Integrate Clustering and Mathematical Programming for Supporting Reverse Logistics Optimization: Methodology and Case Study

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Abstract: The following research documentation focuses on building a network for reverse logistics of products that are taken back for disassembly and retrieval of reusable components for remanufacturing. The goal is to achieve optimization between the costs and the clustering.

Keywords: Disassembly, Clustering Algorithm, Reuse, Recycling, Remanufacturing, Optimization.

1 Introduction

The rapid development of today's technology and appetite for latest models of goods and products by consumers are fuelling the rate at which new products appear every day. This leads to an increase in quantity of used and outdated products for scrapping. The greater part of the scrap comes from automobiles, household appliances, and consumer electronic good and at an increasing rate from computers. The requirements of the consumers determine the quantity of the products thrown away. Except the technical innovations, the different rate of living and the purchasing capacity also influence the problem.

It is required an appropriate algorithm to provide convenient summarisation and consistent grouping of the products thrown away in order they to be transported with less costs and resources and to be remanufactured. Manufacturers have started to realize that they must turn their attention to the development of new methodologies for reverse logistics. These investigations are based not only on economical reasons, but also encompass many different environmental manufacturing problems. The balance between the economical and the environmental factors is also under investigation nowadays.

As manufacturers change from isolated actors 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 to support the networking of environmentally conscious product suppliers, manufacturers, distributors and customers. The goal is to provide a way in which original equipment manufacturers (OEMs) can reclaim various models of a product for remanufacturing. Guide *et al.* [1997] pointed out that the operational characteristics of remanufacturing are different from their manufacturing counterpart [1]. Therefore, SCM for remanufacturing has to consider the reverse logistics as an integrated function of an enterprise [2]. The challenge here is to model the system so that it can facilitate both intra- and inter-enterprise supply chain networks for collecting and remanufacturing EOL products. This network can be modeled as a Bidirectional Supply Chain, 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.
• 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.

This paper presents a reverse supply chain of equipment moving from the consumers through the collecting, sorting, disassembling and recycling. The following sections review the literature in the areas of clustering, planning for disassembly and remanufacturing. Section three describes the stages of reverse supply chain and clustering algorithm forming the network of feeding lines from consumers to the public places for “worn- out” products. Section four presents optimal solution and illustrates an example. Finally, section five provides some conclusions.

2 Literature Review

Some social investigations pointed out that every year one European throws away about fifteen kilograms electrical and electronic equipment. This means that more than six million tones of computers, television sets, refrigerators and other technical devices are being thrown away. This number continues to increase.

A lot of publications and projects have tried to give a decision of this problem. Most publications in this direction reveal different representations of algorithms for data reduction. Applications of clustering embrace many diverse fields (establishing taxonomies; efficient retrieval algorithms in computer and information science; grouping of test subject and of test items in educational research; and so on). The range of algorithms which have been proposed (for most part since the early 1960s with the advent of computing power on a wide scale) has been correspondingly large. Most published work in Cluster Analysis involves the use of either of two classes of clustering algorithm: hierarchical or non- hierarchical algorithms. Hierarchical algorithms have been dominant in the literature. Each of the many clustering methods- and of the many hierarchical methods- which have been proposed over the last two decades has possibly advantageous properties. Many textbooks catalogue these methods. Non- hierarchical routines also have been widely implemented. Closely related to the single linkage hierarchical method is the minimal spanning tree.

Previous work in the product disassembly and recycling can be classified based on of three techniques: disassembly scheduling, disassembly sequence planning and mathematical programming. A novel scheduling algorithm presented by Taleb, Gupta and Brennan addresses the issue of parts and materials commonality when scheduling disassembly [3]. In a disassembly environment, inventory management is complex due to the presence of multiple demand sources at the component level of the product structure. Commonality introduces a new layer of complexity by creating alternative procurement sources for the common component items.

