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A Bi-directional Supply Chain Optimization Model for Reverse Logistics

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Abstract—This paper focuses on Supply Chain Optimization system for reverse logistics. The solution approach employs an adaptation of the Materials Requirements Planning (MRP) technique, termed as Components Requirements Planning, to determine the number of components needed to remanufacture products in each time period throughout the planning horizon.

I. INTRODUCTION

Reverse logistics of end-of-life (EOL) products encompasses many different characteristics of environmentally conscious manufacturing, including disassembly, reuse, recycling, and remanufacturing. Reverse logistics is gaining increased attention not only because of environmental factors but also for economic reasons.

As manufacturers have changed from isolated business units to integrated network partners, they require effective and efficient Supply Chain Management (SCM) strategies for materials, components, and products. SCM can help speed up the reverse logistics through the availability of advanced information technologies like Enterprise Resource Planning (ERP) and World Wide Web (WWW) to support the networking of environmentally conscious product suppliers, manufacturers, distributors and customers. This research focuses on Supply Chain Optimization system for reverse logistics of products that are taken back for disassembly and retrieval of reusable components for remanufacturing. The goal is to provide a way in which manufacturers can reclaim various models of a product for remanufacturing (e.g. computers that have reached their EOL) [1, 2].

Guide *et al.* [3] pointed out that the operational characteristics of remanufacturing are different from their manufacturing counterpart. Hence, SCM for remanufacturing has to consider the reverse logistics as an integrated function of an enterprise [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. This network can be

modeled as a Bi-directional Supply Chain (Fig. 1), where products flow in both directions:

- A *Reverse Supply Chain* represents the products collected from consumers and businesses and returned back to manufacturers, often via distributors. Electronic products in the reverse supply chain may consist of EOL or end-of-lease products, products traded-in, and products returned due to legislative requirements.
- A *Forward Supply Chain* represents the flow of items from the suppliers to the manufacturers to the distributors and finally to the consumers. New components and used products are delivered to the manufacturers, who remanufacture the products before they are distributed to customers at the other end of the supply chain.

One particular constraint on reverse logistics today is the need for disassembly prior to their retrieval, according to their demand. However, when only the components in demand are retrieved, major subassemblies that need proper disposal are left behind in a disassembly facility. Most often the remaining components must be disposed of at a cost: such cost constituting the hidden costs of the process. Hence, our main focus in this paper is on the systematic decision making approach used to determine the aggregate number of a variety of products to disassemble in order to fulfill the demand of a variety of components, and yet have an environmentally benign policy of minimizing waste generation.

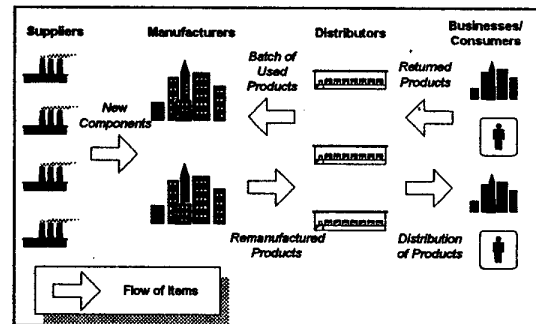


Fig. 1. A Bi-directional Supply Chain Model.

This paper is organized as follows. The next section briefly describes the areas of remanufacturing and planning for disassembly. Section III presents the model formulation. Section IV addresses the Components Requirement Planning (CRP) procedure for the optimization of reverse logistics. Section V illustrates the procedure with a case study. Finally, section VI provides a summary of the paper.

II. BACKGROUND

Remanufacturing is a process of restoring worn-out products to "like-new" conditions, thus providing quality standards of new products with used parts at a considerably reduced cost. The planning and control functions of remanufacturing are significantly more complicated than traditional manufacturing [5]. Because of this, developing analytical models to analyze remanufacturing systems is a challenging task.

One particular requirement in a remanufacturing system is the need for disassembly of 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.

Numerous studies in planning and scheduling have looked at product disassembly in order to fulfill the demand of the components. Gupta and Taleb [6] 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.* [7] and Taleb and Gupta [8] 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.

Recently, some authors have applied mathematical programming in the area of materials and components reclamation. Isaacs and Gupta [9] investigated the impact of automobile design on disposal strategies by using goal programming to solve the problem. Veerakamolmal and Gupta [10] 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.

For a comprehensive review of the literature in the area of environmentally conscious manufacturing and product recovery, see the paper by Gungor and Gupta [11].

