

January 01, 2006

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### Recommended Citation

Gupta, Surendra M. and Nukala, Satish, "Strategic and tactical planning of a closed-loop supply chain network under uncertainty" (2006).. Paper 108. <http://hdl.handle.net/2047/d10010038>

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## **Bibliographic Information**

Nukala, S. and Gupta, S. M., "Strategic and Tactical Planning of a Closed-Loop Supply Chain Network under Uncertainty", ***Proceedings of the SPIE International Conference on Environmentally Conscious Manufacturing VI***, Boston, Massachusetts, pp. 157-164, October 1-3, 2006.

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# Strategic and Tactical Planning of a Closed-Loop Supply Chain Network under Uncertainty

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## ABSTRACT

While the strategic planning of a supply chain, which is typically a long range planning, deals with the design aspect of the supply chain (what products should be processed/produced in what facilities etc.), tactical planning is typically a medium-range planning that involves the optimization of flow of goods and services across the supply chain. In this paper, we present a multi-criteria optimization model for the strategic and tactical planning of a closed-loop supply chain under uncertainty, where the aspiration levels for various goals are more likely to be in the “approximately more/less than” and/or “more/less is better” form. We use fuzzy goal programming technique to solve the problem. When solved, the model identifies simultaneously the most economical used-product to re-process in the supply chain, the efficient production facilities and the right mix and quantity of goods to be transported across the supply chain. A numerical example is considered to illustrate the methodology.

**Key words:** Strategic Planning, Closed-Loop Supply Chain, Fuzzy Goal Programming

## 1. INTRODUCTION

Both consumer and government concerns for the environment are driving many original equipment manufacturers (OEM) to engage in additional series of activities stemming from the reverse supply chain. As a result, economically feasible production and distribution systems are established that enable remanufacturing of used-products in conjunction with the manufacturing of new products [1], [2]. The combination of forward/traditional supply chain and reverse supply chain forms the closed-loop supply chain (CLSC). While this process is mandatory in Europe, it is still in its infancy in the United States.

Strategic, Tactical and Operational planning are the three important stages of planning in a Supply Chain. Strategic planning primarily deals with the design (what products should be processed/produced in what facilities etc.) of the supply chain that is typically a long-range planning performed every few years when a supply chain needs to expand its capabilities. Tactical planning involves the optimization of flow of goods and services across the supply chain and is typically a medium-range planning performed on a monthly basis. Finally, Operational planning is a short-range planning that deals with the day-to-day production planning and inventory issues on the factory floor.

Much work is done in the area of designing forward and reverse supply chains (for example see [3], [4]). However, not many models deal with both the forward and reverse supply chains together. While the issue of environmental consciousness is not addressed in the forward supply chain models, the models dealing with reverse supply chain assume that each incoming used product is economical to re-process and each available production facility is efficient enough to re-process the incoming used products. As a result, there is a risk of re-processing uneconomical used products in inefficient facilities. Pochampally and Gupta [5] addressed these drawbacks in a reverse supply chain and proposed a three phase mathematical programming approach for its strategic planning. Nukala and Gupta [6] extended Pochampally and Gupta’s work to a closed-loop supply chain and proposed a unified single phase approach for its strategic and tactical planning. They used pre-emptive goal programming technique to solve the model proposed in [6] assuming equally weighted goals and deterministic aspiration levels. In this paper, we refine Nukala and Gupta’s [6] methodology to approximate the problem on hand to real world situations by addressing multiple goals with aspiration levels more likely to be in the “approximately more/less than” and/or “more/less is better” form. We use fuzzy goal programming technique [7] to solve the problem. When solved, the model identifies simultaneously the most economical used-product

to re-process in the supply chain, the efficient production facilities and the right mix and quantity of goods to be transported across the supply chain.

## 2. FUZZY GOAL PROGRAMMING

Goal programming (GP) extends linear programming to situations involving multiple goals/objectives. In GP, it is necessary to specify aspiration levels for the goals and the overall deviation from the aspiration levels are minimized. In most of the real world scenarios, the aspiration levels and weights/importance levels of goals are imprecise in nature. In such situations, fuzzy goal programming (FGP) comes in handy allowing the decision maker to obtain compromising results for multiple goals with varying aspiration levels. In FGP, the aspiration levels are more likely to be in the “approximately more/less than” and/or “more/less is better” form.