It has been presented an algorithm for scheduling the disassembly of a discrete, well- defined product structure. The principle surrounding disassembly scheduling of a product into components is somewhat similar to material requirements planning (MRP). The algorithm determines the disassembly schedule for the components such that demands for those components are satisfied [4][5].

Disassembly sequence planning deals with sequencing disassembly operations so that system resources are fully used. P. Veerakamolmal and S. Gupta applied planning and sequencing procedures to create an efficient disassembly plan that minimizes processing time, and, thus, disassembly cost [6]. The technique stresses the significance of product structure representation, clustering of component modules, and disassembly sequence. The result is optimal makespan schedule for the disassembly plan.

Recently, some authors have applied mathematical programming to disassembly. Isaacs and Gupta investigated the impact of automobile design on disposal strategies by using goal programming to solve the program. The authors explained the increasing interest of automobile manufacturers in designing light automobiles and their effectiveness on recycling and reuse. Several case studies represented to demonstrate the method [7].

Hoshino et al. used a mathematical model to analyze probability and recycling rates for

recycle- oriented manufacturing system. Goal programming was used to solve the maximum limits of two performance measurers: total profit and recycling rate[8].
For additional literature on disassembly and recycling see Moyer and Gupta and Gungor and Gupta [9][10].

3 Problem Statement

The problem demands finding an optimal way for the "worn- out" products to reach the plants for remanufacturing. Most often this process is divided in two main levels, known at the literature as "feeding line" and "line haul". Figure 1 illustrates visually the problem statement. The first level describes the process the products are moved from the consumers (the first point) to the middle point. The second level is from middle point to the remanufacturing plants (end point).

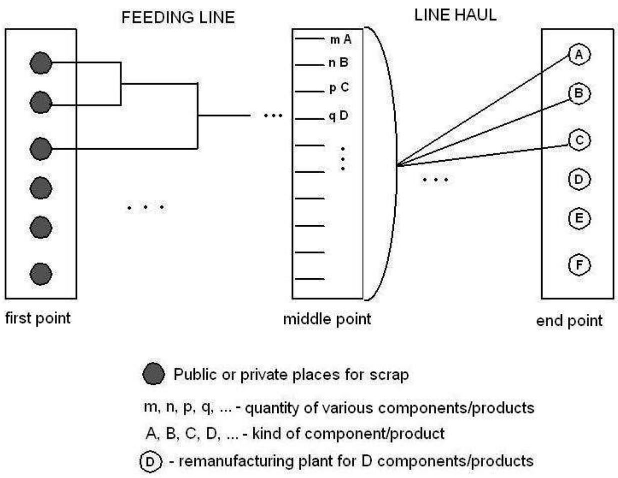

Figure 1:Problem statement

The first point is a group of many public and private places for old technical products and components. The public ones are for households and the private ones are for business companies that also give big part of the "worn-out' products. It could be said that this private and public places in the first point are "almost fixed" because there is not so wide possibility to choose their location. They are located near to the consumers in order to be easy for people to throw products away. The middle point is not fixed. Its location is specified by algorithm that could give the optimal price and time for the transportation of products and components. This situation, that requires an appropriate algorithm to form the transportation network, is illustrated in Figure 2.
The second level of the problem is concerned with the mentioned line haul. It is about determining the number of products to disassemble in a given time period to fulfill the demand of various

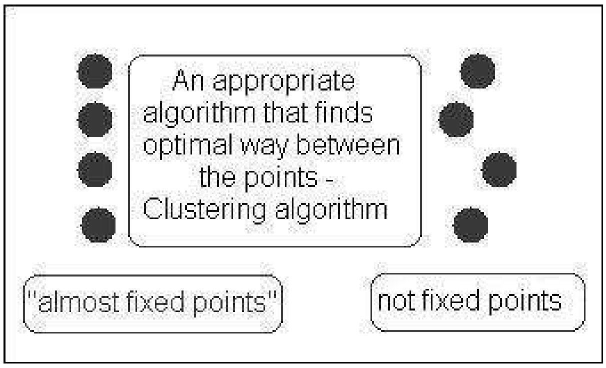

Figure 2: Kind of algorithm required

components during different time periods. This requires a method of determining the timing and the number of products to disassemble to obtain the desired number of components to supply for remanufacturing. In addition, if there is an insufficient number of a product available for disassembly, an order for the components from external sources must be issued to fulfill the designated demand (Figure3).The exact problem statement here is finding a technique to determine the yield of components from a batch of mixed products.

