 21 |
| Planned Disassembly | | 22 | 31 | 10 | 32 | 30 | 20 | 20 | 10 |
| Expected Inventory | 14 | 13 | 3 | 16 | 8 | 0 | 2 | 4 | 15 |

**Figure 9. Example Module Inventory Record**

## Component Inventory Management

The record for managing used module inventories finally closes the loop. An example for Component 1 is shown in Figure 10. The gross requirements come from Figure 6. The component receipts come from the disassembly schedules, adjusted for the component yield from the assets in Figure 7. The planned component inventory is the difference between the requirements and receipts added to the preceeding week's inventory. The following expressions summarize the calculations:

$$\mathrm{DISASSREC}_{T,\ COMP1} = \mathrm{DISASS}_{T,\ MODA} * \mathrm{YIELD}_{A,1} + \mathrm{DISASS}_{T,\ MODC} * \mathrm{YIELD}_{C,1}$$

$$\mathrm{PURCHASE}_{T,\ COMP1} = \mathrm{NETNETREQ}_{T,\ COMP1}$$

$$\mathrm{EXPINV}_{T,\ COMP1} = \mathrm{EXPINV}_{T-1,\ COMP1} + \mathrm{DISASSREC}_{T,\ COMP1} - \mathrm{GROSSREQ}_{T,\ COMP1} + \mathrm{PURCHASE}_{T,\ COMP1}$$

Inventory record for Component 1 (RFI)

| Week | Invt. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Gross Requirements |  | 14 | 42 | 14 | 42 | 56 | 0 | 42 | 14 |
| Exp. Receipts from Disass. |  | 33 | 29 | 13 | 36 | 60 | 0 | 23 | 23 |
| Planned Purchases |  |  |  |  |  |  | 26 |  |  |
| Exp. Inventory | 15 | 34 | 21 | 20 | 14 | 18 | 44 | 25 | 34 |

Figure 10. Example Component Inventory Record

## Conclusions

This article showed the development of a material planning system to provide an integrated approach to help defense asset remanufacturing depots effectively manage both the demand and supply sides of their missions. This approach overcomes many of the limitations of previous work by incorporating commonality, variable yields, multiple periods and disposal of inventory no longer needed. Moreover, the plans that are developed in any period are updated the next—taking into account actual deliveries, receipts, yields and so forth. Thus, corrections for deviations are possible on a timely basis. The information requirements for the system are substantial, however. Estimates of sales, returns, and yields are necessary for the system to function. Yet, when required, many managers currently make these estimates on an ad hoc basis. The high level of uncertainty means that safety stock must be held, and the information provided by the system can help to manage those levels. More empirical work needs to be done, however, to see if the information costs are warranted.

Currently the parameter values are based on experience, intuition and common practice. Our example uses a week as the standard time unit. Current IT capabilities allow adjusting this method to a virtually continuous planning process. Further research is necessary to investigate how robust the system is to different planning horizons, to highly uncertain asset return, to extended forecast horizon and to long lead-times. Since the system is integrated, the dynamics of forecast, trade-in and yield error need to be studied. It is still necessary to determine the safety stock levels and the length of the planning horizons. Fine-tuning can be accomplished with the availability of real data regarding the volume of defense asset returns, remanufactured asset needs, bills of material and recovery yields of different components. Until these data become available, this model can be improved with the definition of robust safety stocks, and simulating the demand using parameters that resemble the operating environment in these depots.

THIS PAGE INTENTIONALLY LEFT BLANK

# List of References

Debo, L.G., Toktay, L.B., & VanWassenhove, L.N. (2005). market segmentation and production technology selection for remanufacturable products. *Management Science, 51*(8), 1193-1205.

Dekker, R., M. Fleischmann, K. Inderfurth, L.N. Van Wassenhove (Eds.), 2004. *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*. Berlin: Springer-Verlag.

Dowlatshahi, S. (2000). Developing a theory of reverse logistics. *Interfaces, 30*, 143-155.