In this paper we use the additive FGP model presented by Tiwari, Dharmar and Rao [7] that employs the usual addition as an operator to aggregate the fuzzy goals. A linear membership function  $\mu_i$  that represents fuzziness in fuzzy modeling in the case of maximizing a fuzzy goal [8], [9] is expressed as:

$$\mu_i = \begin{cases} 1 & \text{if } G_i(X) \geq g_i \\ \frac{G_i(X) - L_i}{g_i - L_i} & \text{if } L_i \leq G_i(X) \leq g_i \\ 0 & \text{if } G_i(X) \leq L_i \end{cases} \quad (1)$$

where  $g_i$ ,  $L_i$  and  $U_i$  are the aspiration level, lower tolerance limit and upper tolerance limit respectively for the fuzzy goal  $G_i(X)$ . In the case of minimizing the fuzzy goal, the membership function is expressed as:

$$\mu_i = \begin{cases} 1 & \text{if } G_i(X) \leq g_i \\ \frac{U_i - G_i(X)}{U_i - g_i} & \text{if } g_i \leq G_i(X) \leq U_i \\ 0 & \text{if } G_i(X) \geq U_i \end{cases} \quad (2)$$

The simple form of the FGP problem with  $p$  fuzzy goals can be stated as:

$$\begin{aligned} &\text{maximize} \quad V(\mu) = \sum_{i=1}^p \mu_i \\ &\text{subject to} \quad \mu_i = \frac{G_i(X) - L_i}{g_i - L_i} \text{ or } \mu_i = \frac{U_i - G_i(X)}{U_i - g_i} \\ & \quad \quad \quad AX \leq b \\ & \quad \quad \quad \mu_i \leq 1 \\ & \quad \quad \quad X, \mu_i \geq 0, \quad i = 1, 2, \dots, p \end{aligned} \quad (3)$$

where  $V(\mu)$  is the fuzzy achievement function or fuzzy decision function. The objective is to obtain  $\mu_i$  value as close to 1 as possible. The weighted additive model is widely used in GP and multiobjective optimization problems to reflect the relative importance of goals. In this approach, the decision maker assigns weights as coefficients of individual terms in

the simple additive fuzzy achievement function to reflect their relative importance. The objective function for the weighted additive model is expressed as:

$$\text{maximize } V(\mu) = \sum_{i=1}^p w_i \mu_i \quad (4)$$

where  $w_i$  is the relative weight of the  $i$ -th fuzzy goal. In this paper we use Fibonacci numbers to assign weights to the goals. Fibonacci numbers are 0, 1, 1, 2, 3, 5, 8 etc. (the next number is a result of the summation of the previous two numbers). We apply the concept starting with numbers 1 and 2. For example, for two goals, the weights would be in the ratio of 1:2, which approximately are 0.33 and 0.66. These weights are assigned to the two goals according to their priority levels.

In some situations, the goals/objectives are not commensurable, or the goals are such that unless a particular goal or subset of goals is achieved, other goals should not be considered. In such situations, the weighting scheme is not appropriate. The problem is divided into  $k$  sub problems, where  $k$  is the number of priority levels. In the first sub problem the fuzzy goals belonging to the first priority level will be considered and solved using the simple additive model. At other priority levels, the membership values achieved at earlier priority levels are added as additional constraints. In general the  $i$ -th sub problem becomes

$$\begin{aligned} &\text{maximize } \sum_s (\mu_s)_{pi} \\ &\text{subject to } \mu_s = \frac{G_s - L_s}{g_s - L_s}, \\ &AX \leq b, \\ &(\mu)_{pr} = (\mu^*)_{pr}, \quad r = 1, 2, \dots, j-1, \\ &\mu_s \leq 1, \\ &X, \mu_i \geq 0, \quad i = 1, 2, \dots, p \end{aligned} \quad (5)$$

where  $(\mu_s)_{pi}$  refers to the membership functions of the goals in the  $i$ -th priority level and  $(\mu^*)_{pr}$  is the achieved membership function value in the  $r$ -th ( $r \leq j-1$ ) priority level.

