# Optimizing the Supply Chain in Reverse Logistics

**Pitipong Veerakamolmal**
IBM Global Services
Supply Chain Planning – Business Innovation Services
404 Wyman Street,
Waltham, MA 02454.

and

**Surendra M. Gupta***
Laboratory for Responsible Manufacturing
334 SN, Department of MIME
Northeastern University
360 Huntington Avenue
Boston, MA 02115.

**ABSTRACT**

Supply chain planning systems in reverse logistics present the industry with new problems that demand new approaches. The specific problem of the reverse logistics for the end-of-life (EOL) products addressed in this study is to determine the number of products to disassemble in a given time period to fulfill the demand of various components during that and subsequent time periods. We present a mathematical programming based model to solve the problem. When the problem is solved, it gives the number and timing of each product type to be disassembled in order to fulfill the demand of components needed at minimal disassembly and disposal costs. We illustrate the solution methodology with a case example.

**Keywords:** Disassembly, remanufacturing, reverse logistics, supply chain planning

## 1. INTRODUCTION

The supply chain planning in reverse logistics of end-of-life (EOL) products embraces many different characteristics of environmentally conscious manufacturing, including disassembly, reuse, recycling, and remanufacturing[1]. As manufacturers change from isolated business units to integrated network partners, they require effective and efficient Supply Chain Planning (SCP) strategies for materials, components, and products. SCP can help speed up the reverse logistics through the availability of online marketplace to support the networking of environmentally conscious product suppliers, manufacturers, distributors and customers. Online marketplace allows manufacturers and their network of suppliers and strategic partners to collaborate and conduct business over the internet, which aims to reduce the cost of doing business and boost the efficiency of participants (Fig. 1). This research focuses on the SCP system in reverse logistics to provide a way in which manufacturers can reclaim various models of a product for remanufacturing[2, 3].

The operational characteristics of reverse logistics are different from their manufacturing counterpart[4]. The challenge here is to model the system so that it can facilitate both intra- and inter-enterprise supply chain network for collecting and remanufacturing EOL products[5]. This network can be modeled as a supply chain, where products flow in both directions. A reverse supply chain represents the products collected from consumers and businesses back to manufacturers. They may consist of end-of-lease products, product traded-ins, and products returned due to legislative requirements. A forward supply chain represents the flow of items from manufacturers back to the consumers as refurbished products or components.

Some of the unique characteristics of the reverse logistics problem are highlighted below.

*Correspondence: e-mail: gupta@neu.edu; URL: http://www.coe.neu.edu/~smgupta/
Phone: (617)-373-4846; Fax: (617)-373-2921

*Supply/Demand Balancing:* Perhaps the most difficult variable to forecast is the distribution of the returns of EOL or end-of-lease products over the planning horizon. Forecasters often face unexpected supply/demand patterns that will depend on their product's success in the market and competing products.

*Accumulation:* There will be accumulations of certain kinds of parts due to uneven market demands for certain components. For instance, there may be higher demands for certain models of memory chips and hard drives while other dismantled parts with no demand pile up on the operations floor.