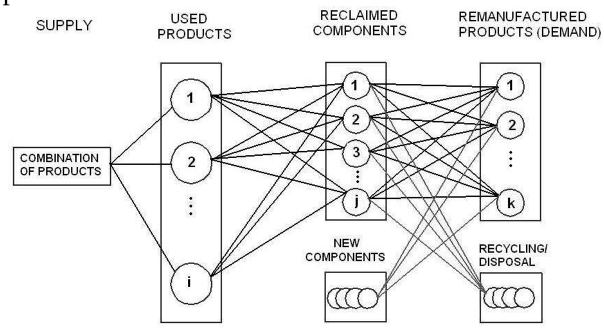

Figure 3:Possible different destinations for a recycled component

4 Main Problem Solution

In this section a sequence for finding an optimal solution for collecting, sorting, disassembling and recycling of products is discussed.
In order the different demands of various components to be fulfilled a batch of different products has to be disassembled. The cost of remanufacturing products with disassembled components may be influenced by additional factors.

4.1 Clustering Algorithm

When the old technical products are thrown away the main problem to be solved is how they to be transported in less cost and to be disassembled in order to fulfill the demand of components. There is an algorithm giving a solution for forming an appropriate transportation network. It is known in the literature as clustering algorithm. The application of its hierarchical version is highly effective and is appropriate when the transportation of stored products has to be improved. Its effectiveness is measured by time and space efficiency and also regards some external factors (such as amount of relevant materials retrieved, variety of products). The degree of clustering also influences the effectiveness of the method: when the percentage of the clustering is higher, the costs are lower, and vise versa.

Since no effectiveness can be reached this way, the method proposes an optimal decision by regarding the clustering and the expenses. The approximate point where the percentage of clustering and the cost meet the optimal solution is shown in figure 4.

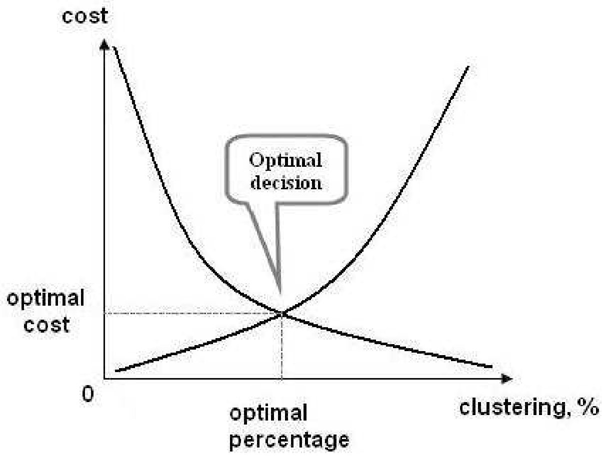

Figure 4:The optimal solution

Another advantage of the hierarchical cluster analysis is that it can be visualized by so called dendrogram.

It provides a resume of many of the proximity and classificatory relationships in a body of data. In other words, when a batch with various products has to be transported and disassembled, a dendrogram clearly illustrates one possible acceptable decision (Figure 5).The algorithm can be easily realized by using implemented software.