III. MODEL FORMULATION

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. The bi-directional SCM model demonstrates the management of demand and supply for the remanufacturing process (Fig. 2). 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 demands. 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.

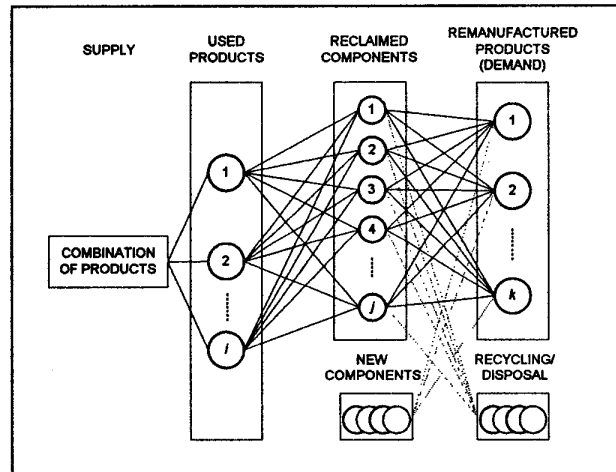


Fig. 2. Supply and Demand of Product/Component.

IV. COMPONENTS REQUIREMENTS PLANNING PROCEDURE

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 components 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;

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

Net Requirement (NR_t): Number of components needed after accounting for Receipts from External Sources and Available Balance in period t ;

$$NR_t = \text{Max}[0, (GR_t - SR_t - AB_t)]$$

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;

$$NU_t = \text{Min}[NR_t, OH_t]$$

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;

$$NC_t = \text{Max}[0, (NR_t - OH_t)]$$

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 ;

$$ND_t = \text{Max}[0, (OH_{t-SL} - NU_{t-SL} - GR_{t-SL+1} - GR_{t-SL+2} - \dots - GR_t)] + \text{Max}[0, (SR_{t-SL} - GR_{t-SL})]$$

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.

Next, we 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. 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).

The following procedure also provides the process planner with a detailed components retrieval plan, which leads to an enhanced CRP performance in the bi-directional supply chain environment. A flowchart of the procedure is presented in Fig. 3. Refer to the mathematical programming formulation in Gupta *et al.* [12].

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), (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 $(NR_t) \leq$ 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 $[(OH_t) = (OH_t) - (QP_{ij}Q_rY_i)]$. 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 $(QP_{ij}Q_rY_i)$; $[(ND_t) = (ND_t) + (QP_{ij}Q_rY_i)]$.

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.

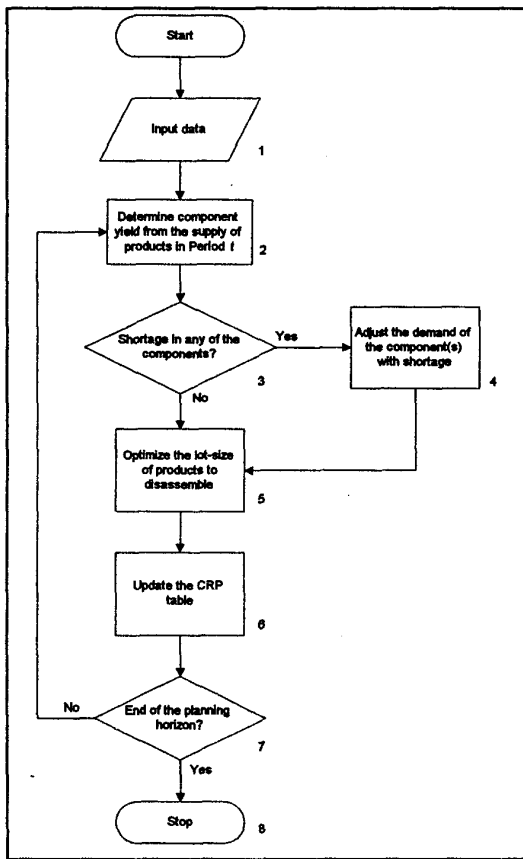


Fig. 3. Flow Chart of the Optimization Procedure.

V. CASE STUDY

The following case study is used to illustrate the application of the supply chain optimization procedure. A computer company remanufactures and distributes two new computer models ($PC5$ and $PC6$), that partially utilize the components from four different computer models ($PC1$, $PC2$, $PC3$ and $PC4$) at the end of their lease terms (Fig. 4 and 5). 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.

