PRODUCT RECOVERY PLANNING FOR REMANUFACTURING UNDER UNCERTAINTY

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ABSTRACT

Product recovery and remanufacturing often requires refitting an existing forward distribution network with additional capabilities to provide such reverse logistics functions as collection, disassembly, remanufacturing, and disposal. The resulting network structure forms a link between two markets, namely a "supply market" from which used products are collected and a "demand market" in which remanufactured products are sold. Both markets coincide to form closed-loop flows of used and remanufactured products thus giving rise to the coordination issue of mismatch between supply and demand in terms of timing and quantity. This paper proposes a stochastic mixed integer programming model that takes into consideration the supply and demand uncertainties in a multi-period planning horizon and simultaneously solves for the location and capacity of the disassembly and remanufacturing facilities, the production, shipment and stocking of the optimal quantities of remanufactured products and cores.

INTRODUCTION

Because of environmental, legal, social, and economic factors, product recovery and remanufacturing is gaining increasing popularity among society, government, and industry worldwide. A number of governmental legislations are forcing producers to take care of their End of Life (EOL) products. For instance, the Waste Electrical and Electronic Equipment (WEEE) directive (directive 2002/96/EC), which contains mandatory requirements on collection, recycling, and recovery for all types of electrical goods with a minimum rate of 4 kilograms per head of population per annum became European law in 2003 (Georgiadis and Besiou, 2010). WEEE-like legislation was also introduced in Canada, Japan, China, and many states in the U.S. (Quariguasi Frota Neto et al. 2007). Until recently much of the remanufacturing was driven by cost cutting considerations and limited to low-volume high-value items. For example, the reuse of parts and materials obtained from high-value, end-of-lease copiers, reportedly saves the Xerox Corporation 40% to 65 % in manufacturing cost (Ginsburg 2001). However many companies, attempting to combine good business sense with environmental sustainability, are now increasingly remanufacturing high-volume low-value items such as single-use cameras, mobile phones, ink-jet printers, and cartridges (Guide et al 2003). For instance, Eastman Kodak Company reuses on average 76% of the weight of a disposed camera in the production of a new one (Savaskan et al 2004).

Remanufactured products are generally upgraded to the quality standards of new products so that they can be sold as new products. The production and distribution systems which combine product recovery and remanufacturing are referred to as closed-loop supply chains. Closed-loop supply chains differ from traditional supply chains in many aspects. In a traditional supply chain the product is moved forward, and the customer is typically at the end of the chain. However, a closed-loop supply chain includes not only the forward processes, but also the reverse activities of product return and recovery. These activities include: acquisition of used products from end-users and their transportation to disassembly sites, recovery and storage of reusable units, disposition of non-reusable units, and remanufacturing of reusable units.

Closed-loop networks link together two distinct markets, namely a "disposer market" from which used products are collected, and a "reuse market" in which demand for remanufactured product exists. The intercession role that closed-loop networks play between these two heterogeneous markets gives rise to the issue of coordination between supply and demand in a recovery operation. Availability of used products for recovery is less predictable than supply of new input materials in a traditional supply chain. Therefore, mismatch between supply and demand with respect to quantity and timing is more prevalent in closed-loop than in traditional supply chains (Fleischmann et al 2001).

Another major characteristic of recovery networks is the level of uncertainty about the quality of used products. In general, used product quality is not known beforehand and can, depending on the condition of the individual product, be subject to considerable variability. As a result, disassembly inspection and testing activities play an important role in transitioning the product from the disposer to the reuse market. The quantity of used products that may be reused, and the quantity to be disposed of, and hence the magnitude and destination of the various reverse flows can only be determined after disassembly and testing.

Moreover, even if technically feasible, a recovery operation may not be economically attractive. Since total recovery costs (collection, disassembly, processing, and transportation) depend to a large extent on the structure of the logistics network (the relative location and size of disassembly centers to plants, collection points and disposal sites, and on the relative location and size of plants to markets, then optimal design of the closed-loop network becomes critical to the economic viability of the recovery operation. For a recovery operation to function effectively, the issues of: (1) mismatches between supply and demand, (2) quality uncertainty, and (3) network structure need to be taken into account when formulating closed-loop logistics models.

The objective of the paper is to formulate a multi-period cost-minimization integrated network design and recovery planning model that provides unambiguous answers to such questions as: (1) Which plants and which disassembly centers should be opened and operated during the planning horizon? (2) Which plants should service which market's product demand, in what quantity, and in which period? (3) How many units of used products are to be collected from each customer zone and shipped to each disassembly center in every period? (4) How many reusable units should each disassembly center ship to each plant in every time period? (5) How many reusable units should be held in inventory at each disassembly center in every period? (6) In which disposal site and in what quantity should non-reusable units be disposed of in every time period?