### 3. METHODOLOGY

We consider the following scenario in our model. Suppose that the manufacturer has incorporated a remanufacturing process for used products into her original production system, so that products can be manufactured directly from raw materials, or remanufactured from used-products. The final demand for the product is met either with new or remanufactured products.

#### **Nomenclature used in the methodology**

$A_{iuv}$  = decision variable representing number of used-products of type  $i$  transported from collection center  $u$  to remanufacturing facility  $v$

$B_{iww}$  = decision variable representing number of used-products of type  $i$  transported from production facility  $v$  to demand center  $w$

$b_i$  = probability of breakage of product  $i$

$TA_{uv}$  = cost to transport 1 unit from collection center  $u$  to remanufacturing facility  $v$

$TB_{vw}$  = cost to transport 1 unit from remanufacturing facility  $v$  to demand center  $w$

$CC_u$  = cost per product retrieved at collection center  $u$

$CNP_v$  = cost to produce 1 unit of new product at production facility  $v$

$CR_v$  = cost to remanufacture at production facility  $v$

$C_{di}$  = disposal cost of product  $i$   
 $DI_i$  = disposal cost index of component  $y$  in product  $x$  (0 = lowest, 10 = highest)  
 $DT_i$  = disassembly time for product  $i$   
 $DC$  = disassembly cost/unit time  
 $i$  = product type  
 $MINTPS$  = minimum through-put per supply  
 $N_{ivw}$  = decision variable representing number of new products type  $i$  transported from production facility  $v$  to demand center  $w$   
 $Nd_{iw}$  = net demand for product type  $i$  (remanned or new) at demand center  $w$   
 $PRC_i$  = % of recyclable contents by weight in product  $i$   
 $RCYR_i$  = total recycling revenue of product  $i$   
 $RSR_i$  = total resale revenue of product  $i$   
 $RCRI_i$  = recycling revenue index of component  $y$  in product  $x$   
 $S_{1v}$  = storage capacity of remanned facility  $v$  for used products  
 $S_{2v}$  = storage capacity of remanned facility  $v$  for remanned and new products  
 $S_u$  = storage capacity of collection center  $u$   
 $SP_i$  = selling price of a unit of new product of type  $i$   
 $SU_{iu}$  = supply of used product  $i$  at collection center  $U$   
 $SF_v$  = supply of used products at production facility  $v$ , different from  $SU_i$ , these are products that are fit for remanned, after accounting for recycled and disposed products + new products  
 $TP_v$  = through-put (considering only remanned products) of production facility  $v$   
 $U$  = collection center  
 $V$  = remanned facility  
 $W$  = demand center  
 $W_i$  = weight of product  $i$   
 $x_1$  = space occupied by 1 unit of used product (square units per product)  
 $x_2$  = space occupied by 1 unit of remanned or new product (square units per product)  
 $Y_v$  = decision variable signifying selection of production facility  $V$  (1 if selected, 0 if not)  
 $Z_{iu}$  = decision variable representing number of units of product type  $i$  picked for remanned at collection center  $u$  ( $SU_{iu} - Z_{iu}$  = recycled or disposed)  
 $\delta_v$  = factor that accounts for un-assignable causes of variations at production facility  $v$

### Goals

We consider three goals in our GP model:

1. Maximize the total profit in the CLSC (TP)
2. Maximize the revenue from recycling (RR)
3. Minimize the number of disposed items (NDIS)

The first two goals involve minimizing the negative deviation from the respective target values while the third goal which has an “environmentally benign” character rather than a financial basis, involves minimizing the positive deviation from the target value.

