CRUCIAL ISSUES IN CLOSED-LOOP SUPPLY CHAIN DESIGN

Second World Conference on POM and 15th Annual POM Conference, Cancun, Mexico, April 30 - May 3, 2004

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ABSTRACT

Although many quantitative models have been reported in the literature for designing a supply chain, none of them address issues that are crucial for the supply chain to successfully operate in a closed-loop. To that end, we examine the following: (i) selection of economical products to process, (ii) identification of efficient production facilities in the region where the supply chain is to be designed, (iii) optimal transportation of products across the supply chain, (iv) prediction of success potentials of collection centers that are being considered for inclusion in the supply chain, (v) sale of used products on potential second-hand markets, (vi) evaluation of marketing method – especially in the reverse supply chain, and (vii) involvement of consumers and local government, along with company executives, in decision-making. Possible strategies to approach these issues are also suggested.

MOTIVATION

While a forward supply chain is a series of activities required to produce new products from raw materials and distribute them to consumers, a reverse supply chain is a series of activities
required to retrieve used products from consumers and re-process (recycle/remanufacture) them to recover their residual market values. The combination of forward and reverse supply chains is called a closed-loop supply chain (see Figure 1).

Production of new products from conceptual design to final delivery such that the environmental standards and requirements are satisfied, is what is suggested by environmental consciousness. In the last decade, environmental consciousness has become an obligation of many facilities in the forward supply chain, enforced primarily by governmental regulations and customer perspective on environmental issues [5]. At the same time, many of these facilities are also driven, mainly by profitability [4], to engage in the reverse supply chain.

Although many quantitative models (for example, see [4], [8], [9]) have been reported in the literature for designing a supply chain, each of them deals with either the forward supply chain or the reverse supply chain, but not both simultaneously (in practice, collection and re-processing of used products are often carried out by the same parties that are involved in the forward supply chain [5]). Furthermore, while no model for designing the forward supply chain addresses the issue of environmental consciousness, every model for designing the reverse supply chain assumes that the chain is profited by re-processing economical used products in efficient facilities. With these drawbacks as a starting point, in this paper, we examine each of the following issues that are crucial for a supply chain to successfully operate in a closed-loop:

i. Selection of economical products to process,

ii. Identification of efficient production facilities in a region where the supply chain is to be designed,

iii. Optimal transportation of products (new, used, and re-processed) across the supply chain,
iv. Prediction of success potentials of collection centers that are being considered for inclusion in the supply chain,

v. Sale of used products on potential second-hand markets,

vi. Evaluation of marketing method – especially of the reverse supply chain, and

vii. Involvement of consumers and local government, along with company executives, in decision-making.

We also suggest a possible strategy to approach each of the above issues.

**SELECTION OF ECONOMICAL PRODUCTS**

Before a new product design is selected for production (in the forward supply chain), an analysis (calculation of expected sale revenue per expected production cost) is always performed to predict how economical the new product would be. However, in practice, it is also desirable to include the revenues and costs associated with the reverse supply chain in the analysis, before the product design is chosen for production. Furthermore, due to uncertainties in supply, quality and re-processing times of the product in the reverse supply chain, *imprecise* cash flows ensue and so it is important that concepts such as fuzzy logic [11] be employed for the analysis.

A fuzzy cost-benefit function such as the following may be formulated for the product of interest:

\[
FCB = \frac{\text{Equivalent Value of } (SR + UR + CR)}{\text{Equivalent Value of } (MC + CC + RC + DC + LC + IC)};
\]

where \( FCB \) is the fuzzy cost-benefit function, equivalent value is the cash flow represented in a common point in time (the most commonly used equivalent values are present worth, annual worth and future worth), \( SR \) is the total new product sale revenue (revenue from selling new products), \( UR \) is the total reuse revenue (revenue from direct-sale/usage-in-remanufacturing of
usable components of used products), \( CR \) is the total recycle revenue (revenue from selling material obtained from recycling of unusable components of used products), \( MC \) is the total new product production cost (cost to produce new products), \( CC \) is the total collection cost (cost to collect used products from consumers), \( RC \) is the total re-processing cost (cost to remanufacture/recycle used products), \( DC \) is the total disposal cost (cost to dispose of the material left over after remanufacturing and/or recycling of used products), \( LC \) is the loss-of-sale cost (cost due to loss of sale, which might occur every now and then, due to lack of supply of used products), \( IC \) is the investment cost (capital required for the production facility and its machinery). Then, in order to select the most economical product to process in a closed-loop supply chain, from a set of candidate products, we suggest the following steps:

**Step 1:** Eliminate every product whose \( FCB \) is less than 1.0.

**Step 2:** Assign the product that has the lowest \( IC \) as the defender and the product with the next-lowest \( IC \) as the challenger.