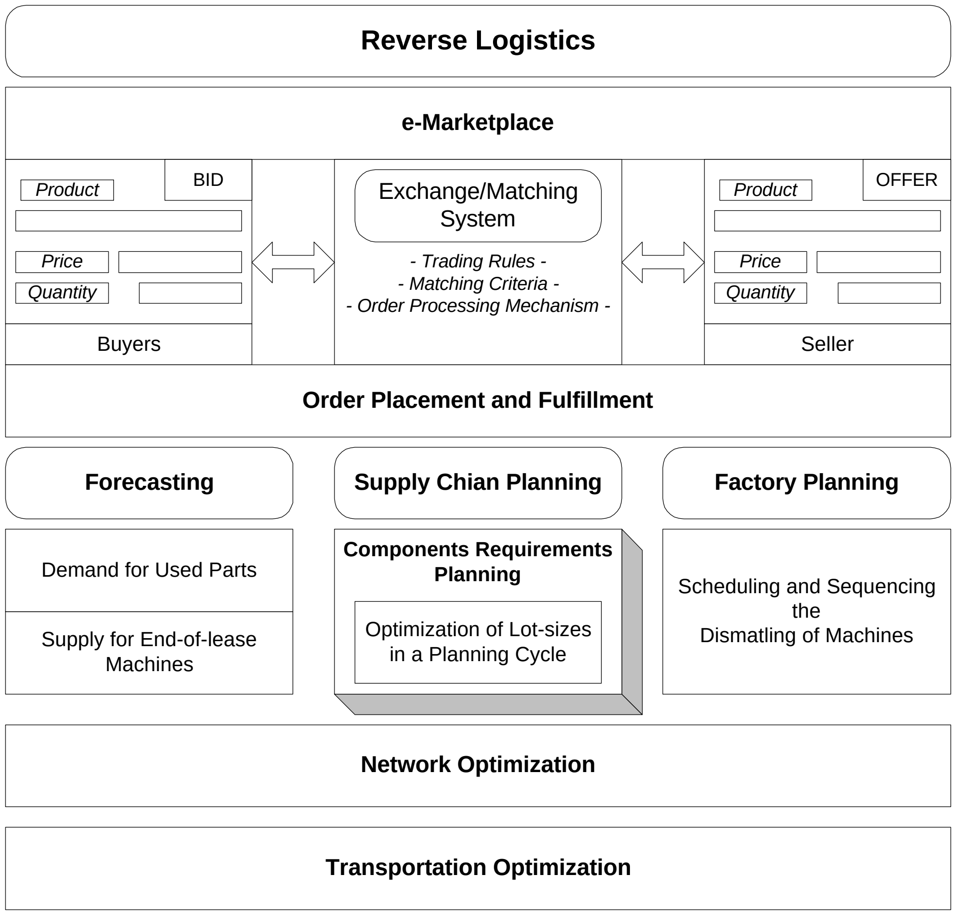


Fig. 1. Supply Chain Planning Model for Reverse Logistics.

*Logistical Network:* In a reverse logistics supply chain environment there will be potentially three separate entities: the assembly plant, the disassembly plant and the recycling plant. Operations therefore have to be planned from a larger perspective that comprise those three entities. The inventory policies will alter in terms of the level and location of buffer stocks. From the supply of products, to collection, to dismantling, to reuse and/or recycling, the inventory of products and components must be properly maintained to balance the supply and demand of resources.

*Transportation:* Plant location decisions are influenced by the transportation cost of raw materials. However, when dealing with disassembly and recycling, the control for the flow of products is expected to increase several folds. Manufacturers will have to consider this problem and plan the locations of new assembly, disassembly or recycling plants appropriately. It is often more problematic than not to consider if, for example, there are demands for a hundred used hard drives on the East coast, is it more cost effective to ship machines from the West coast, or to dismantle them and ship only the needed parts?

The main focus in this paper is on the systematic decision making approach used to determine the number of products to disassemble in a given time period to fulfill the demand of various components during that and subsequent time periods. The paper is organized as follows. The next section briefly describes the areas of remanufacturing and planning for disassembly, which are important aspects of reverse logistics. Section 3 discusses economic, environmental and operations problems in reverse logistics. Section 4 presents the problem statement. Section 5 addresses the Components Requirement Planning (CRP) procedure for the optimization of reverse logistics. Section 6 illustrates the procedure with a case example. Finally, section 7 provides some conclusions.

## 2. BACKGROUND

A process of producing products by employing used parts yet having quality standards of new products is called remanufacturing. This process restores worn-out products to "like-new" conditions at a considerably reduced cost. The planning and control functions of remanufacturing are significantly more complicated than traditional manufacturing[6]. Because of this, developing analytical models to analyze remanufacturing systems is a challenging task. One particular requirement in a remanufacturing system is the need to disassemble reclaimed products based on the demand of their components. Previous works in the area of product disassembly can be classified into two categories based on the technique that is employed, viz., planning and scheduling, and the application of mathematical optimization methodology.

Many authors have looked at product disassembly in order to fulfill the demand of the components. Gupta and Taleb[7] presented an algorithm for scheduling the disassembly of a discrete, well-defined product structure. The algorithm determines the disassembly schedule for the components such that the demands for those components are satisfied. In their subsequent papers, Taleb *et al*.[8] and Taleb and Gupta[9] improved the methodology to include components/materials commonality as well as the disassembly of multiple product structures. However, they did not address the remanufacturing problem.

Some authors have applied mathematical programming in the area of materials and components reclamation. Isaacs and Gupta[10] investigated the impact of automobile design on disposal strategies by using goal programming to solve the problem. Veerakamolmal and Gupta[11] employed mathematical programming to balance the lot sizes for the disassembly of multiple-products. The methodology optimizes the number of products of various types for disassembly in order to fulfill the demand for components. The result offers the minimum lot size for disassembly while maximizing the revenue from selling the retrieved components.

## 3. PROBLEMS ENCOUNTERED IN REVERSE LOGISTICS

### 1. Economic Problems

The last few years have seen a tremendous growth in the demand for durable consumer goods. The rapid development and improvement of products have given rise to additional demand resulting in shortened lifetime of most products. This in turn has increased the quality of used products scrapped. The bulk of the scrap comes from automobiles, household appliances, consumers electronic goods, and at an increasing rate from computers. In reverse logistics, the value of returned products may decrease more rapidly than their new counterparts. Accelerating the process of the reverse supply chain to drive value preservation is critical. Coupled with the rapidly increasing return volumes, the complexity of return logistics becomes problematically complex.