The membership functions for the three goals are:

$$\mu_1 = \begin{cases} 1 & \text{if } TP \geq TP^* \\ \frac{TP - TP_L}{TP^* - TP_L} & \text{if } TP_L \leq TP \leq TP^* \\ 0 & \text{if } TP \leq TP_L \end{cases} \quad (6)$$

where,  $TP^*$  is the aspiration level of total profit (TP) and  $TP_L$  is the lower tolerance level of TP.

$$\mu_2 = \begin{cases} 1 & \text{if } RR \geq RR^* \\ \frac{RR - RR_L}{RR^* - RR_L} & \text{if } RR_L \leq RR \leq RR^* \\ 0 & \text{if } RR \leq RR_L \end{cases} \quad (7)$$

where,  $RR^*$  is the aspiration level of recycling revenue (RR) and  $RR_L$  is the lower tolerance level of RR.

$$\mu_3 = \begin{cases} 1 & \text{if } NDI \leq NDI^* \\ \frac{NDI_U - NDI}{NDI_U - NDI^*} & \text{if } NDI^* \leq NDI \leq NDI_U \\ 0 & \text{if } NDI \geq NDI_U \end{cases} \quad (8)$$

where,  $NDI^*$  is the aspiration level of number of disposed items (NDI) and  $NDI_U$  is the upper tolerance level of NDI.

According to the concept of Fibonacci numbers, starting with 1 and 2, the weight values for  $\mu_1$ ,  $\mu_2$  and  $\mu_3$  are 0.5, 0.33 and 0.17. The objective function for the weighted FGP model is as follows:

$$\text{Maximize } V(\mu) = (0.5 * \mu_1) + (0.33 * \mu_2) + (0.17 * \mu_3) \quad (9)$$

### **Total Profit and Related Terms**

The total profit (TP) is the difference between all the revenues and all the costs considered in the model.

#### **Revenues**

1. Reuse Revenue (all product types together, taken 1 unit at a time)

$$\sum_i \sum_u \{Z_{iu} RSR_i\}$$

2. Recycle Revenue (all product types together, taken 1 unit at a time)

$$\sum_i \sum_u \{(SU_{iu} - Z_{iu}) RCY_i W_i PRC_i\} C_{rf}$$

3. New Product Sale Revenue

$$SP_i * N_{iww}$$

#### **Costs**

1. Collection/Retrieval Cost

$$\sum_u \sum_i CC_u SU_{iu}$$

2. Processing Cost = Disassembly cost of used products + Remanufacturing cost of used products + New Products production cost in the forward supply chain

$$\left( DC \sum_i \sum_u \sum_v DT_i A_{iuv} \right) + \sum_i \sum_u \sum_v CR_v B_{iuv} + \sum_i \sum_u \sum_v CNP_v N_{iuv}$$

3. Inventory Cost: Assuming inventory carrying cost at collection center (used products) is 20% of collection cost ( $CC_u$ ); inventory carrying cost at production facility (remanufactured or new products) is 25% of remanufacturing or new product production cost, whichever is applicable.

$$\sum_i \sum_u \sum_v (CC_u / 5) \cdot A_{iuv} + \left( \sum_i \sum_v \sum_w \{ (CR_v / 4) B_{i vw} + (CNP_v / 4) * N_{i vw} \} \right)$$

4. Transportation Costs: Used products from collection centers to production facility + Remanufactured and New Products from production facilities to demand centers.

$$TA_{uv} \sum_i \sum_u \sum_v A_{iuv} + TB_{vw} \sum_i \sum_v \sum_w (B_{i vw} + N_{i vw})$$

5. Disposal Cost: Products that can't be remanufactured or recycled (all product types together, taken 1 unit at a time)

$$\sum_i \sum_u \{ (SU_{iu} - Z_{iu}) DI_i W_i (1 - PRC_i) \} C_{df}$$

### System Constraints

1. The number of used-products sent to all production facilities from a collection center  $u$  must be equal to the number of used-products picked for remanufacturing at that collection center.

$$\sum_v A_{iuv} = Z_{iu}$$

2. Demand at each center  $w$  must be met with either by new or remanufactured goods.

$$\sum_v (B_{i vw} + N_{i vw}) = Nd_{iw} \forall w$$

3. Number of remanufactured products transported from a production facility  $v$  to a demand center  $w$  = (Number of used products fit for remanufacturing, transported from collection center  $u$  to that production facility) \*  $\delta_v$   $\forall v$  i.e., no loss of products in the supply chain due to reasons other than common cause variations, over which there's no control.  $\delta_v$  is a factor that accounts for the un-assignable causes of variation at the production facility  $v$ .