4.2 Supply and demand of products/components

The problem formulation considers a set of demand constrains that must be satisfied. Suppose there are *n* different types of products to be disassembled to fulfill the demand of various

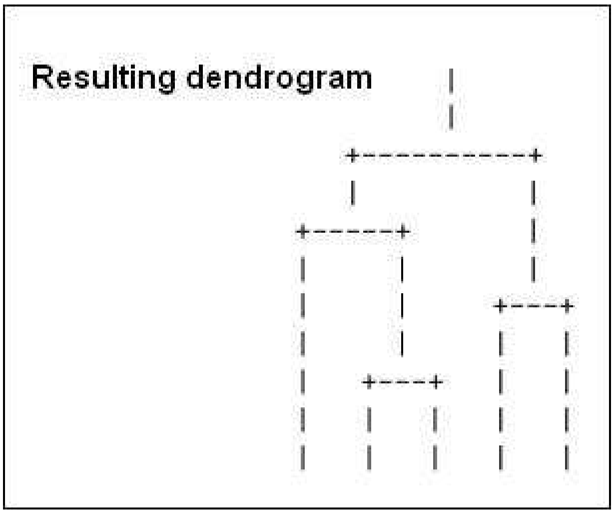

Figure 5:An example of dendrogram

quantities of *m* components (P_1, P_2, ..., P_m). A set of supply constraints is assigned to account for components availability in the products. Components structure differs from one product to another. This means that not all the components are in every product, and there may be multiple components of the same type in a single product. In addition, there is a set of precedence constraints to disassemble a product. The precedence relationship of subassemblies plays an important role in finding the strategy of sequencing components for removal. For example, a sequence to disassemble a product could be {P_1->P_2->P_3}, but the sequence to disassemble another product could be {P_1->P_3->P_2->P_4}. To reach component P_3 in the first product a disassembler must first remove component P_1 and P_2 while in the second product, the disassembler needs just to remove component P_1. The result is that it may take less time (and hence cost less) to retrieve P_3 from the second product than from the first.

Major costs in the system are acquisition, disassembly labor, and disposal. Of the three, disassembly costs are most challenging to calculate. Furthermore, because the disassembly process, considered here is driven by the demand of the components that can be retrieved from more than one type of product, we need to determine the yield of components from a batch of mixed products. To meet these objectives a methodology is presented to determine product disassembly time (both for complete and partial disassembly) and the yield of various components from the products. Finally, to find the most economical combination of products to disassemble, mathematical programming is applied to solve the aggregate- planning problem of fulfilling the demand for different types of components, keep the quantity of partially discarded products in check, and incur the lowest disposal cost.

The model assumes that:

- There is ample supply of products that have been disposed of at the end of their lives.
- There are multiple types of products with common components.
- Component quality is consistent throughout the product line.
- The planning cycle is one period.
- Sequencing of the disassembly process is known (see Veerakamolmal and Gupta for a methodology) [11][12].
- No inventory of components is maintained.
- There are disposal costs for each leftover component.

The analytical solution involves the following nomenclature. These terms are important in order to be made list of equations that are the most important part of the solution. This is the way to reach the optimization model of the problem.