### 2. Environmental Problems

The most prominent evidence of our environmental problem comes from the growing need for waste disposal. Originally, the majority of our municipal wastes were landfilled. However, the shortcomings of our reliance on landfilling has become evident: they pose unacceptable environmental risks because of their location or simply because they have filled up, and they pose hazardous risks to human health through ground water contamination and toxic air emissions. As a result, numerous landfills, especially in larger cities where enormous amount of waste is generated everyday, have closed down. While new landfills are being built at a relatively slower rate, they are located further away, thus sending the costs of hauling waste much higher. Furthermore, U.S. Congress passed a toxic waste cleanup bill known as "Superfund", stating that the costs of cleaning up contaminated waste sites be shared among those who dispose. The growing expense of waste management has, in turn, helped justify the need to escalate recycling and reuse.

### 3. Operational Problems

Some of the type of questions that need answers include the following.

- What is the least number of machines I need in order to disassemble the parts demanded?
- What are the most economical machines to dismantle evaluating fair market value of the machine?

- Should we dismantle machines where the current residual value or fair market value is greater than the sum of the parts (e.g. for computers, usually 5-6 parts are valuable: motherboard, display panel, keyboard, HDD, memory, CD-ROM drive)?
- Must the system always select the machines which yield more reliable parts when the yield of model is greater than or equal to other machines when dismantled to meet parts demand (e.g., 100 parts demanded can be found in Machine 1 & Machine 2. However, machine 1 has 80% reliability yield and Machine 2 has 50%)?

## 4. PROBLEM STATEMENT

The primary objective of the model developed in this paper is to provide a cost efficient way in which manufacturers can reclaim products for remanufacturing. We assume that the supply of products, which have been disposed of at the end of their lives, is finite. Since shortages in this supply are eminent which, in turn, lead to possible shortages in the supply of components for remanufacturing, the method has to account for the possibility of component inventory and/or ordering additional (new) components to fulfill the demand. After disassembly, unwanted components and materials are sent for recycling or proper disposal. Due to possible deterioration in the conditions of some recovered components, inventory of only certain components is maintained. The shelf life of each component may vary.

## 5. COMPONENTS REQUIREMENTS PLANNING PROCEDURE

Components Requirement Planning (CRP) addresses the problem of determining the disassembly schedule for all the products. We assume that the batch of products to be disassembled is composed of two or more models of appliances belonging to the same product platform, i.e. there is component commonality within these products. The products are disassembled to obtain the various components. The terminology used in components requirements planning is explained below:

**Gross Requirements** ($GR_t$): Demand of products and components in period $t$;
**Receipts from External Sources** ($SR_t$): Additional components received in period $t$ from other sources (unplanned);
**Available Balance** ($AB_t$): Number of components in inventory at the beginning of period $t$. Note that the number of items in inventory is influenced by the shelf life of each component;

$$AB_t = \begin{cases} Max[0, (OH_{t-1} - NU_{t-1})] + \\ Max[0, (AB_{t-1} - GR_{t-1} + SR_{t-1} - ND_{t-1})], \text{if } (SL > 0); \\ 0, \text{otherwise} \end{cases}$$

**Net Requirement** ($NR_t$): Number of components needed after accounting for Receipts from External Sources and Available Balance in period $t$;
$NR_t = Max[0, (GR_t - SR_t - AB_t)]$
**On Hand from Disassembly** ($OH_t$): Total yield of the component from the supply of products in period $t$;
**Number Used From Disassembly** ($NU_t$): Number of components used from disassembly;
$NU_t = Min[NR_t, OH_t]$
**Number of New Components Required** ($NC_t$): The number of new components that have to be ordered in period $t$. This occurs when there are not enough components On Hand from Disassembly to satisfy the Net Requirement;
$NC_t = Max[0, (NR_t - OH_t)]$
**Number of Components Discarded** ($ND_t$): Number of components that are not needed after disassembly and/or have reached the end of their shelf lives in period $t$;
$ND_t = Max[0, (OH_{t-SL} - NU_{t-SL} - GR_{t-SL+1} - GR_{t-SL+2} - ... - GR_t)] + Max[0,(SR_{t-SL} - GR_{t-SL})])$
**Assembly Lead Time** ($LT$): The time it takes to assemble products;
**Ordering Lead Time** ($RT$): The time required to obtain the products for disassembly;
**Shelf Life** ($SL$): Number of periods that a component can be kept in inventory without becoming obsolete/degraded. An unwanted component has a shelf life of zero.

We assume the following:

- There is an upper limit to the number of each type of used product ($S_i$) available from the distributors in each time period.
- The dissembler may order any number of used products of each type (up to a maximum of $S_i$) from the distributors, in each time period, to fulfill the demand of components. Any additional need has to be fulfilled with new components.

