PRODUCT REMANUFACTURING PLANNING AND REVERSE LOGISTICS NETWORK DESIGN

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ABSTRACT

For a remanufacturing operation to function effectively the existing network of facilities must be redesigned in the form of a closed-loop system to handle the arising forward flows of goods to the customer and return flows of cores from end users. At the same time the organization must plan the quantities to collect, disassemble, store and remanufacture in such a way to meet demand at the minimum cost. This paper presents a multi-period cost minimization mixed integer programming model that simultaneously solves for the location of the remanufacturing/distribution and disassembly facilities, the transshipment, production, stocking, and disposition of the optimal quantities of remanufactured products and cores.

Keywords: Closed-Loop Supply Chains, Reverse Logistics, Remanufacturing, Mixed-Integer Programming.

INTRODUCTION

Recovery of used products and their remanufacturing into new ones has gained justifiable popularity among environmentally friendly companies in recent years. The production and distribution systems which combine product recovery and remanufacturing are referred to as closed-loop supply chains. 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 (Fleischmann et al 2001). The intersection of these two heterogeneous markets produces mismatch between supply and demand. 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.

Another characteristic of closed-loop product 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. Therefore the product recovery ratio is subject to uncertainty.

Remanufacturing can be carried out by a local manufacturer or an original equipment manufacturer (Pranab and Harry 2001). Considered in this paper is the latter case wherein the manufacturer remanufactures products from returned cores and other major components in parallel with the manufacturing of new products in the same facilities. In this environment, recovery networks are not commonly established from scratch but are designed using the existing set of plants and other logistics facilities. To this end, it is important to know which plants and disassembly centers to open and operate, and the number of units to process, store, and distribute out of them. Also, since capacity and recovery cost are facility-dependent, there is interest in determining whether it is economical to collect all returns and, by virtue of consequence, service all customer zone demands; and if not determining the appropriate level of collection remanufacturing and distribution of the recovery operation. Hence, facility and transportation decisions have to be integrated with recovery planning decisions so that material requirements, inventory levels, demand, and capacity constraints over the various stages of collection, disassembly, recovery, and disposition can be coordinated in a most economical way.

In this paper a multi-period, multi-echelon logistics network model is developed for designing a closed-loop supply chain and planning product recovery for remanufacturing. The supply chain structure consists of a number of plants and disassembly centers (to be selected from a set of potential locations) and a number of existing customer zones and disposal sites at fixed locations. Decisions provided by the cost-minimizing mixed-integer programming model determine the following: (1) the plants and disassembly centers to operate during the planning horizon, (2) the quantity to be produced at each plant and shipped to each customer zone in every time period, (3) the quantity of used products to be collected from each customer zone and shipped to each disassembly center in every period, (4) the quantity of reusable units each disassembly center ships to each plant in every time period, (5) the inventory of reusable units held at each disassembly center in every period, (6) the quantity of non-reusable units produced in each disassembly center and shipped to each disposal site in every time period.

MODEL DEVELOPMENT

The proposed 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.

The following assumptions are postulated: (1) the supply chain facilities (plants, customer zones, disassembly centers, and disposal sites), already exist. (2) Plant production capacities, customer zone collection capacities, and disassembly center capacities are known. (3) A product recovery ratio determines the number of reusable units resulting from disassembly and inspection of used units. This ratio is common to all units regardless of the disassembly center they are processed in and the customer zone they are collected from. (4) Inventory of reusable units is held at the disassembly centers. (5) 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 assumption is designed in such a way to ensure an adequate inventory turnover at each center and thereby reduce obsolescence of the reusable unit inventory in the supply chain. (6) Disposal sites are third-party owned and have unlimited capacities.

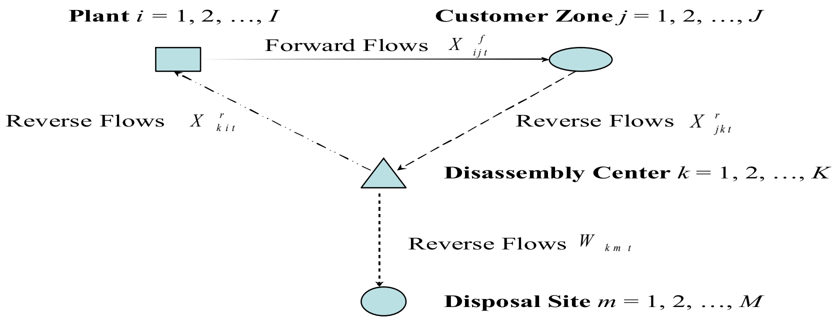

Fig. 1 Closed-Loop Network

Notation

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, $t \in T$;