A_{ik}	subassembly node *k* in product *i*;
CF	recycling revenue factor ($/unit of index scale);
CI_j	recycling revenue index of component P_j (index scale 0=lowest, 10=highest);
$CP_i(.)$	common disassembly path of the component list (.) in product *i*;
CRP_j	percentage (fraction) of recyclable contents by weight in component P_j;
D_j	Vector representing the total demand for component P_j (unit);
DF	disposal cost factor ($/unit of index scale);
DI_j	disposal cost index of component;
$DP_i(P_j)$	disassembly path of component P_j from the root node of product *i*;
DW_j	weight of component P_j (lb.);
I_i	row vector of *i* one's;
I_{ii}	identity matrix of rank *i*;
$LS(A_{ik})$	leaf successor set of subassembly node *k* in product *i*;
$LS^s(A_{ik})$	set of selected leaf successor of subassembly node *k* in product *i*;
$LS(Root_i)$	leaf successor set of the root node in product *i*;
$LS^s(Root_i)$	set of selected leaf successor of the root node in product *i*;
m	total number of components in the problem space;
MS	process makespan (time for the disassembly and retrieval of the components from the products) (unit time);
n	total number of products in the problem space;
P_j	component *j*;
PC	processing (e.g. disassembling, sorting, cleaning, identification and packaging) cost per unit time ($/unit of index scale);
Q_{ij}	multiplicity matrix representing the number of each type of component P_j obtained from each type of product *i*;
QP_{ij}	quality control variable representing the percentage (fraction) of component P_j*s* obtained from each type of product *i* that are not damaged;
$Root_i$	root node of the product *i*;
RV_j	Resale value of component *j* ($/unit);
s_i	total number of subassembly nodes in product *i*;
S_i	Vector representing the supply of product *i* from all sources;
SL	shelf life;
Sub_{ik}	subassembly node *k* of product *i*;
$T(Root_i)$	time to disassemble root node of the product of the product *i* (unit time);
$T(A_{ik})$	time to disassemble subassembly *k* from product *i* (unit time);
TC_i	cost of acquisition and transportation for product *i* ($/unit);
TD_i	total disassembly time for every component in product *i* (unit/unit);
TD_i^s	total disassembly time for a set of selected components in product *i* (unit/time);
TCR	total recycling time revenue ($);
TDC	total disposal cost ($);
TPC	total processing cost ($);
TRR	total resale revenue ($);
W_{ij}	matrix representing the number of units of component P_j obtained from product *i* that

	may require recycling and/or disposal;
W_j	vector representing the total number of units of component P_j that may require recycling and/or disposal;
Xij	matrix representing the number of units of component P_j retrieved from product *i* used to fulfill the total demand for components;
Y_i	vector representing the number of each of product *i* in the batch to be disassembled;
Y_{ij}	matrix representing the total yield of the number of component P_j retrieved from product *i*;
Z	Integer Programming (optimal) objective value;
$\lceil \alpha \rceil$	the smallest integer that is larger than or equal to a;
$\{\beta_{ij}\}$	element in row *i* and column *j* of matrix β_{ij};
$\{\gamma_i\}$	The i^{th} element in vector γ_i;

Table 1:Used nomenclature

4.3 The Optimization Model

As mentioned above, in this section is presented an optimization model o find a batch consisting of different products to disassemble in order to fulfill the demand of various components.

There are additional cost factors that may influence the cost of remanufacturing products with disassembled components. Such factors include the percentage of good quality components, the component's shelf life, and the actual demand for each component. Once disassembled, broken (or sub- standard) components are immediately tagged for recycling/ disposal. They must be recycled for their useful material contents and any residual must be properly disposed of.

A component is said to have a positive demand attribute if it can be used for remanufacturing. On the other hand, the demand would be zero for a component which may be outdated and, thus, cannot be used for remanufacturing. Following disassembly, quality components are sent to remanufacturing. Those with shelf lives (SL) of one or more period(s) can be stored in the remanufacturer's inventory for use in the subsequent period(s).

4.3.1 The Objective Function

The objective function consists of four major terms, viz., total resale revenue (TRR), total recycling revenue (TCR), total processing cost (TPC), and total disposal cost (TDC) as follows (1):

$$\text{Maximize } Z = TRR + TCR \;\; TPC \;\; TDC \quad (1)$$

Each term is described below.

Total Resale Revenue

TRR is directly influenced by RV_j and TC_i. RV_j is the resale value of component P_j, and TC_i is the cost per unit of acquiring and transporting product i from the distribution centers (or collection sources) to the disassembly subsystem. The revenue equation represents revenue less the total cost of product acquisition, which can be formulated as shown in (2):