MODEL DEVELOPMENT

The proposed network design and recovery planning model follows the closed loop network structure shown in Fig. 1. We consider four types of facilities, namely plants where remanufacturing of the reusable units takes place, disassembly centers where the inspection and disassembly function of the used units is carried out, disposal sites where non-reusable units are disposed of, and customer zones in which remanufactured units are sold and from which used units are collected. Moreover, two outcomes are possible for the collected used units: recovery and disposal. Only a given fraction of the used units processed in the disassembly centers is deemed recoverable and therefore reusable during remanufacturing, the remaining units are considered non-reusable and thus disposable. We also consider two types of flows: forward and reverse flows. Forward flows represent shipments of remanufactured units from plants to customer zones. The reverse flows represent: (1) transportation of used units from customer zones to disassembly centers, (2) shipments of reusable units from disassembly centers to plants, and (3) transportation of non-reusable units from disassembly centers to disposal sites.

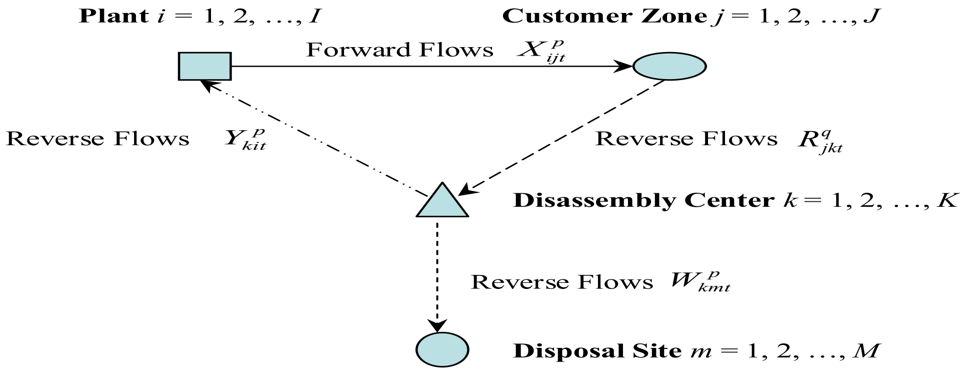

Fig. 1 Closed-Loop Network

The following assumptions are postulated: (1) The supply chain facilities (plants, customer zones, disassembly centers, and disposal sites), already exist. (2) Demand for remanufactured products and supply of used products at customer zones are subject to uncertainties described by a given set of scenarios. (3) Plant production capacities, customer zone collection capacities, and disassembly center capacities are known. (4) A given product recovery ratio determines the number of reusable units resulting from the disassembly and inspection of a certain number of used units. This ratio is common to all used units regardless of the disassembly center they are processed in and the customer zone they are collected from. (5) Inventory of reusable units is held at the disassembly centers. (6) A minimum proportion of the reusable units recovered within a given disassembly center in a time period must be shipped out of that center in that period. This minimum quantity is a management policy designed to achieve an adequate inventory turnover at each center and thereby reduce obsolescence of the reusable unit inventory in the supply chain. (7) Disposal sites have unlimited capacities.

Primary Sets and indices

I = Set of plants in which the product may be remanufactured, $i \in I$;
K = Set of disassembly centers in which returns may be processed, $k \in K$;
J = Set of customer or demand points, $j \in J$;
M = Set of disposal sites, $m \in M$;
T = Set of time periods, $t \in T$;
P = Set of demand of scenarios, $p \in P$;
Q = Set of product return scenarios, $q \in Q$;
R = Set of product recovery scenarios, $r \in R$;

Supply/Demand Parameters

Demand uncertainty is represented by a set of p scenarios, associated with a probability π^{p}. Likewise, used product return uncertainty is represented by a set of q scenarios, along with their corresponding probability π^q. Uncertainty surrounding used product quality is, in a similar manner, represented by a set of r scenarios, along with their respective probability π^r. Also, let π^{pq} define the joint probability of the concurrent occurrence of demand scenario p and return scenario q. These probabilities will generally satisfy the conditions that $\sum_{p\in P}\pi^p = \sum_{q\in Q}\pi^q = \sum_{r\in R}\pi^r = \sum_{p\in P}\sum_{q\in Q}\pi^{pq} = 1$. Furthermore let

$D_{jt}^p =$ Customer zone j demand under scenario p during time period t;

$d_{jt}^q =$ Customer zone j used product return under scenario q during period t;

$S_i =$ Plant i production capacity per period;

$S_j =$ Customer zone j used product collection/storage capacity per period;

$S_k =$ Center k disassembly capacity per period;

$m_k =$ Minimum shipment quantity requirement out of an open center k to plants per period; this quantity may be construed as the center's break-even shipment quantity over the given planning horizon;

$\theta_k =$ Center k inventory storage capacity;

$\lambda^r =$ Product recovery ratio during disassembly under scenario r;

Cost Parameters

$f_i =$ Fixed cost for opening and operating plant i;

$f_k =$ Fixed cost for opening and operating center k;

$c_{ki} =$ Per unit remanufacturing cost at plant i using materials sourced from processing center k; this cost comprises unit production cost at plant i, plus unit transportation cost from center k to plant i.