Supply/Demand Parameters

$D_{jt} =$ Product demand at customer zone *j* during period *t*;
$S_i =$ Plant *i* production capacity per period;
$S_j =$ Customer zone *j* used product collection capacity per period;
$S_k =$ Center *k* disassembly capacity per period;
$\theta_k =$ Center *k* inventory storage capacity per period;
$A =$ Policy factor specifying the minimum proportion of reusable units to be shipped out of each disassembly center to plants in every period, $0 \le A \le 1$;
$d_{jt} =$ Product return forecast at customer zone *j* during period *t*;
$\lambda =$ Product recovery ratio, $0 \le \lambda \le 1$;

Cost Parameters

$F_i =$ Fixed cost of opening and operating plant *i*;
$F_k =$ Fixed cost of opening and operating disassembly center *k*;
$C_{ki} =$ Per unit remanufacturing cost at plant *i* using a reusable unit sourced from center *k*. This cost includes production cost at plant *i*, transportation cost from center *k* to plant *i* and the cost of material sourced from center *k*;

$C_{jk} =$ Per unit disassembly cost at center *k* of a used product collected in customer zone *j*. This cost includes collection cost
at zone *j*, transportation cost from *j* to *k*, and disassembly cost at *k*;

$C_{km} =$ Per unit disposal cost at site *m* of a non-reusable unit processed at center *k*. This cost includes disposal cost at site *m* and transportation cost from *k* to *m*;

$H_k =$ Per unit per period inventory holding cost of a reusable unit in inventory at center *k*;

$P_j =$ Unit penalty cost for not collecting a used product from customer zone *j*;

$G_j =$ Unit penalty cost of not serving demand of customer zone *j*. Observe that G_j could be quantified by taking the relative importance of the different customer zones *j*'s into account; alternatively it could be related to the cost of meeting demand of zone *j* by resorting to external suppliers.

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

Decision Variables

$X^f_{ijt} =$ Forward flow: units shipped from plant *i* to customer zone *j* in period *t*;

$X^r_{jkt} =$ Reverse flow: units of used product shipped from customer zone *j* and to center *k* in period *t*;

$X^r_{kit} =$ Reverse flow: reusable units shipped from center *k* to plant *i* in period *t*. Observe that since no inventory of remanufactured units is held at the plants, this quantity also reflects the number of units produced in plant *i* out of cores sourced from center *k* in period *t*;

$W_{kmt} =$ Non-reusable units shipped from disassembly center *k* to site *m* for disposal in period *t*;

$B_{jt} =$ Units of unsatisfied demand from customer zone *j* in period *t*;

$I_{kt} =$ Disassembled units held in inventory at center *k* at the end of period *t*;

$U_{jt} =$ Uncollected units of used product from customer zone *j* at the end of period *t*;

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

Constraints

$$\sum_{j \in J} X^f_{ijt} \le S_i Z_i, \qquad i \in I, t \in T; \qquad (2)$$

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.

$$\sum_{i \in I} X^f_{ijt} + B_{jt} = D_{jt}, \qquad j \in J, t \in T; \qquad (3)$$

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

$$\sum_{k \in K} X^r_{kit} = \sum_{j \in J} X^f_{ijt}, \qquad i \in I, t \in T; \qquad (4)$$

Equation (4) is a material balance constraint ensuring that the total number of reusable units going into a plant *i* (or reverse flow) equals the total number of remanufactured units coming out of that plant (or forward flow) in every time period. Input into plant *i* can be sourced from any open disassembly center *k* and the output of such a plant can be shipped to any customer zone *j*.

$$I_{k,t-1} + \lambda \sum_{j \in J} X^r_{jkt} = \sum_{i \in I} X^r_{kit} + I_{kt}, \qquad k \in K,\, t \in T; \qquad (5)$$

Constraints (5) ensure product flow balance between inventory of reusable units, processing of used units, and shipment of reusable units at disassembly center k in time period t. Used units are yield a λ proportion of reusable units. Inventory at center k may be carried to provide better customer service or to satisfy forecasted demand that exceed production capacities in future time periods.

$$I_{kt} \le \theta_k Y_k, \qquad k \in K,\, t \in T; \qquad (6)$$

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

$$\sum_{k \in K} X^r_{jkt} + U_{jt} = d_{jt}, \qquad j \in J,\, t \in T; \qquad (7)$$

Constraints (7) ensure product flow balance between collection of used units, forecasted return of used units and uncollected units of used product at customer zone *j* in time period *t*. Observe that the number of used units collected at zone *j* determines the total reverse flow from zone *j* to all open disassembly centers.