- Quality control factors ($QP_{ij}$) are used to account for the possibility of damaged products due to normal wear and tear during their use, or other mishaps during the collection, disassembly, or retrieval processes.
- After the disassembly of products, the components with no demand are recycled for materials or sent to disposal.
- The demanded components are sorted into good quality and defective lots. The defective components are recycled for materials or sent to disposal. The good quality components are sold to the remanufacturer if they can be utilized in the current period. The good quality components, which cannot be utilized in the current period (over-supply), are recycled for materials or sent to disposal, if their shelf lives are zero. Otherwise, they are sold to the remanufacturer for use in the subsequent period(s).

We now present a supply chain optimization procedure to determine the lot-sizes of products (for disassembly) to obtain from the distributors to fulfill the components requirements for remanufacturing. The procedure, while determining if there is a potential shortage in the supply of reusable components, optimizes the lot-size of products to disassemble in each time period. It also provides the process planner with a detailed component retrieval plan, which leads to an enhanced CRP performance in the reverse logistics supply chain environment.

**Procedure:**

***Step 1***: Input the required data such as: the length of the planning horizon ($T$), the demand of products to remanufacture ($GR_t$), and the maximum supply of products $(S_i)_t$ (end-of-lease or available at each product distribution center) in period $t$, ($1 \leq t \leq T$). In addition, prepare product specific information such as: the disassembly times, the components commonality and multiplicity, the demand, the value, the weight, the recycling cost factor, and the disposal cost index for each component. Set $t = 1$.

***Step 2***: Determine the maximum yield for demanded components after quality percentages have been accounted for.

***Step 3***: Assess to see if there are enough components to fulfill the demand (that is, for each component $P_j$, check if ($NR_t$) ≤ maximum component yield). If yes, set the demand ($D_j$) equal to the Net Requirement ($NR_t$) of each component, and go to *Step 5*. If not, proceed to *Step 4* for shortage adjustment.

***Step 4***: Calculate the number of components to order from outside sources ($NC_t$) to make up for the shortage(s). Since any potential shortage would be fulfilled by placing the order for new components ($NC_t$), $D_j$ can be obtained by deducting $NC_t$ from the Net Requirements ($NR_t$) $[(D_j) = (NR_t) - (NC_t)]$.

***Step 5***: Formulate and solve the IP model. Using the demand of reusable components ($D_j$), the maximum supply of products ($S_i$), and the product/component specific information, obtain the number of products to order for disassembly and the net profit (or loss) from the resale, recycle and disposal of components as demonstrated in Gupta *et al.*[12].

***Step 6***: Update the CRP table. For the current time period, update $OH_t$, $NU_t$, $NC_t$ and $ND_t$. Note that the number of defective components must be deducted from component yield $[(OH_t) = (OH_t) - (QP_{ij} \cdot Q_j \cdot Y_i)_t]$. Also, since damaged stock is recycled and/or disposed of in the same period, the modified number of components discarded in period $t$ ($ND_t$) becomes the sum of the actual $ND_t$ and the damaged component yield $(QP_{ij} \cdot Q_j \cdot Y_i)_t$ $[(ND_t) = (ND_t) + (QP_{ij} \cdot Q_j \cdot Y_i)_t]$.

***Step 7***: Check if the whole planning horizon has been planned ($t = T$). If yes, proceed to *Step 8*. If not, set $t = t + 1$ and go to *Step 2*.

***Step 8***: Stop.

## 6. CASE EXAMPLE

We consider a case example to illustrate the application of the supply chain optimization procedure. A computer company remanufactures and distributes two new computer models (*PC*5 and *PC*6), that partially utilize the components from four different computer models (*PC*1, *PC*2, *PC*3 and *PC*4) at the end of their lease terms (Fig. 2 and 3). Let the planning horizon be ten periods, and the Assembly and Ordering Lead Times ($LT$ and $RT$) be one period each (assume that items can be disassembled in the same period they are received). Tables 1 and 2 show a sample of the input data that is required on each product and its components.

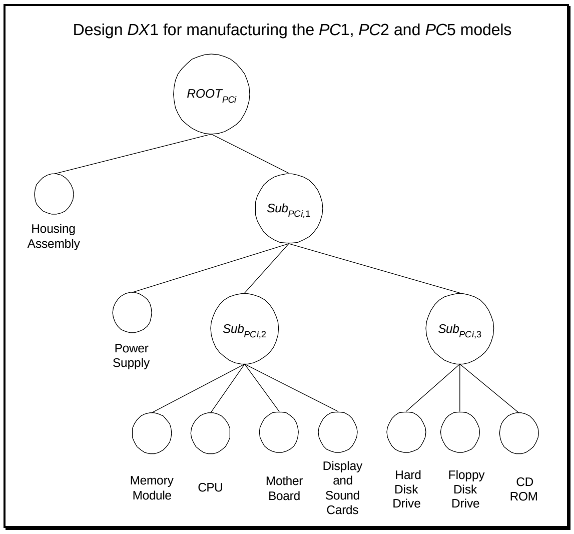


Fig. 2. Product structure for models *PC*1, *PC*2, and *PC*5.