$c_{jk} =$ Per unit disassembly cost at center k of a used product collected at demand point j; this cost includes unit collection cost at point j, transportation cost per unit from j to k, and disassembly cost of a unit at k.

$c_{km} =$ Per unit disposal cost at site m of a non-recoverable unit processed at center k. This cost includes disposal cost of a unit at disposal site m plus unit transportation cost from k to m;

$h_k =$ Per unit per period inventory holding cost of a disassembled unit in inventory at center k;

$p_j =$ Unit penalty cost for not collecting returns of customer zone j;

$g_j =$ Unit penalty cost of not serving demand of customer zone j. g_j could be quantified by taking the relative importance of different markets into account; alternatively it could be related to the cost of meeting demand by resorting to external suppliers.

$t_{ij} =$ Unit transportation cost of a product from plant i to customer zone j;

Decision Variables

$X_{ijt}^p =$ Forward flow: units shipped from plant i to customer zone j under demand scenario p in period t;

$R_{jkt}^q =$ Reverse flow: units of used product shipped from customer zone j and to center k under return scenario q in period t;

$Y_{kit}^p =$ Units of cores shipped from center k to plant i under demand scenario p in period t. This flow reflects, by the same token, the number of units produced in plant i out of cores sourced from center k to respond to demand scenario p in period t;

W^q_{kmt} = Units shipped from disassembly center k to disposal site m under return scenario q in period t;

B^p_{jt} = Units of unsatisfied demand at customer zone j under scenario p in period t;

I^{pq}_{kt} = Disassembled units held in inventory at center k at the end of period t under demand scenario p and return scenario q;

U^q_{jt} = Uncollected used units at customer zone j under scenario q at the end of period t;

$$Z_i = \begin{cases} 1, \text{ if product is produced in plant } i; \\ 0, \text{ otherwise.} \end{cases} \qquad V_k = \begin{cases} 1, \text{ if used product is disassembled in center } k; \\ 0, \text{ otherwise.} \end{cases}$$

Constraints

$$\sum_{j\in J} X^p_{ijt} \le S_i Z_i, \qquad i\in I,\ p\in P,\ t\in T; \tag{2}$$

Constraints (2) specify that the total flow out of plant *i*, and thereby the total number of units produced at plant *i*, during period *t* must be less than or equal to that plant production capacity if the product is produced in such a plant; and must be equal to zero otherwise.

$$\sum_{i\in I} X^p_{ijt} + B^p_{jt} = D^p_{jt}, \qquad j\in J,\ p\in P, t\in T; \tag{3}$$

Constraints (3) ensure product flow balance between forward product flows into demand point *j*, and demand requirement for demand point *j* at time period *t*, and account for the possibility of unsatisfied demand at that demand point. Unsatisfied demand occurs when not enough returned cores are collected or when product demand is greater than production and/or disassembly capacities.

$$\sum_{k\in K} Y^p_{kit} = \sum_{j\in J} X^p_{ijt}, \qquad i\in I,\ p\in P, t\in T; \tag{4}$$

Equation (4) is a material balance constraint ensuring that the sum of the quantities going into a plant *i* (or reverse flow) equals the sum of the quantities coming out of that plant (or forward flow) in every time period.

$$I^{pq}_{k,t-1} + \sum_{r\in R}\sum_{j\in J} \pi^r \lambda^r R^q_{jkt} = \sum_{i\in I} Y^p_{kit} + I^{pq}_{kt}, \qquad k\in K,\ p\in P, q\in Q, t\in T; \tag{5}$$

Constraints (5) ensure product flow balance between inventory, recovery, and shipment of disassembled units at disassembly center *k* in time period *t*. Inventory, determined in this case on the basis of the expected number of recovered parts taken over all possible recovery scenarios, may be carried to provide better customer service or to satisfy forecasted demand that exceed production capacities in future time periods.

$$I^{pq}_{kt} \le \theta_k V_k, \qquad k\in K,\ p\in P, q\in Q, t\in T; \tag{6}$$

Constraints (6) specify that the total number of disassembled units stored in inventory at center *k* in period *t* cannot be larger than the inventory storage capacity of that center.

$$\sum_{k\in K} R^q_{jkt} + U^q_{jt} = d^q_{jt}, \qquad j\in J,\ q\in Q, t\in T; \tag{7}$$