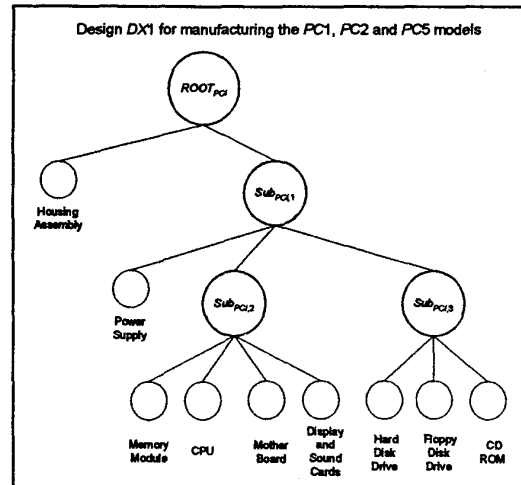


Fig. 4. Product structure for models $PC1$, $PC2$, and $PC5$.

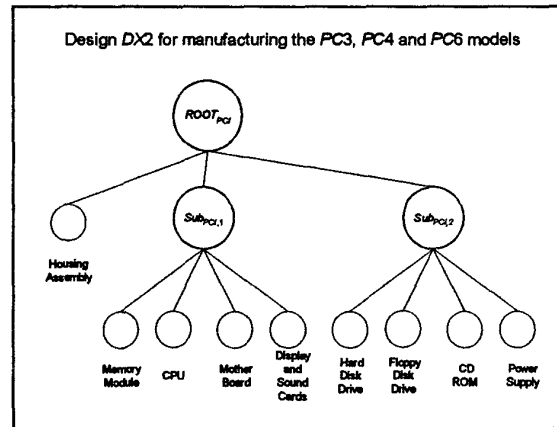


Fig. 5. Product structure for models $PC3$, $PC4$, and $PC6$.

Using all the input data, the procedure detailed in the previous section is applied to the case study. 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 study 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 study, 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).

Table 1. Component Yield Structure of Computers.

Component Number	Component Name	Multiplicity (Of)					
		Supply				Demand	
(i)		PC1	PC2	PC3	PC4	PC5	PC6
1	Housing Assembly (PC1, PC2)	1	1	-	-	-	-
2	Housing Assembly (PC3, PC4)	-	-	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 (PC1, PC2, PC5)	1	1	-	-	1	-
10	Mother Board (PC3, PC4, PC6)	-	-	1	1	-	1
11	Display and Sound Cards (PC1 - PC4)	1	1	1	1	-	-
12	4 GB Hard Drive	1	-	-	-	-	-
13	8.1 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 (PC1 - PC4)	1	1	1	1	-	-
17	Power Supply (PC1 - PC4)	1	1	1	2	-	-
18	Housing Assembly (PC5)	-	-	-	-	1	-
19	Housing Assembly (PC6)	-	-	-	-	-	1
20	Display and Sound Cards (PC5, PC6)	-	-	-	-	1	1
21	DVD-ROM Drive (PC5, PC6)	-	-	-	-	1	1
22	Power Supply (PC5, PC6)	-	-	-	-	1	1

Table 2. Supply and Demand Information.

Time Period (t)	1	2	3	4	5	6	7	8	9	10
Supply										
PC1	75	75	75	50	50	45	45	30	0	0
PC2	65	70	105	90	90	80	80	75	0	0
PC3	85	70	100	100	90	85	100	115	0	0
PC4	85	105	110	145	130	130	150	140	0	0
Demand										
PC5	0	0	85	100	110	120	85	70	135	150
PC6	0	0	100	125	125	100	95	125	150	150

The above insight suggests that, in the bi-directional 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.

Another interesting observation is that the design of a product structure may also influence the preference for its disassembly. Notice that PC3 and PC4 are preferred over PC1 and PC2. This is partly due to the fact that PC3 and PC4 require less time to disassemble (and hence less processing costs) than PC1 and PC2. Another reason is that PC3 and PC4 are both built with more expensive, more advanced components, which in turn, prove to be more attractive for reclamation. Hence, in the bi-directional 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 3. Components Yield for the Case Study.