$$\sum_w B_{i vw} = \sum_u A_{iuv} * \delta_v \forall v$$

4. Total number of used products of type  $i$  picked for remanufacturing at  $u$  must be at most equal to the total number of used products fit for remanufacturing.

$$Z_{iu} \leq SU_{iu} (1 - b_i)$$

5. Total number of used products of all types collected at all collection centers must be at least equal to the net demand.

$$\sum_i \sum_u SU_{iu} \geq \sum_i \sum_w Nd_{iw}$$

6. Number of remanufactured products must be at most equal to the net demand; this is to avoid excess remanufacturing.

$$\sum_i \sum_u Z_{iu} \leq \sum_i \sum_w Nd_{iw}$$

### Facilities Space Constraints

7. Space constraints for used products at production facility  $v$ ,

$$x_1 \sum_i \sum_u A_{iuv} \leq S_{1v} \cdot Y_v$$

8. Space constraint for new and remanufactured products at production facility  $v$ , assuming new and remanufactured products occupy the same space.

$$\sum_i \sum_w x_2 (B_{i vw} + N_{i vw}) \leq S_{2v} * Y_v$$

9. Space constraint for used products at collection center

$$x_1 \sum_i \sum_v a_{iuv} \leq S_u$$

### **Production Facility's Potentiality Constraints, valid only for remanufactured products**

$$10. (TP_v / SF_v) Y_v \geq MINTPS \quad (\text{MINTPS} = \text{minimum through-put per supply})$$

### **Non-Negativity Constraints:**

$$A_{iuv}, B_{ivw}, N_{iww}, Z_{iu} \geq 0, \quad \forall u, v, w$$

$$Y_v \in [0,1] \quad \forall v, \quad 0 \text{ if facility } v \text{ not selected, } 1 \text{ if selected.}$$

### **Illustrative Example**

We consider a Closed-Loop Supply Chain with three collection centers, two production facilities to choose from, two demand centers to be served and three brands of similar products.

The example data we take to implement the FGP model is as follows:

$CCu = 0.01$ ;  $SU_{11}=50$ ;  $SU_{12}=45$ ;  $SU_{13}=25$ ;  $SU_{21}=35$ ;  $SU_{22}=38$ ;  $SU_{23}=22$ ;  $SU_{31}=30$ ;  $SU_{32}=35$ ;  $SU_{33}=28$ ;  $DC=0.05$ ;  $DT_1=10$ ;  $DT_2=12$ ;  $DT_3=9$ ;  $CR_1=13$ ;  $CR_2=10$ ;  $CNP_1=60$ ;  $CNP_2=45$ ;  $TA_{11}=0.01$ ;  $TA_{12}=0.09$ ;  $TA_{21}=0.5$ ;  $TA_{22}=0.1$ ;  $TA_{31}=0.02$ ;  $TA_{32}=0.04$ ;  $TB_{11}=0.04$ ;  $TB_{12}=0.03$ ;  $TB_{21}=0.09$ ;  $TB_{22}=0.05$ ;  $DI_1=4$ ;  $DI_2=6$ ;  $DI_3=5$ ;  $W_1=0.8$ ;  $W_2=1.0$ ;  $W_3=0.9$ ;  $PRC_1=0.5$ ;  $PRC_2=0.6$ ;  $PRC_3=0.75$ ;  $Cd_1=0.2$ ;  $Cd_2=0.5$ ;  $Cd_3=0.3$ ;  $RSR_1=30$ ;  $RSR_2=40$ ;  $RSR_3=45$ ;  $RCYR_1=1.5$ ;  $RCYR_2=2$ ;  $RCYR_3=2.5$ ;  $RCRI_1=7$ ;  $RCRI_2=4$ ;  $RCRI_3=5$ ;  $SP_1=65$ ;  $SP_2=53$ ;  $SP_3=60$ ;  $Nd_{11}=20$ ;  $Nd_{12}=15$ ;  $Nd_{21}=16$ ;  $Nd_{22}=22$ ;  $Nd_{31}=25$ ;  $Nd_{32}=20$ ;  $\delta_1=0.4$ ;  $\delta_2=0.6$ ;  $b_1=0.2$ ;  $b_2=0.4$ ;  $b_3=0.3$ ;  $X_1=0.7$ ;  $S_{11}=400$ ;  $S_{12}=400$ ;  $S_1=150$ ;  $S_2=150$ ;  $S_3=150$ ;  $X_2=0.7$ ;  $S_{21}=500$ ;  $S_{22}=500$ ;  $TP^*=3500$ ;  $TP_L=2000$ ;  $RR^*=1000$ ;  $RR_L=800$ ;  $NDI^*=60$ ;  $NDI_U=100$ ;  $MINTPS=0.25$ .