Ferguson, M., & Toktay, L.B. (2006). The effect of competition on recovery strategies. *Production and Operations Management, 15*(3), 351-368.

Ferrer, G. (2003). Yield information and supplier lead time in remanufacturing operations. *European Journal of Operational Research, 149*(3), 540-556.

Ferrer, G., & Swaminathan, J. (2006). Managing new and remanufactured products. *Management Science, 52*(1), 15-26.

Ferrer, G., & Whybark, D.C. (2000). Successful remanufacturing systems and skills. *Business Horizons*, *33*(6), 55-64.

Fleischmann, M., Bloemhof-Ruwaard, J., Dekker, R., & Van der Laan, E. (1997). Quantitative models for reverse logistics: A review. *European Journal of Operational Research, 103*, 1-17.

Guide, V.D., Jayaraman, V., Srivastava, R., Benton, W. (2000). Supply-chain management for recoverable manufacturing systems. *Interfaces, 30*, 125-142.

Guide, V.D.R., Jr. (2000). Production planning and control for remanufacturing: Industry practice and research needs. *Journal of Operations Management, 18*(4), 467-483.

Guide, Jr., V.D.R., L.N. Van Wassenhove (Eds.), 2003. *Business Aspects of Closed-Loop Supply Chains*. Pittsburgh, PA: Carnegie Mellon University Press.

Hormozi, A.M. (1997). Parts remanufacturing in the automotive industry. *Production and Inventory Management Journal, 38*(First Quarter), 26-31.

Inderfurth, K., & Jensen, T. (1998). Analysis of MRP policies with recovery options. In *Proceedings of the Tenth International Working Seminar on Production Economics* (pp. 265-3000). Igls/Innsbruck, Austria.

Klausner, M., & Hendrickson, C. (2000). Reverse-logistics strategy for product take-back. *Interfaces, 30*, 156-165.

Krupp, J.A.G. (1988). Structuring bills of material for automotive remanufacturing, *Production and Inventory Management Journal*, Fourth Quarter, 46-50.

Mahadevan, B., & Pyke, D. (2001). *Periodic review inventory policies for remanufacturing* (Working paper). Hanover, NH: Dartmouth College.

Majumder, P., & Groenevelt, H. (2001). Competition in remanufacturing. *Production and Operations Management, 10*(2), 125-141.

McCaskey, J., Donald, W., & Smith, R.D. (1993). MRP logic for remanufacturing—A new approach. In *APICS 1993 Remanufacturing Seminar* (pp. 15-21). APICS.

Panisset, B.D. (1988). MRP II for repair/refurbish industries. *Production and Inventory Management Journal*, Fourth Quarter, 12-15.

Purser, R.E., Park, C., & Montuori, A. (1995). Limits to anthropocentrism: Toward an ecocentric organization paradigm. *Academy of Management Review, 20*(4), 1053-1090.

Rahman, M.M., & Schroer, B.J. (1998). Optimum production conditions for JIT, MRP, OPT. In *Proceedings of the 29th Annual Meeting of the Decision Sciences Institute* (pp. 1158-1162). Las Vegas, NV: Decision Science Institute.

Richter, K., & Sombrutzki, M. (2000). Remanufacturing planning for the reverse Wagner/Whitin models. *European Journal of Operational Research, 121*, 304-315.

Szendel, T.N. (1993). Structuring and using remanufacturing bills of materials. In *APICS 1993 Remanufacturing Seminar* (pp. 140-146). APICS.

Van der Laan, E., Dekker, R., & Salomon, M. (1999). An investigation of lead–time effects in manufacturing/remanufacturing systems under simple PUSH and PULL control strategies. *European Journal of Operational Research, 115*, 195-214.

Van der Laan, E., Dekker, R., Salomon, M., & Ridder, A. (1996). An (s, Q) inventory model with remanufacturing and disposal. *International Journal of Production Economics*, *46-47*, 339-350.