**Step 3:** Calculate the ratio of the equivalent value of incremental total revenue (between the challenger and the defender) to the equivalent value of incremental total cost (between the challenger and the defender). If this ratio is less than 1.0, eliminate the challenger. Otherwise, eliminate the defender.

**Step 4:** Repeat steps 2 and 3 until only one product (which is the most economical one in the set) is left.

**IDENTIFICATION OF EFFICIENT PRODUCTION FACILITIES**

No model in the literature for identification of efficient production facilities either addresses the issue of environmental consciousness in the forward supply chain or considers the criteria (for evaluation of each facility) associated with the reverse supply chain. We suggest a four-level
hierarchy (see Figure 2) to facilitate solving the problem of identification of efficient production facilities in a region where the closed-loop supply chain is to be designed. The first level in the hierarchy contains our objective, i.e., evaluation of the efficiency of each production facility, the second level contains the main criteria for evaluation, the third level contains the sub-criteria under each main criterion, and the fourth (last) level contains all the production facilities of interest. The main criteria and the corresponding sub-criteria are as follows (criteria that are traditionally considered for evaluation – for example, quality of new products – are not presented here):

- Environmentally conscious design
  - Design for disassembly
  - Design for recycling
  - Design for remanufacturing

- Environmentally conscious manufacturing
  - Energy sources
  - Cooling systems
  - Waste management

- Attitude of management
  - Environmentally friendly thinking
  - Flexibility to handle uncertainties
  - Usage of automated disassembly systems

- Potentiality
  - Throughput per supply of used products
  - Product of throughput and average disassembly time of used products
Increment in quality of products after re-processing

- Cost
  - Fixed cost
  - Operational cost

- Customer service
  - Incentives to collection centers
  - Incentives to customers disposing of used products at collection centers and buying re-processed goods at demand centers
  - Utilization of incentives from government
  - Meeting environmental regulations

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [10] or a similar technique may then be employed for the evaluation of production facilities. The basic concept of TOPSIS is that the rating of the alternative (production facility, in this case) selected as the best from a set of different alternatives, should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in a geometrical (i.e., Euclidean) sense.

OPTIMAL TRANSPORTATION OF PRODUCTS

Any supply chain must involve optimal transportation of products. To this end, we suggest that a transshipment model be solved to achieve transfer of the right mix and quantities of products (new, used, and re-processed) across the supply chain.

The following is a single time-period transshipment model formulation to achieve transfer of the right mix and quantities of products (used as well as remanufactured) across the supply chain:
Nomenclature for the transshipment model

\( a_1 \) space occupied by one unit of remanufactured product (square units/product);

\( a_2 \) space occupied by one unit of used product (square units/product);

\( CAP_v \) capacity of production facility \( v \) to remanufacture products;

\( C_u \) cost per product retrieved at collection center \( u \) ($/product);

\( d_w \) demand of remanufactured products at demand center \( w \);

\( I_{uv} \) decision variable representing the number of products to be transported from collection center \( u \) to production facility \( v \);

\( O_{vw} \) decision variable representing the number of products to be transported from production facility \( v \) to demand center \( w \);

\( R_v \) cost of remanufacturing per product at production facility \( v \) ($/product);

\( S_{1v} \) storage capacity of production facility \( v \) for remanufactured products (square units);

\( S_{2v} \) storage capacity of production facility \( v \) for used products (square units);

\( S_u \) storage capacity of collection center \( u \) for used products (square units);

\( SUP_u \) supply at collection center \( u \);

\( TI_{uv} \) cost of transporting one product from collection center \( u \) to production facility \( v \) ($/product);

\( TO_{vw} \) cost of transporting one product from production facility \( v \) to demand facility \( w \) ($/product);

\( u \) collection center;

\( v \) production facility;

\( w \) demand center.
**Formulation of the transshipment model**

Here, it is assumed that the inventory cost of a used product is 25 percent of its retrieval cost, \( C_u \), and that of a remanufactured product is 25 percent of its remanufacturing cost, \( R_v \). The formulation of the transshipment model is as follows:

**Minimize**

\[
\begin{align*}
\sum_{u} \sum_{v} C_u I_{uv} + & \quad \text{Retrieval costs} \\
\sum_{u} \sum_{v} TI_{uv} + \sum_{v} \sum_{w} TO_{v} O_{vw} + & \quad \text{Transportation costs} \\
\sum_{v} \sum_{w} R O_{v} + & \quad \text{Remanufacturing costs} \\
\sum_{u} \sum_{v} (C_u / 4) I_{uv} + \sum_{v} \sum_{w} (R_v / 4) Q_{vw}; & \quad \text{Inventory costs}
\end{align*}
\]

