A Green Supply Chain Network Design Considering Carbon Dioxide Emissions, Energy Consumption and Economic Performance

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Abstract. The aim of most supply chain network design problems is to minimize the total cost of the supply chain. One of the most important problems in the today's world is climate changes and its impact on environment and humanity. The green supply chain concept because of its emphasis on energy efficiency, reduction of greenhouse gas emissions, and recycling end of life products, has been considered as an effective solution to this concern. In this article we introduced a green supply chain network design model with forward and reverse flows, considering green procurement and also some tradition costs of supply chain such as fixed cost, transportation cost, purchasing raw material. Two major factors of the model are the energy consumption cost and the Costs of carbon dioxide emissions when the upper limit is exceeded. The concerned supply network includes suppliers, planets, distribution centers and customers in forward scene, and collection centers and disposal centers in backward direction. Each plant can be established by standard or environmentally friendly technology. Multiple types of vehicles with different capacity, cost and CO2 emission are used throughout the supply chain. The problem is formulated as a mixed integer nonlinear programming model and solved using Lingo. Numerical experiments are performed to illustrate the efficiency of the proposed approach.

Keywords: Green Supply Chain, Network Design Problem, Carbon Dioxide Emissions, Energy Consumption.

1 INTRODUCTION

Climate change and its impacts on the earth and humanity are gaining momentum , menacing the integrity and security of economies and the quality of life of vulnerable populations. the main elements to climate change are Anthropogenic green house gases (GHGs), as their atmospheric concentrations have grown markedly since pre-industrial times, with an increase rate of 70% between 1970 and 2004 (Tarek Abdallah 2004).

In order to responding to climate change, the Kyoto Protocol was signed in 1997 and came into force in 2005. The protocols' goals require an emissions reduction of green-house gases by an average of 5% from 1990 levels by 2012 in 37 industrialized countries (Protocol, K., 2007). One of the great achievements in this protocol is emissions trading mechanism. The advantage of this mechanism is that some firms can reduce their emissions more economically than others. This mechanism reduces the pressure on companies to reduce carbon emissions throughout their operations, by allowing them to either invest in other economical emissions reduction projects or purchase carbon credits (Nordhaus 2007).

On the other environmental impacts of end of products (EOL) and limited availability to natural resources are other important problems that have been considered by many researchers in two last decades. Supply chains have more environmental impacts on environment and in order to reduce their environmental impacts, green supply chain is defined. Srivastava (2007) describe green supply chains as ‘‘integrating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, as well as the end of life management of the product after its useful life’’. To have a green supply chain, it is necessary minimizing (preferably eliminating) the negative effect that the supply chain has on the environment. So that, in order to reducing environmental effects of supply chains and for limited availability of natural resources we consider green supply chain concept and also reverse logistics, as a tool of green supply chain for this paper. For this goal we use closed loop supply chains concept too. Wells et al (2005) have defined closed loop supply chains as: “In general terms, closed loops consist of two supply chains: a forward and a reverse chain whereby a recovered product re-enters the traditional forward chain”. therefore, if target is the closed loop supply chain, reverse logistics, which is a means of green supply chain management, is the best approach to reaching that target, because in order to minimize waste, a reverse flow must be introduced into the supply chain and it should be managed in order to make best use of the materials/products returned, through repair and reuse, refurbishment, remanufacturing, cannibalization, or recycling (kumar et al 2006).

In this paper we propose a mixed integer non-linear programming model for a green supply chain with forward and reverse flows where minimizes some traditional supply chains cost such as: fixed cost, transportation cost, energy consumption cost, purchasing raw material cost and co2 emission cost with considering emission trading mechanism. The rest of paper is organized as follows: section 2 gives some literature about the green supply chains. Section 3 introduces the mathematical model of problem. Section 4 shows the numerical examples results and findings and section 5 gives final conclusion.

2 LITERATURE REVIEW

Mincirardi et al (2002) introduced a multi-objective model to minimize solid waste in a supply chain. Bin and Jun (2007) introduced a non-linear mixed integer program for a green supply chain, taking into consideration the effect of e-commerce on the supply chain. They concluded that e-commerce can significantly reduce supply chain costs while also optimizing the green supply chain management. Paksoy et al (2010) proposed a supply Chain model to minimize total cost, prevent more CO_2 gas emissions and encourage customers to use recyclable products. They considered different transportation choices between echelons, according to CO_2 emissions. Wang et al (2011) proposed a multi-objective optimization model that captures the trade-off between the total cost and the environment influence. They were interested in the environmental investments decisions in the design phase. Fatemi ghomi et al (2012) developed a multi-objective optimization problem for a green supply chain that considers the cost elements of the supply chain, such as transportation, holding and backorder costs, and also, the environmental effect components of the supply chain, such as the amount of NO_2, CO and volatile organic particles produced by facilities and transportation in the supply chain. Also they utilized a memetic algorithm in combination with the Taguchi method to solve their model. Tarek abdallah et al (2012) developed a mixed integer program for the carbon-sensitive supply chain that minimizes emissions throughout the supply chain by taking into consideration green procurement also known as environmental sourcing. They also presented a sample case study with a life cycle assessment of three scenarios based on different carbon emissions costs.