$$\sum_{k \in K} X^r_{jkt} \le S_j, \qquad j \in J,\, t \in T; \qquad (8)$$

Constraints (8) require that the total number of used units collected at customer zone *j* in time period *t* to be less than the collection capacity of that zone.

$$\sum_{j \in J} X^r_{jkt} \le S_k Y_k, \qquad k \in K,\, t \in T; \qquad (9)$$

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.

$$\sum_{i \in I} X^r_{kit} \ge A \lambda \sum_{j \in J} X^r_{jkt}, \qquad k \in K,\, t \in T; \qquad (10)$$

Constraints (10) require that the total flow out of any open center *k* in period *t* meets the minimum output requirement *A* for that center. Management may specify the value of *A* in such a way to ensure a minimum outflow activity for center *k* thereby preventing such a center from becoming just an inventory storage location of reusable units.

$$\sum_{m \in M} W_{kmt} = (1-\lambda) \sum_{j \in J} X^r_{jkt}, \qquad k \in K,\, t \in T; \qquad (11)$$

Constraints (11) specify the number of non-reusable units transported from disassembly center *k* to site *m* for disposal. Observe that a proportion $(1-\lambda)$ of the used units collected from all customer zones and processed in center *k* are non-reusable and must therefore be disposed of.

Objective Function

$$\text{Min} \sum_{i\in I} F_i Z_i + \sum_{k\in K} F_k Y_k + \sum_{t\in T}[\sum_{j\in J}(P_j U_{jt} + G_j B_{jt}) + \sum_{k\in K} H_k I_{kt} +$$
$$\sum_{i\in I}\sum_{k\in K} C_{ki} X^r_{kit} + \sum_{j\in J}\sum_{k\in K} C_{jk} X^r_{jkt} + \sum_{k\in K}\sum_{m\in M} C_{km} W_{kmt} + \sum_{i\in I}\sum_{j\in J} T_{ij} X^f_{ijt}] \qquad (1)$$

Objective function (1) minimizes the total multi-period cost of remanufacturing, collection, disassembly, disposal, inventory, and transportation of the recovery operation. The components of the objective function may be described as follows:

Fixed cost at plants and disassembly centers over the entire planning horizon $=\sum_{i\in I} F_i Z_i + \sum_{k\in K} F_k Y_k$.

Multi-period variable production cost at the plants $=\sum_{t\in T}\sum_{i\in I}\sum_{k\in K} C_{ki} X^r_{kit}$.

Inventory costs at processing centers $=\sum_{t\in T}\sum_{k\in K} H_k I_{kt}$.

Penalty cost of unsatisfied demand at customer zones $=\sum_{t\in T}\sum_{j\in J} G_j B_{jt}$.

Penalty cost of uncollected returns at customer zones $=\sum_{t\in T}\sum_{j\in J} P_j U_{jt}$.

Collection, transportation, and processing costs of used units $=\sum_{t\in T}\sum_{j\in J}\sum_{k\in K} C_{jk} X^r_{jkt}$.

Disposal and transportation costs of non-reusable units $=\sum_{t\in T}\sum_{k\in K}\sum_{m\in M} C_{km} W_{kmt}$.

Transportation cost of new units from plants to retailers $=\sum_{t\in T}\sum_{i\in I}\sum_{j\in J} T_{ij} X^f_{ijt}$.

COMPUTATIONAL EXPERIMENT

The proposed model was tested on nine randomly generated supply chain networks consisting of 10 plants, 10 customer zones, 5 disassembly centers, and 3 disposal sites, operating in a 4 time period planning horizon. Each of the nine problem set reflects a specific product recovery environment combining a given product recovery ratio λ and a used product return rate α. Three values of λ with $\lambda = (0.3, 0.6, 0.9)$ are selected to reflect low, medium, and a high recovery ratio respectively. Product return rate at customer zone j in period t is assumed to be related to the demand for remanufactured products in such as way that $d_{jt} = \alpha \times D_{jt}$ with three values of $\alpha = (0.4, 0.7, 1.0)$ selected to reflect low, medium, and high return scenarios respectively. Optimal solutions of the resulting mixed integer problem, consisting of 300 constraints, and 980 variables (15 of which were of the binary type), were obtained in less than 1.2 CPU sec. using the ILOG OPL Studio 3.5 optimization software running on a Pentium IV PC with 512 MB of RAM.

CONCLUSION

Closed-loop supply chains are complex networks of facilities and product flows. The economic viability of a product recovery operation depends to a large extent on the optimal design of logistics network and management of forward and reverse product flows. The proposed multi-period planning model provides cost-minimizing solutions to these complex issues under different product recovery ratios λ and product remanufacturing costs.