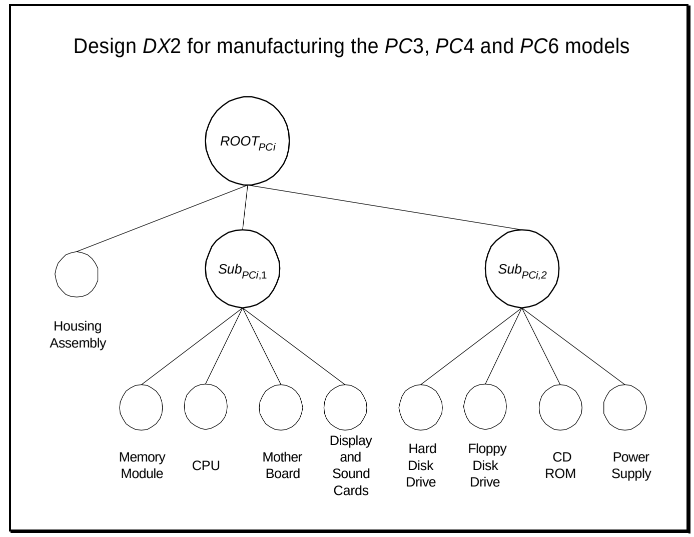


Fig. 3. Product structure for models *PC*3, *PC*4, and *PC*6.

The procedure detailed in the previous section is applied to the case example using all the input data,. The components yield, the result of the optimization in each period, and the partial listing of CRP are shown in Tables 3, 4 and 5. The results for this case example show that the lead times (for assembly and disassembly) have adverse effects on the behavior of the supply chain, causing a certain degree of oversupply and potential shortages (Tables 3 and 4). For example, in the case example, the demand figures have been assumed to include the seasonal effects of consumer demand. Customers tend to order a higher number of computers in periods nine and ten. The results from CRP scheduling show that, with the total lead time of two periods, there are shortages in period 7 of components 9, 13 and 14, and in period 8 of components 9, 13, 14, and 15, even though there is ample supply of products in periods 9 and 10 (Table 5). This suggests that, in the reverse logistics supply chain where customers usually trade-in (or swap) the computers in that same period, manufacturers may not be able to take full advantage of the reusable components retrieved from the traded-in products to fulfill the demand of remanufactured products, if the assembly and disassembly lead times are long.

The design of a product structure may also influence the preference for its disassembly. Notice that *PC*3 and *PC*4 are preferred over *PC*1 and *PC*2. This is partly due to the fact that *PC*3 and *PC*4 require less time to disassemble (and hence less processing costs) than *PC*1 and *PC*2. Another reason is that *PC*3 and *PC*4 are both built with more expensive, more advanced components, which in turn, prove to be more attractive for reclamation. Hence, in the reverse logistics supply chain, products built with components of higher value will make remanufacturing more attractive provided, of course, proper procedures are available for the collection, disassembly and retrieval.

Table 1. Supply and Demand Information.

| Time Period (*t*) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Supply** | | | | | | | | | | |
| ***PC*1** | 75 | 75 | 75 | 50 | 50 | 45 | 45 | 30 | 0 | 0 |
| ***PC*2** | 65 | 70 | 105 | 90 | 90 | 80 | 80 | 75 | 0 | 0 |
| ***PC*3** | 85 | 70 | 100 | 100 | 90 | 85 | 100 | 115 | 0 | 0 |
| ***PC*4** | 85 | 105 | 110 | 145 | 130 | 130 | 150 | 140 | 0 | 0 |
| **Demand** | | | | | | | | | | |
| ***PC*5** | 0 | 0 | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 |
| ***PC*6** | 0 | 0 | 100 | 125 | 125 | 100 | 95 | 125 | 150 | 150 |

Table 2. Component Structure of Computers.