**subject to**

\[
\begin{align*}
\sum_{v} O_{vw} = d_w; \forall w & \quad \text{Demand at each demand center must be met} \\
\sum_{u} I_{uv} \geq \sum_{w} O_{vw}; \forall v & \quad \text{Total output of each production facility is at most its total input} \\
\sum_{w} a_1 O_{vw} \leq S_{1v} Y_v; \forall v & \quad \text{Total space occupied by remanufactured products at each production facility is at most its capacity for remanufactured products} \\
\sum_{v} a_2 I_{uv} \leq S_u; \forall u & \quad \text{Total space occupied by used products at each collection center is at most its capacity} \\
\sum_{u} a_2 I_{uv} \leq S_{2v} Y_v; \forall v & \quad \text{Total space occupied by used products at each production facility is at most its capacity for used products} \\
I_{uv} \geq 0; \forall u, v & \quad \text{Quantities of transported products are non-negative numbers} \\
O_{vw} \geq 0; \forall v, w & \quad \text{Total output of each production facility is at most its capacity to remanufacture}
\end{align*}
\]
PREDICTION OF SUCCESS POTENTIALS OF COLLECTION CENTERS

The success of the reverse supply in a closed-loop supply chain begins with the success of the collection centers involved (see Figure 1). We suggest a neural network approach to evaluate the success potential (contribution to the efficiency of the reverse supply) of a collection center of interest, which is being considered for inclusion in the supply chain, using the available linguistic data of the collection centers that already exist in the supply chain. Fuzzy logic [11] can be employed to convert linguistic (for example, “very good”, “poor”, etc.) ratings (performance measures) of the existing collection centers with respect to criteria for evaluation and their (collection centers’) overall ratings, into numerical ratings. However, fuzzy logic cannot be employed for the impacts (importance values) of the criteria [1], because it is very difficult in the first place, for an expert to give linguistic impacts (we use the term, “impacts”, for criteria for evaluation, and “ratings” for the collection centers). To this end, we suggest a three-phase approach to evaluate the success potential of a collection center of interest, as follows: In phase I, criteria for evaluation of the collection center of interest are identified. Then, in phase II, fuzzy ratings of the existing collection centers are used to construct and train a neural network. The number of input-output pairs used for training is the number of existing collection centers. Also, we suggest that three layers be considered in the neural network, with a random number (say, 5) of nodes in the hidden layer. The number of node(s) in the output layer is one (representing the overall rating), and that in the input layer is equal to the number of criteria identified in phase I (representing the ratings with respect to the criteria). The following equation could be used with

\[ \sum_{v} I_{uv} \leq SUP_{u}, \forall u \]
the results obtained from the trained neural network, to determine the impacts of the criteria for evaluation.

\[
W_{jk} = \frac{\sum_{j}^{m} \frac{I_{ij}}{\sum_{i}^{n} |I_i|} O_{jk}}{\sum_{v}^{n} \sum_{j}^{m} \frac{I_{ij}}{\sum_{i}^{n} |I_i|} O_{jk}}
\]  

(12)

Then, in phase III, using the impacts obtained in phase II and linguistic ratings of the collection center of interest with respect to the criteria for evaluation, a fuzzy TOPSIS [2] (combination of the fuzzy logic [11] and the TOPSIS [10]) approach can be employed to obtain the overall rating (success potential) of that collection center.

**SALE OF USED PRODUCTS ON POTENTIAL SECOND-HAND MARKETS**

The most important driver for companies interested in collecting used products is recoverable value through re-processing. However, the companies seldom know when those products were bought and why they were discarded. Also, the products do not indicate their remaining life periods. Hence, they often undergo partial or complete disassembly for subsequent re-processing. We are of the opinion that for some used products, it might make more “sense” to make necessary repairs to the products and sell them on the second-hand markets than to disassemble them for subsequent remanufacture and/or resale. To this end, we suggest that an expert system be built using Bayesian updating process [6], to decide if it is “sensible” to repair the used product of interest for subsequent sale on a second-hand market (we assume here that the used product of interest functions improperly; it is obviously “sensible” to sell a properly...
functioning used product on a second-hand market). Bayesian updating is an uncertainty modeling technique that assumes that it is possible for an expert in a domain to guess a probability to every hypothesis or assertion in that domain, and that this probability can be updated in light of evidence for or against the hypothesis or assertion. In this case, we must use fuzzy logic [11] to calculate certain probabilities that are difficult to guess (for example, it is difficult to guess how often a component is observed needing repair when it is decided that repairing the used product is “sensible”).