Van der Laan, E., Salomon, M., Dekker, R., & Van Wassenhove, L. (1999). Inventory control in hybrid systems with remanufacturing. *Management Science*, *45*, 733-747.

Vollmann, T.E., Berry, W.L., & Whybark, D.C. (1997). *Manufacturing planning and control systems*. New York: Irwin/McGraw-Hill.

# Appendix A. Asset Disassembly Schedule Determination

A linear programming model (LP) is used to determine the asset disassembly schedule. The input data consists of the net requirements for the parts (Figure 6), the yield data for the parts in assets (Figure 7), and the beginning inventory for each part (Figure 6). The objective is to disassemble the minimum number of modules in the planning horizon. Other objectives—such as cost or final inventory reduction, can be easily formulated. The formulation is:

$$Minimize \sum_{i}^{M} \sum_{t}^{T} Z_{i,t}$$

subject to

$$I_{k,t-1} + \sum_{i=1}^{M} Z_{i,t} * Y_{i,k} \geq N_{k,t} \quad \forall k, \forall t$$

$$Z_{i,t} \geq 0, \quad \forall i, \forall t$$

$$I_{k,t} \geq 0, \quad \forall k, \forall t$$

$$I_{k,0} = B_k, \quad \forall k$$

where:
$Z_{i,t}$ = type i modules disassembled in period t.
$Y_{I,k}$ = expected usable fraction of type k components in module i.
$N_{k,t}$ = net requirement for component type k in period t.
$I_{k,t}$ = inventory of type k components at the end of period t.
$B_k$ = inventory of component k at the beginning of the planning horizon.
$i$ = 1, 2 … M, the module index up to the number of modules, M.
$k$ = 1, 2 … C, the component index up to the number of components, C.
$t$ = 1, 2 … T, the time index up to the end of the planning horizon, T.

The model has T*M decision variables and T(2C+M)+C constraints: satisfying the net requirement, the non-negativity of disassembled modules, the non-negativity of component inventory and the initial conditions. This LP problem is usually small and can be solved on a PC.

THIS PAGE INTENTIONALLY LEFT BLANK

# 2003 - 2008 Sponsored Research Topics

## Acquisition Management

- Software Requirements for OA
- Managing Services Supply Chain
- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Portfolio Optimization via KVA + RO
- MOSA Contracting Implications
- Strategy for Defense Acquisition Research
- Spiral Development
- BCA: Contractor vs. Organic Growth

## Contract Management

- USAF IT Commodity Council
- Contractors in 21st Century Combat Zone
- Joint Contingency Contracting
- Navy Contract Writing Guide
- Commodity Sourcing Strategies
- Past Performance in Source Selection
- USMC Contingency Contracting
- Transforming DoD Contract Closeout
- Model for Optimizing Contingency Contracting Planning and Execution

## Financial Management

- PPPs and Government Financing
- Energy Saving Contracts/DoD Mobile Assets
- Capital Budgeting for DoD
- Financing DoD Budget via PPPs
- ROI of Information Warfare Systems
- Acquisitions via leasing: MPS case
- Special Termination Liability in MDAPs

## Human Resources

- Learning Management Systems
- Tuition Assistance
- Retention
- Indefinite Reenlistment
- Individual Augmentation

## Logistics Management

- R-TOC Aegis Microwave Power Tubes
- Privatization-NOSL/NAWCI
- Army LOG MOD
- PBL (4)
- Contractors Supporting Military Operations
- RFID (4)
- Strategic Sourcing
- ASDS Product Support Analysis
- Analysis of LAV Depot Maintenance
- Diffusion/Variability on Vendor Performance Evaluation
- Optimizing CIWS Lifecycle Support (LCS)

## Program Management

- Building Collaborative Capacity
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to Aegis and SSDS
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Terminating Your Own Program
- Collaborative IT Tools Leveraging Competence

A complete listing and electronic copies of published research are available on our website: www.acquisitionresearch.org

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL
555 DYER ROAD, INGERSOLL HALL
MONTEREY, CALIFORNIA 93943

www.acquisitionresearch.org