Upon solving the FGP model using LINGO, we get the following solution:

$Z_{12}=15$ ;  $Z_{13}=20$ ;  $Z_{21}=21$ ;  $Z_{22}=17$ ;  $Z_{31}=5$ ;  $Z_{32}=18$ ;  $Z_{33}=18$ ;  $N_{111}=7$ ;  $N_{211}=10$ ;  $A_{121}=15$ ;  $A_{131}=20$ ;  $A_{212}=21$ ;  $A_{222}=17$ ;  $A_{311}=5$ ;  $A_{312}=9$ ;  $A_{321}=18$ ;  $A_{331}=17$ ;  $A_{332}=20$ ;  $B_{111}=13$ ;  $B_{112}=15$ ;  $B_{311}=25$ ;  $B_{312}=6$ ;  $B_{221}=7$ ;  $B_{222}=22$ ;  $B_{322}=15$ ;  $Y_1=1$ ;  $Y_2=1$ .

with achieved goal values

$TP=3500$ ;  $RR=1000$ ;  $NDI=77$

and membership values

$\mu_1=1$ ;  $\mu_2=1$ ;  $\mu_3=0.59$ .

## **4. CONCLUSIONS**

In this paper, we formulated a fuzzy goal programming model that addresses some of the critical issues in the strategic and tactical planning stages of a closed-loop supply chain network. The model addresses multiple goals with aspiration levels more likely to be in the “approximately more/less than” and/or “more/less is better” form. When solved, the model identifies the most economical used-products and their quantities to be re-processed in the closed-loop supply chain, the efficient production facilities and the right mix and quantities of goods to be transported across the supply chain. A numerical example was considered to illustrate the methodology.

## **REFERENCES**

- [1] Lambert, A. J. D. and Gupta, S. M., *Disassembly Modeling for Assembly, Maintenance, Reuse, and Recycling*, CRC Press, Boca Raton, FL, 2005.
- [2] Savaskan, R. C., Bhattacharya, S. and Van Wassenhove Luk, N., “Closed-Loop Supply Chain Models with Product Remanufacturing”, *Management Science*, **50** (2), 239-252, 2004.
- [3] Fleischmann, M., *Quantitative Models for Reverse Logistics: Lecture Notes in Economics and Mathematical Systems*, Springer-Verlag, Germany, 2001.
- [4] Talluri, S. and Baker, R. C., “A multi-phase mathematical programming approach for effective supply chain design”, *European Journal of Operations Research*, **141**, 544-558, 2002.
- [5] Pochampally, K. K. and Gupta, S. M., “Strategic Planning of a Reverse Supply Chain network”, *International Journal of Integrated Supply Management*, **1** (4), 421-441, 2005.
- [6] Nukala, S. and Gupta, S. M., “A Single Phase Unified Approach for Designing a Closed-Loop Supply Chain Network”, *Proceedings of the Seventeenth Annual Conference of Production and Operations Management Society*, 2006.

- [7] Tiwari, R. N., Dharmar, S. and Rao, J. R., "Fuzzy goal programming – An additive model", *Fuzzy Sets and Systems*, **24**, 27-34, 1987.
- [8] Zimmermann, H. J., "Description and optimization of fuzzy systems", *International Journal of General Systems*, **2**, 209-215, 1976.
- [9] Zimmermann, H. J., "Fuzzy programming and linear programming with several objective functions", *Fuzzy Sets and Systems*, **1**, 45-55, 1978.