We also suggest a Quality Function Deployment (QFD) approach [3] to select the most potential market to sell the repaired used product in, from a set of candidate second-hand markets. In a QFD approach, “performance aspects” are defined as the features that the decision-maker wishes to consider in the selection process, and “enablers” as the characteristics possessed by the alternatives (second-hand markets, in this case) and can be used to satisfy the performance aspects. The following are the performance aspects of the second-hand markets, which may be considered in the QFD approach (it should be noted here that by a second-hand market, we mean, a “store” where second-hand products are sold, along with new products):

a) Before-Sale-Performance (BSP) (reflects the ability to attract new customers to the second-hand market)
b) While-Sale-Performance (WSP) (reflects the ability to motivate the customers to buy second-hand products while the customers are in the second-hand market)
c) After-Sale-Performance (ASP) (reflects the ability to attract old customers to the second-hand market)

The following are the enablers that may be considered in the QFD approach:

- Good advertisement (AD)
- High difference of prices between new and second-hand products (DP)
- Greenness of the sale (GS)
- Incentives (warranty, service, etc) (IC)
- Low average price of products (LP)
- Good location of sale of second-hand products (placement in front of the new ones, etc) (LS)
- Proper maintenance of second-hand products (as proper as it is for new products) (MN)
- Discounts to returning customers (RC)
- Good return/exchange policy (RP)
- Reputation of the store (RS)
- Variety of second-hand products on the shelves (VS)

The enablers for BSP are LP, IC, RS, and AD, those for WSP are DP, GS, IC, MN, AD, VS, RP, and LS, and those for ASP are RC and AD.

**EVALUATION OF MARKETING METHOD**

The success of a closed-loop supply chain is very heavily dependent on the level of public participation (especially in the reverse supply chain) which in turn is shouldered by the marketing method of that supply chain. Hence, it is absolutely necessary that the planned marketing method be evaluated with respect to motivators (numerous and often conflicting with each other) of public participation, before actually implementing the method.

The following is a fairly exhaustive list of self-explanatory drivers for the public to participate in a reverse supply chain program:

1. Knowledge of drivers of implementation of the reverse supply chain program (KD)
ii. Awareness of the reverse supply chain program being implemented (AR)

iii. Simplicity of the reverse supply chain program (SR)

iv. Convenience for disposal of used products at collection centers (CD)

v. Incentives for disposal of used products (ID)

vi. Effectiveness of collection methods (EC)

vii. Information supplied about used products being collected (IU)

viii. Regularity of collection of used products (RC)

ix. Design of special methods for abusers of the reverse supply chain program (AB)

x. Good locations of centers where re-processed goods are sold (LR)

xi. Incentives to buyers of re-processed goods (IB)

xii. Co-operation of the program organizers with the local government (CL)

We suggest a fuzzy TOPSIS [2] approach to evaluate the marketing method with respect to the above drivers.

**IN VolvEmEnt OF CoNsUmeRS AND LoCAL GOVERNMENT IN DECISION-MAKING**

Traditionally, supply chain company executives are the sole decision-makers for operating the supply chain. However, for a closed-loop supply chain to operate successfully, it is very important that two more groups (viz., consumers and local government officials) be involved in the decision-making process involving the design of the supply chain. Furthermore, since these three groups have multiple, conflicting, and incommensurate goals, the decision must be based on the maximized consensus among the groups, as follows:

i. **Consumers** whose primary concern is convenience,

ii. **Local government officials** whose primary concern is environmental consciousness, and
iii. **Supply chain company executives** whose primary concern is *profit*.

Borda [7] proposed a method in which marks of $m-1, m-2, \ldots, 1, 0$ are assigned to the first ranked, second ranked, \ldots, last ranked alternative, for each group. That means that higher marks correspond to more importance. Consensus rating for each alternative is then determined as the sum of the individual marks for that alternative. Then the alternative with the highest consensus rating is declared the winner. That means that the different groups unanimously choose the alternative that obtains the highest consensus rating as the most preferred one.

**CONCLUSIONS**

Many quantitative models have been reported in the literature about designing a supply chain. However, none of them address issues that are crucial for the supply chain to successfully operate in a closed-loop. In this paper, we examined a variety of such issues, and suggested possible strategies to approach to each of them.

**REFERENCES**


Figure 1. A Generic Closed-Loop Supply Chain
Figure 2. Levels of Hierarchy for Identification of Efficient Production Facilities