| Component Number ($i$) | Component Name | Multiplicity ($Qij$) Supply PC1 | PC2 | PC3 | PC4 | Demand PC5 | PC6 |
|---|---|---|---|---|---|---|---|
| 1 | Housing Assembly ($PC$1, $PC$2) | 1 | 1 | - | - | - | - |
| 2 | Housing Assembly ($PC$3, $PC$4) | - | - | 1 | 1 | - | - |
| 3 | Memory Module, 16 MB, SDRAM | 2 | - | - | - | - | - |
| 4 | Memory Module, 32 MB, SDRAM | 2 | 4 | 2 | - | 2 | 2 |
| 5 | Memory Module, 64 MB, SDRAM | - | - | 2 | 4 | 2 | 2 |
| 6 | Pentium II 350 MHz CPU and Heat Sink | 1 | - | - | - | - | - |
| 7 | Pentium II 400 MHz CPU and Heat Sink | - | 1 | 1 | - | 1 | - |
| 8 | Pentium II 450 MHz CPU and Heat Sink | - | - | - | 2 | - | 2 |
| 9 | Mother Board ($PC$1, $PC$2, $PC$5) | 1 | 1 | - | - | 1 | - |
| 10 | Mother Board ($PC$3, $PC$4, $PC$6) | - | - | 1 | 1 | - | 1 |
| 11 | Display and Sound Cards ($PC$1 - $PC$4) | 1 | 1 | 1 | 1 | - | - |
| 12 | 4 GB Hard Drive | 1 | - | - | - | - | - |
| 13 | 9.1 GB Hard Drive | - | 1 | 2 | - | 2 | - |
| 14 | 12.6 GB Hard Drive | - | - | - | 2 | - | 2 |
| 15 | 1.44-MB Diskette Drive | 1 | 1 | 1 | 1 | 1 | 1 |
| 16 | 32X CD-ROM Drive ($PC$1 - $PC$4) | 1 | 1 | 1 | 1 | - | - |
| 17 | Pow er Supply ($PC$1 - $PC$4) | 1 | 1 | 1 | 2 | - | - |
| 18 | Housing Assembly ($PC$5) | - | - | - | - | 1 | - |
| 19 | Housing Assembly ($PC$6) | - | - | - | - | - | 1 |
| 20 | Display and Sound Cards ($PC$5, $PC$6) | - | - | - | - | 1 | 1 |
| 21 | DVD-ROM Drive ($PC$5, $PC$6) | - | - | - | - | 1 | 1 |
| 22 | Pow er Supply ($PC$5, $PC$6) | - | - | - | - | 1 | 1 |

Table 3. Components Yield for the Case Example.

| Periods | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Supply of Products** | | | | | | | | | | |
| $PC$ 1 | 75 | 75 | 75 | 50 | 50 | 45 | 45 | 30 | 0 | 0 |
| $PC$ 2 | 65 | 70 | 105 | 90 | 90 | 80 | 80 | 75 | 0 | 0 |
| $PC$ 3 | 85 | 70 | 100 | 100 | 90 | 85 | 100 | 115 | 0 | 0 |
| $PC$ 4 | 85 | 105 | 110 | 145 | 130 | 130 | 150 | 140 | 0 | 0 |
| **Yield of Component $P_i$** | | | | | | | | | | |
| $P_1$ | 140 | 145 | 180 | 140 | 140 | 125 | 125 | 105 | 0 | 0 |
| $P_2$ | 170 | 175 | 210 | 245 | 220 | 215 | 250 | 255 | 0 | 0 |
| $P_3$ | 150 | 150 | 150 | 100 | 100 | 90 | 90 | 60 | 0 | 0 |
| $P_4$ | 580 | 570 | 770 | 660 | 640 | 580 | 610 | 590 | 0 | 0 |
| $P_5$ | 510 | 560 | 640 | 780 | 700 | 690 | 800 | 790 | 0 | 0 |
| $P_6$ | 75 | 75 | 75 | 50 | 50 | 45 | 45 | 30 | 0 | 0 |
| $P_7$ | 150 | 140 | 205 | 190 | 180 | 165 | 180 | 190 | 0 | 0 |
| $P_8$ | 170 | 210 | 220 | 290 | 260 | 260 | 300 | 280 | 0 | 0 |
| $P_9$ | 98 | 101 | 126 | 98 | 98 | 87 | 87 | 73 | 0 | 0 |
| $P_{10}$ | 127 | 131 | 157 | 183 | 165 | 161 | 187 | 191 | 0 | 0 |
| $P_{11}$ | 310 | 320 | 390 | 385 | 360 | 340 | 375 | 360 | 0 | 0 |
| $P_{12}$ | 75 | 75 | 75 | 50 | 50 | 45 | 45 | 30 | 0 | 0 |
| $P_{13}$ | 176 | 157 | 228 | 217 | 202 | 187 | 210 | 228 | 0 | 0 |
| $P_{14}$ | 127 | 157 | 165 | 217 | 195 | 195 | 225 | 210 | 0 | 0 |
| $P_{15}$ | 248 | 256 | 312 | 308 | 288 | 272 | 300 | 288 | 0 | 0 |
| $P_{16}$ | 310 | 320 | 390 | 385 | 360 | 340 | 375 | 360 | 0 | 0 |
| $P_{17}$ | 395 | 425 | 500 | 530 | 490 | 470 | 525 | 500 | 0 | 0 |

Table 4. Result of the Optimization in Each Period.