Constraints (7) ensure product flow balance between collection of returns, and forecasted returns at demand point *j* in time period *t*, and by the same token accounts for any uncollected returns at that demand point and time period.

$$\sum_{k\in K} R^q_{jkt} \le S_j, \qquad j\in J,\ q\in Q,\ t\in T; \tag{8}$$

Constraints (8) require that the total number of units collected at demand point *j* in time period *t* to be less than the specified collection/storage capacity of that demand point.

$$\sum_{j\in J} R^q_{jkt} \le S_k V_k, \qquad k\in K,\ q\in Q,\ t\in T; \tag{9}$$

Equation (9) requires the total flow into center *k*, and thereby the total number of units processed at such a center, during period *t* to be less than or equal to that center processing capacity if returns are disassembled in such a center; and must be equal to zero otherwise. Used units collected from customer zones are assumed to be processed within the same time period in which they are collected.

$$\sum_{i\in I} Y^p_{kit} \ge m_k V_k, \qquad k\in K,\ p\in P,\ t\in T; \tag{10}$$

Constraints (10) require that the total flow out of any open center *k* in period *t* meets the minimum output requirement for that center.

$$\sum_{m\in M} W^q_{kmt} = \sum_{r\in R}\sum_{j\in J} \pi^r (1-\lambda^r) R^q_{jkt}, \qquad k\in K,\ q\in Q,\ t\in T; \tag{11}$$

Constraints (11) specify the number of non-recoverable units transported from disassembly center *k* to disposal sites.

Objective Function

$$\begin{aligned}\text{Min } & \sum_{i\in I} f_i Z_i + \sum_{k\in K} f_k V_k + \sum_{t\in T}\Big[\sum_{p\in P}\pi^p\Big(\sum_{i\in I}\sum_{k\in K} c_{ki} Y^p_{kit} + \sum_{j\in J} g_j B^p_{jt} + \sum_{i\in I}\sum_{j\in J} t_{ij} X^p_{ijt}\Big) + \\ & \sum_{q\in Q}\pi^q\Big(\sum_{j\in J} p_j U^q_{jt} + \sum_{j\in J}\sum_{k\in K} c_{jk} R^q_{jkt} + \sum_{k\in K}\sum_{m\in M} c_{km} W^q_{kmt}\Big) + \sum_{p\in P}\sum_{q\in Q}\pi^{pq}\Big(\sum_{k\in K} h_k I^{pq}_{kt}\Big)\Big] \end{aligned} \tag{1}$$

Objective function (1) minimizes the *expected value* of the total multi-period cost of production, collection, disassembly, disposal, inventory, and transportation of the network taken over all the given scenarios. The components of the objective function may be described as follows:

Fixed costs at plants and disassembly centers over the entire planning horizon = $\sum_{i\in I} f_i Z_i + \sum_{k\in K} f_k V_k$.

Multi-period variable production cost at the plants = $\sum_{p\in P}\pi^p\big(\sum_{t\in T}\sum_{i\in I}\sum_{k\in K} c_{ki} Y^p_{kit}\big)$.

Inventory costs at processing centers = $\sum_{p\in P}\sum_{q\in Q}\pi^{pq}\big(\sum_{t\in T}\sum_{k\in K} h_k I^{pq}_{kt}\big)$.

Penalty cost of unsatisfied demand at customer zones = $\sum_{p\in P}\pi^p\big(\sum_{t\in T}\sum_{j\in J} g_j B^p_{jt}\big)$.

Penalty cost of uncollected returns at customer zones = $\sum_{q\in Q}\pi^q\big(\sum_{t\in T}\sum_{j\in J} p_j U^q_{jt}\big)$.

Collection, transportation, and processing costs of used units = $\sum_{q\in Q}\pi^q\big(\sum_{t\in T}\sum_{j\in J}\sum_{k\in K} c_{jk} R^q_{jkt}\big)$.

Disposal and transportation costs of non-recyclable units = $\sum_{q\in Q}\pi^q\big(\sum_{t\in T}\sum_{k\in K}\sum_{m\in M} c_{km} W^q_{kmt}\big)$.

Transportation cost from plants to customer zones = $\sum_{p\in P}\pi^p\big(\sum_{t\in T}\sum_{i\in I}\sum_{j\in J} t_{ij} X^p_{ijt}\big)$.

Conclusion

Product collection, recovery, remanufacturing, transportation and distribution are complicated decisions subject to logistical constraints as well as demand uncertainty for remanufactured products and supply and quality uncertainty of the used products. Under such environments, the proposed stochastic mixed integer model determine the optimal design of the recovery network, and specify the optimal supply chain flows along with the optimal levels of unsatisfied demand and non-collection of used units over a multi-period planning horizon in such a way to minimize the total cost of the recovery operation.