In this paper we extended the green supply chain model presented by Tarek abdallah et al (2012) considering reverse logistics as a tool of green supply chain management, different options for transportation and different building technologies for plants according to building technologies that presented in bouchriha (2011) paper.

3 PROBLEM DEFINITION

The integrated supply network considered in this study includes multiple suppliers, multiple production/recovery sites, multiple distribution centers, multiple demand points, multiple collection centers and multiple disposal centers. The best locations to establish production/recovery, distribution, collection and disposal sites from some existing potential locations are the main outputs of the study. Also we want to determine which suppliers to deliver raw materials along with their respective quantities, which plants should supply products to selected distribution centers, the optimized flows of product from selected distribution centers to selected customers with satisfied demands, optimized flows between customers and collection centers, how much collected products will ship to plant for recovery from collected centers and how much products will send to selected disposal centers from collection centers, while costs of supply chain with carbon emission cost are minimized. The major assumptions are that:

1. Customer demands are fixed and deterministic.
2. Plants building technology are: eco-building and standard building.
3. Recovery and recycling is done in opening plants.
4. Capacities for distribution centers, disposal centers and collection centers are deterministic.
5. Each supplier has a threshold amount of raw material to establish a contract.
6. There are two options for transportation.

The problem is formulated as an integer programming as follows:

3.1 Sets

N: set of suppliers

I: set of plants

J: set of distribution centers

C: set of customers

H: set of collection centers

V: set of disposal centers

L: set of products

M: set of transportation options

B: set of building technology

R: set of raw materials

3. 2 Parameters

FI_i^b : Fixed cost at opening a production/recovery center at location i with building technology b.

FJ_j : Fixed cost of opening a distribution center at location j.

FH_h: Fixed cost of opening a collection center at location h.

FV_v : Fixed cost of opening a disposal center at location v.

cp_n^r: Unit cost of purchasing raw material type r from supplier at location n.

NR_l^r: Number of units of raw material type r required to produce one unit of product type l.

TA_n^r: Threshold amount of raw material r required by supplier at location n to establish a contract.

DEM_c^l: Demand of costumer c for product type l.

$CO2P_i^{bl}$: Unit CO2 emission in a production/recovery center at location i with building technology b to produce one unit of product type l.

$CO2REC_i^{bl}$: Unit CO2 emission in a production/recovery center at location i with building technology b to recovery one unit of o products l.

CTP_m: Unit transportation cost between centers using transportation mode m.

$DIST1_{ni}$: Distance between a supplier at location n and production/recovery center at location i.

$DIST2_{ij}$: Distance between production/recovery center at location i and distribution center at location j.

$DIST3_{jk}$: Distance between a distribution center at location j and costumer at location c.

$DIST4_{kh}$: Distance between a customer at location c and collection center at location h.

$DIST5_{hi}$: Distance between a collection center at location h and plant at location i.

$DIST6_{hv}$: Distance between a collection center at location h and disposal center at location v.

$CO2T_m$: Unit CO2 emission using transportation mode m.

$CO2RM_n^r$: Unit CO2 embedded in raw material r from supplier at location n.

$ECCT_M$: Unit energy consumption costs using transportation mode m.

ECC_i^b: Unit energy consumption using a production /recovery center at location i with building technology b to produce.

$ECCREC_i^b$: Unit energy consumption using a production /recovery center at location i with building technology b to recovery.

$PROCAP_i^b$: Plant production capacity.

$RECCAP_i^b$: Plant recovery capacity.

$DISCAP_j$: Capacity of distribution for a distribution center.

$COLLCAP_h$: Capacity of collection for a collection center.

$DSPCAP_v$: Capacity of disposal for a disposal center.

ROR_l: Rate of return for product from customer.

$RORCP_l$: Rate of return for product from collection center to plant.

$RORCD_l$: Rate of return for product from collection center to disposal center.

CCO2: CO2 emission cost.

$CO2^{CAP}$: Maximum amount of carbon credit.

3.3 Decision variables

$X1_{ni}^{rm}$: Quantity of raw material r shipped from supplier n to production/recovery center i using transportation mode m.

$X2_{ij}^{lm}$: Quantity of products type l shipped from production/recovery center i to distribution center j using transportation mode m.

$X3_{jc}^{lm}$: Quantity of product type l shipped from distribution center j to costumer c using transportation mode m.

$X4_{ch}^{lm}$: Quantity of products type l shipped from costumer to collection center h using transportation mode m.

$X5_{hi}^{m}$: Quantity of products shipped from collection center h to production/recovery center i using transportation mode m.

$X6_{hv}^{m}$: Quantity of products shipped from collection center h to disposal center v using transportation mode m.

$CO2^{CUR}$: All amount of carbon dioxide emission in throughout supply chain.

$Y1_{i}^{b}$: 1 if a production/recovery center with building technology b is opened at location i, 0 otherwise.

$Y2_{j}$: 1 if a distribution center is opened at location j, 0 otherwise.