| **Time Period (*t*)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|---|---|
| **Profit (or Loss)** | ($2,652) | ($1,399) | $127 | $753 | $2,059 | $3,416 | $1,358 | $1,535 |
| **Number of products to order for disassembly (units)** | | | | | | | | |
| ***PC*1** | 73 | 73 | 53 | 40 | 32 | 20 | 45 | 30 |
| ***PC*2** | 65 | 70 | 105 | 90 | 90 | 80 | 80 | 75 |
| ***PC*3** | 62 | 66 | 78 | 96 | 70 | 54 | 100 | 115 |
| ***PC*4** | 75 | 103 | 110 | 134 | 127 | 130 | 150 | 140 |

Table 5. Partial Listing of CRP for the Case Example.

| **Time Period (*t*)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Item *PC* 5** | | | | | | | | | | |
| Gross Requirements (Demand): | 0 | 0 | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 |
| **Item *PC* 6** | | | | | | | | | | |
| Gross Requirements (Demand): | 0 | 0 | 100 | 125 | 125 | 100 | 95 | 125 | 150 | 150 |
| **Item Sub*PC* 5,1** | | | | | | | | | | |
| Gross Requirements: | 0 | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 | 0 |
| **Item Sub*PC* 5,2** | | | | | | | | | | |
| Gross Requirements: | 0 | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 | 0 |
| **Item Sub*PC* 5,3** | | | | | | | | | | |
| Gross Requirements: | 0 | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 | 0 |
| **Item Sub*PC* 6,1** | | | | | | | | | | |
| Gross Requirements: | 0 | 100 | 125 | 125 | 100 | 95 | 125 | 150 | 150 | 0 |
| **Item Sub*PC* 6,2** | | | | | | | | | | |
| Gross Requirements: | 0 | 100 | 125 | 125 | 100 | 95 | 125 | 150 | 150 | 0 |
| **Number of Product PC1 to Disassemble:** | 73 | 73 | 53 | 40 | 32 | 20 | 45 | 30 | 0 | 0 |
| **Number of Product PC2 to Disassemble:** | 65 | 70 | 105 | 90 | 90 | 80 | 80 | 75 | 0 | 0 |
| **Number of Product PC3 to Disassemble:** | 62 | 66 | 78 | 96 | 70 | 54 | 100 | 115 | 0 | 0 |
| **Number of Product PC4 to Disassemble:** | 75 | 103 | 110 | 134 | 127 | 130 | 150 | 140 | 0 | 0 |
| **Item *P*1** | | | | | | | | | | |
| Number of Components Discarded: | 138 | 143 | 158 | 130 | 122 | 100 | 125 | 105 | 0 | 0 |
| **Item *P*2** | | | | | | | | | | |
| Number of Components Discarded: | 137 | 169 | 188 | 230 | 197 | 184 | 250 | 255 | 0 | 0 |
| **Item *P*3** | | | | | | | | | | |
| Number of Components Discarded: | 146 | 146 | 106 | 80 | 64 | 40 | 90 | 60 | 0 | 0 |
| **Item *P*4 (Shelf Life = 1, Quality = 100%)** | | | | | | | | | | |
| Gross Requirements: | 390 | 450 | 470 | 440 | 360 | 390 | 570 | 600 | 0 | 0 |
| Receipts from External Sources: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 140 | 248 | 460 | 632 | 564 | 468 | 508 | 498 | 0 |
| Net Requirement: | 390 | 310 | 222 | 0 | 0 | 0 | 102 | 92 | 0 | 0 |
| On Hand from Disassembly: | 530 | 558 | 682 | 632 | 564 | 468 | 610 | 590 | 0 | 0 |
| Number Used from Disassembly: | 390 | 310 | 222 | 0 | 0 | 0 | 102 | 92 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of Components Discarded: | 0 | 0 | 0 | 20 | 272 | 174 | 0 | 0 | 498 | 0 |
| **Item *P*5 (Shelf Life = 1, Quality = 100%)** | | | | | | | | | | |
| Gross Requirements: | 390 | 450 | 470 | 440 | 360 | 390 | 570 | 600 | 0 | 0 |
| Receipts from External Sources: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 34 | 128 | 254 | 542 | 648 | 628 | 800 | 790 | 0 |
| Net Requirement: | 390 | 416 | 342 | 186 | 0 | 0 | 0 | 0 | 0 | 0 |
| On Hand from Disassembly: | 424 | 544 | 596 | 728 | 648 | 628 | 800 | 790 | 0 | 0 |
| Number Used from Disassembly: | 390 | 416 | 342 | 186 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of Components Discarded: | 0 | 0 | 0 | 0 | 182 | 258 | 58 | 200 | 790 | 0 |
| ...... | | | | | | | | | | |