:

$$TRR = \sum_i \left[\sum_{\substack{j \exists D_j > 0 \\ and \\ P_j \in LS^s(Root_i)}} (RV_j.\{X_{ij}\}) + \sum_{\substack{j \exists (D_j > 0 \, and \, (SL > 0) \\ and \\ P_j \in LS^s(Root_i)}} (RV_j.\{W_{ij}\}) \right] - \sum_i (TC_i.\{Y_i\}) \quad (2)$$

$$TCR = CF. \left[\sum_i \sum_{\substack{j \exists Df > 0 \\ andSL = 0 \\ and \\ Pj \in LSs(Rooti)}} (CI_j.DW_j.CRP_j \cdot \{W_{ij}\}) + \sum_i \sum_{\substack{j \in Dj = 0 \\ and \\ Pj \in LSs(Rooti)}} (CI_j.DW_j.CRP_j.\{(Y_i.I_{ii}).Q_{ij}\}) + \right.$$

$$+\sum_{i}\sum_{\substack{j\exists Dj>0\,and\,(QPj<100\%)\\ and\\ Pj\in LSs(Rooti)}}((1-QP_{ij}).CI_j.DW_j.CRP_j.\{(Y_i.I_{ii}).Q_{ij}\})\Bigg] \quad (3)$$

Total Recycling Revenue

TCR is calculated by multiplying the component recycling revenue factors by the number of component units recycled for materials as shown in (3).

Note that each component has a percentage of recyclable contents (CRP_j) (the portion not recycled must be properly disposed of). CI_j is the recycling revenue index (varying in value from 1 to 10) representing the degree of benefit generated by the recycling of component P_j (the higher the value of index, the more profitable it is to recycle the component), DW_j is the weight of the component, QP_{ij} is the quality control percentage, and CF is the recycling revenue factor.

Total Processing Cost

TPC can be calculated from the process makespan (MS) and the processing cost per unit time (PC) as follows:

$$\mathrm{TPC} = \mathrm{PC.MS} \quad (4)$$

Where MS can be calculated by:

$$MS = \sum_i TD_i^s \quad (5)$$

And in turn, TD_i^s can be obtained as shown in (14) [Veerakamolmal and Gupta, 1998]:

Total Disposal Cost

TDC is calculated by multiplying the component disposal cost by the number of component units disposed as shown in (15): Note that DI_j is the disposal cost index (varying form 1 to 10) representing the degree of nuisance created by the disposal component P_j (the higher the value of index, the more nuisance the component creates and hence it costs more to dispose it of), DW_j is the weight of the component, QP_j is the quality control percentage, and DF is the disposal cost factor. It should be remarked here that W_{ij} can be writes as:

$$W_{ij} = Y_{ij} - X_{ij} \quad (6)$$

Further, if the demand of component P_j is zero, then X_{ij} will be zero and W_{ij} can be written as

$$W_{ij} = (Y_i.I_{ii}).Q_{ij} \quad (7)$$

The Constraints

The following set of constraints needs to be considered:

- Supply/Demand Constraints

The number of products in the batch to be disassembled (to fulfill the demand of components) must not exceed the number of available products collected from all sources. Thus,

$\{Y_i\} \le \{S_i\}$ for all i. (8)

- Product Structure Constraints

For the integrity of the product, the following must be true:

$\{X_{ij}\} + \{W_{ij}\} = QP_{ij}.\{(Y_i.I_{ii}).Q_{ij}\}$ for all i and all (9)

$j\exists D_j > 0$ and $P_j \in LS^s(Root_i)$ (10)

- Component Demand Fulfillment Constraints

The demand of every type of component must be met. Thus,

$\{I_i.X_{ij}\} = \{D_j\}$ for all i and for all (11)

$j\exists D_j > 0$ and $P_j \in LS^s(Root_i)$ (12)

- Integer and Non-negativity Constraints

The supply of products, the demand of components, and the components recycled and/or disposed of must be non-negative integer values. Thus,