Periods	1	2	3	4	5	6	7	8	9	10
Supply of Products										
PC1	75	75	75	50	50	45	45	30	0	0
PC2	65	70	105	90	90	80	80	75	0	0
PC3	85	70	100	100	90	85	100	115	0	0
PC4	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	80	0	0
P ₄	560	570	770	660	640	580	610	590	0	0
P ₅	510	580	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	128	98	98	87	87	73	0	0
P ₁₀	127	131	157	183	165	161	187	191	0	0
P ₁₁	310	320	360	365	360	340	375	360	0	0
P ₁₂	75	75	75	50	50	45	45	30	0	0
P ₁₃	178	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	360	365	360	340	375	360	0	0
P ₁₇	365	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)	(\$1,398)	\$127	\$753	\$2,059	\$3,418	\$1,358	\$1,535
Number of products to order for disassembly (units)								
PC1	73	73	53	40	32	20	45	30
PC2	65	70	105	90	90	80	80	75
PC3	62	66	78	96	70	54	100	115
PC4	75	103	110	134	127	130	150	140

VI. SUMMARY

In this paper, an optimization-based procedure is applied to solve the aggregate planning problem in the reverse logistics. The objective is 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.

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

Item Period (t)	1	2	3	4	5	6	7	8	9	10
Item PC 5										
Gross Requirements (Demand):	0	0	96	100	110	120	96	70	136	160
Item PC 6										
Gross Requirements (Demand):	0	0	100	126	126	100	96	126	160	160
Item Sub-PC 51										
Gross Requirements:	0	96	100	110	120	96	70	136	160	0
Item Sub-PC 52										
Gross Requirements:	0	96	100	110	120	96	70	136	160	0
Item Sub-PC 53										
Gross Requirements:	0	96	100	110	120	96	70	136	160	0
Item Sub-PC 54										
Gross Requirements:	0	100	126	126	100	96	126	160	160	0
Item Sub-PC 55										
Gross Requirements:	0	100	126	126	100	96	126	160	160	0
Number of Product PC 1 to Disassemble:	73	72	52	40	32	20	45	30	0	0
Number of Product PC 2 to Disassemble:	95	70	105	90	90	80	80	75	0	0
Number of Product PC 3 to Disassemble:	92	66	78	98	70	54	100	115	0	0
Number of Product PC 4 to Disassemble:	76	103	110	134	127	130	150	140	0	0
Item P 1										
Number of Components Discarded:	138	143	158	130	122	100	126	106	0	0
Item P 2										
Number of Components Discarded:	137	169	188	230	197	184	260	265	0	0
Item P 3										
Number of Components Discarded:	148	148	108	80	84	40	90	60	0	0
Item P 4 (Shell Life = 1, Quality = 100%)										
Gross Requirements:	390	450	470	440	380	390	570	800	0	0
Receipts from External Sources:	0	0	0	0	0	0	0	0	0	0
Available Balance:	0	140	248	480	632	584	488	508	498	0
Net Requirement:	390	310	222	0	0	0	102	92	0	0
On Hand from Disassembly:	530	558	852	832	584	488	610	560	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 (Shell Life = 1, Quality = 100%)										
Gross Requirements:	390	450	470	440	380	390	570	800	0	0
Receipts from External Sources:	0	0	0	0	0	0	0	0	0	0
Available Balance:	0	34	128	254	642	648	828	800	790	0
Net Requirement:	390	416	342	186	0	0	0	0	0	0
On Hand from Disassembly:	424	644	568	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

Item Period (t)	1	2	3	4	5	6	7	8	9	10
Item P 6 (Shell Life = 0, Quality = 70%)										
Gross Requirements:	96	100	110	120	96	70	136	160	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:	96	100	110	120	96	70	136	160	0	0
On Hand from Disassembly:	96	100	110	91	65	70	87	73	0	0
Number Used from Disassembly:	96	100	110	91	65	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 12 (Shell Life = 0, Quality = 70%)										
Gross Requirements:	190	200	220	240	170	140	270	300	0	0
Receipts from External Sources:	60	50	26	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	161	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	49	70	77	0	0
Item P 14 (Shell Life = 0, Quality = 70%)										
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	166	201	190	195	226	210	0	0
Number Used from Disassembly:	100	150	165	200	190	195	226	210	0	0
Number of New Components Required:	0	0	35	0	0	55	75	90	0	0
Number of Components Discarded:	50	58	55	68	64	65	75	70	0	0
Item P 15 (Shell Life = 0, Quality = 60%)										
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	289	256	227	300	289	0	0
Number Used from Disassembly:	195	225	235	220	180	195	285	289	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	80	72	0	0
Item P 22										
Number of New Components Required:	0	186	226	236	220	180	195	285	300	0