Table 5. (Continued)

| Time Period (*t*) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| …… | | | | | | | | | | |
| ….. | | | | | | | | | | |
| **Item *P*9 (Shelf Life = 0, Quality = 70%)** | | | | | | | | | | |
| Gross Requirements: | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 | 0 | 0 |
| Receipts from External Sources: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Net Requirement: | 95 | 100 | 110 | 120 | 85 | 70 | 135 | 150 | 0 | 0 |
| On Hand from Disassembly: | 96 | 100 | 110 | 91 | 85 | 70 | 87 | 73 | 0 | 0 |
| Number Used from Disassembly: | 95 | 100 | 110 | 91 | 85 | 70 | 87 | 73 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 0 | 29 | 0 | 0 | 48 | 77 | 0 | 0 |
| Number of Components Discarded: | 43 | 43 | 48 | 39 | 37 | 30 | 38 | 32 | 0 | 0 |
| …… | | | | | | | | | | |
| **Item *P*13 (Shelf Life = 0, Quality = 75%)** | | | | | | | | | | |
| Gross Requirements: | 190 | 200 | 220 | 240 | 170 | 140 | 270 | 300 | 0 | 0 |
| Receipts from External Sources: | 50 | 50 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Net Requirement: | 140 | 150 | 195 | 240 | 170 | 140 | 270 | 300 | 0 | 0 |
| On Hand from Disassembly: | 141 | 151 | 195 | 211 | 172 | 141 | 210 | 228 | 0 | 0 |
| Number Used from Disassembly: | 140 | 150 | 195 | 211 | 170 | 140 | 210 | 228 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 0 | 30 | 0 | 0 | 60 | 72 | 0 | 0 |
| Number of Components Discarded: | 49 | 52 | 66 | 71 | 60 | 48 | 70 | 77 | 0 | 0 |
| **Item *P*14 (Shelf Life = 0, Quality = 75%)** | | | | | | | | | | |
| Gross Requirements: | 200 | 250 | 250 | 200 | 190 | 250 | 300 | 300 | 0 | 0 |
| Receipts from External Sources: | 100 | 100 | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Net Requirement: | 100 | 150 | 200 | 200 | 190 | 250 | 300 | 300 | 0 | 0 |
| On Hand from Disassembly: | 112 | 154 | 165 | 201 | 190 | 195 | 225 | 210 | 0 | 0 |
| Number Used from Disassembly: | 100 | 150 | 165 | 200 | 190 | 195 | 225 | 210 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 35 | 0 | 0 | 55 | 75 | 90 | 0 | 0 |
| Number of Components Discarded: | 50 | 56 | 55 | 68 | 64 | 65 | 75 | 70 | 0 | 0 |
| **Item *P*15 (Shelf Life = 0, Quality = 80%)** | | | | | | | | | | |
| Gross Requirements: | 195 | 225 | 235 | 220 | 180 | 195 | 285 | 300 | 0 | 0 |
| Receipts from External Sources: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Available Balance: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Net Requirement: | 195 | 225 | 235 | 220 | 180 | 195 | 285 | 300 | 0 | 0 |
| On Hand from Disassembly: | 220 | 249 | 276 | 288 | 255 | 227 | 300 | 288 | 0 | 0 |
| Number Used from Disassembly: | 195 | 225 | 235 | 220 | 180 | 195 | 285 | 288 | 0 | 0 |
| Number of New Components Required: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0 | 0 |
| Number of Components Discarded: | 80 | 87 | 111 | 140 | 139 | 89 | 90 | 72 | 0 | 0 |
| …… | | | | | | | | | | |
| **Item *P*22** | | | | | | | | | | |
| Number of New Components Required: | 0 | 195 | 225 | 235 | 220 | 180 | 195 | 285 | 300 | 0 |

## 7. CONCLUSIONS

An optimization-based procedure was applied to solve the supply chain planning problem in the reverse logistics. The objective was to find the most economical combination of products to disassemble (to fulfill the demand for different types of reusable components, while keeping the quantity of partially discarded products in check, and incur the least disposal cost) in each period of the planning horizon. When the problem is solved, it gives the number of each product type to be disassembled in order to fulfill the demand of components needed at minimal disassembly and disposal costs. Hence, from the supply chain perspective, this would result in minimal inventory requirements on both ends—supply of EOL products and disassembled components—of the reverse logistics chain.

Some guidelines for managing reverse logistics are as follows:

- Establish strong processes and infrastructure to set a strong foundation.
- Challenge to manage multiple initiatives across from design, to production, to maintenance, to end-of-lease management, remanufacturing, to disposal.
- Facilitate the collaborative forecasting and planning effort between the functions of part sales, logistics, and the supply/demand coordinator
- Preserve the value by managing the flow through the supply chain, thus reducing the cycle time.
- Provide timely disposition decisions to reduce inventory costs.
- Enable parts auction, sales, and trading exchange through e-marketplace.

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