$\{Y_i\},\{X_{ij}\},\{W_{ij}\} = 0$ and Integer (13)

for all i and all $j\exists D_j > 0$

:

$$TD_i^s = \left(\underset{\forall P_j\in LS^s(Root_i)}{Max}\left\lceil\frac{\{X_{ij}\}}{\{Q_{ij}\}}\right\rceil\right)\left(T(Root_i)\right) + \sum_{k=1}^{s_i}\left\{\left(\underset{\forall P_j\in LS^s(A_{ik})}{Max}\left\lceil\frac{\{X_{ij}\}}{\{Q_{ij}\}}\right\rceil\right)\left(T(A_{ik})\right)\right\} \quad (14)$$

$$TDC = DF.\left[\sum_{i}\sum_{\substack{j\exists D_j>0\\ andSL=0\\ and\\ P_j\in LS^s(Root_i)}} DI_j.DW_j.(1-CPR_j).\{W_{ij}\}) + \sum_{i}\sum_{\substack{j\exists D_j>o\\ and\\ P_j\in LS^s(Root_i)}} DI_j.DW_j.(1-CRP_j).\{Y_i.I_{ii}).Q_{ij}\}) + \right.$$

$$\left. + \sum_{i}\sum_{\substack{j\in(D_j>0)and(QP_j<100\%)\\ and\\ P_j\in LS^s(Root_i)}} ((1-QP_{ij}).DI_j.DW_j.(1-CRP_j).\{(Y_i.I_{ii}).Q_{ij}\})\right] \quad (15)$$

5 Conclusion

In this paper is presented the reverse logistical supply chain model to solve the problem of products remanufacturing. A mathematical programming based model was applied to solve the problem. The objective was to find the most economical combination of products to disassemble, to fulfill the demand for different types of components, while keeping the quantity of partially discarded products in check, and incur the least disposal cost.

References

[1] Guide, V. D. R., Jr., Srivastava, R. and Spencer, M. S., 1997, “An Evaluation of capacity Planning Techniques in a Remanufacturing Environment”, *International Journal of Production Research,* Vol.35(1), 67-82.

[2] Bloomhof –Ruwaard, J. M., Beek, P. van, Hordijk, L. and Wassenhove, L. N. Van, 1995, “Interactions Between Operational Research and Environmental Management”, *European Journal of Operational Research,* Vol. 85, 229-243.

[3] Taleb, K., Gupta, S. M., and Brennan, L., Disassembly of complex products with parts and materials commonality, *Prod. Plan. Con.,* 8(3), 255-269, 1997.

[4] Gupta, S. M. and Taleb, K., Scheduling disassembly, *Int. J. Prod. Res.,* 32(8), 1857-1886, 1994.

[5] Taleb, K. and Gupta, S. M., Disassembly of multiple product structures, *Comp. Ind. Eng.,* 32(4), 949-961, 1997.

[6] Veerakamolmal, P. and Gupta, S. M., Disassembly process planning, *Engineering Design and Automation,* (in press), 1998.

[7] Isaacs, J. A. and Gupta, S. M., A decision tool to assess the impact of automobile design on disposal strategies, *J. Ind. Ecol.,* I(4), 19-33, 1997.

[8] Hoshino, T., Yura, K., and Hitomi, K., Optimization analysis for recycle-oriented manufacturing, *Int. J. Prod. Res.,* 33(8), 2069-2078, 1995.

[9] Moyer, L. and Gupta, S. M., Environmental concerns and recycling/disassembly effects in the electronic industry, *J. Elec. Manuf.,* 7(1), 1-22, 1997.

[10] Gungor, A. and Gupta, S. M., Issues in environmentally conscious manufacturing and product recovery: A survey, *Comp. Ind. Eng.* (accepted), 1999.

[11] Veerakamolmal, P. and Gupta, S. M., Optimal Analysis of Lot- Size Balancing for Multiproducts Selective Disassembly, *International Journal of Flexible Automation and Integrated Manufacturing,* 6(3&4), 1998, 245- 269

[12] Gupta, S. M., Joon Lee, Y., Xanthopulos, Z., Veerakamolmal P., An Optimization Approach or A Reverse Logistics Supply Chain