$Y3_{h}$: 1 if a collection center is opened at location h, 0 otherwise.

$Y4_{v}$: 1 if a disposal center is opened at location v, 0 otherwise.

W_{ni}^{r}: 1 if supplier n supplies raw material r to production /recovery center at location i, 0 otherwise.

Y_{n}^{r}: 1 if supplier n supplies raw material typer, 0 otherwise.

3.4 Model

$$\text{Min} \quad \text{TOTAL COST} = FC+TR+EN+PR+CO2C \tag{1}$$

$$FC = \sum_{i,b} FI_{i}^{b} . Y1_{i}^{b} + \sum_{j} FJ_{j} . Y2_{j} + \sum_{h} FH_{h} . Y3_{h} + \sum_{v} FV_{v} . Y4_{v} \tag{2}$$

$$TR = \sum_{n,i,r,m} X1_{ni}^{rm} . CTP_{m} . DIST1_{ni} + \sum_{i,j,l,m} X2_{ij}^{lm} . CTP_{m} . DIST2_{ij} + \sum_{j,k,l,m} X3_{jk}^{lm} . CTP_{m} . DIST3_{jk} + \sum_{k,h,l,m} X4_{kh}^{lm} . CTP_{m} . DIST4_{kh} + \sum_{h,i,m} X5_{hi}^{m} . CTP_{m} . DIST5_{hi} + \sum_{h,v,m} X6_{hv}^{m} . CTP_{m} . DIST6_{hv} \tag{3}$$

$$EN = \sum_{n,i,r,m} X1_{ni}^{rm} . ECCT_{m} . DIST1_{ni} + \sum_{i,j,l,m} X2_{ij}^{lm} . ECCT_{m} . DIST2_{ij} + \sum_{j,k,l,m} X3_{jk}^{lm} . ECCT_{m} . DIST3_{jk} + \sum_{k,h,l,m} X4_{kh}^{lm} . ECCT_{m} . DIST4_{kh} + \sum_{h,i,m} X5_{hi}^{m} . ECCT_{m} . DIST5_{hi} + \sum_{h,v,m} X6_{hv}^{m} . ECCT_{m} . DIST6_{hv} + \sum_{i,j,l,m,b} X2_{ij}^{lm} . ECC_{i}^{b} + \sum_{h,i,m,b} X5_{hi}^{m} . ECCREC_{i}^{b} \tag{4}$$

$$PR = \sum_{n,i,r,m} X1_{ni}^{rm} \; . \; CP_{n}^{r} \tag{5}$$

$$CO2C = (CO2^{CUR} - CO2^{CAP}) * Z1 * CCO2 \tag{6}$$

Subject to:

$$\sum_{j,k,l,m} X3_{jk}^{lm} = DEM_{k}^{l} \tag{7}$$

$$\sum_{n,i,r,m} X1_{ni}^{rm} . = \sum_{i,j,l,r,m} NR_{l}^{r} . X2_{ij}^{lm} \tag{8}$$

$$\sum_{n,i,r,m} X1_{ni}^{rm} . \geq \sum_{n,i,r} TA_{n}^{r} . W_{ni}^{r} \tag{9}$$

$$W_{ni}^{r} \leq Y_{n}^{r} \tag{10}$$

$$X1_{ni}^{rm} \leq U . W_{ni}^{r} \tag{11}$$

$$\sum_{i,j,l,m} X2_{ij}^{lm} \leq PROCAP_{i}^{b} . Y1_{i}^{b} \tag{12}$$

$$\sum_{j,k,l,m} X3_{jk}^{lm} \leq DISCAP_{j} . Y2_{j} \tag{13}$$

$$\sum_{h,i,m} X5_{hi}^{m} \leq RECCAP_{i}^{b} . Y1_{i}^{b} \tag{14}$$

$$\sum_{k,h,l,m} X4_{kh}^{lm} \leq COLLCAP_{h} . Y3_{h} \tag{15}$$

$$\sum_{h,v,m} X6_{hv}^{m} \leq DSPCAP_{v} . Y4_{v} \tag{16}$$

$$\sum_{i,j,l,m} X2_{ij}^{lm} \leq \sum_{j,k,l,m} X3_{jk}^{lm} \tag{17}$$

$$\sum_{n,i,r,m} X1_{ni}^{rm} . CO2T_m . DIST1_{ni} + \sum_{i,j,l,m} X2_{ij}^{lm} . CO2T_m . DIST2_{ij} + \sum_{j,k,l,m} X3_{jk}^{lm} . CO2T_m . DIST3_{jk} + \sum_{k,h,l,m} X4_{kh}^{lm} . CO2T_m . DIST4_{kh} + \sum_{h,i,m} X5_{hi}^{m} . CO2T_m . DIST5_{hi} + \sum_{h,v,m} X6_{hv}^{m} . CO2T_m . DIST6_{hv} + \sum_{i,j,l,b,m} X2_{ij}^{lm} . CO2PB_i^{bl} + \sum_{h,i,b,m} X5_{hi}^{m} . CO2RECB_i^{bl} + \sum_{n,i,r,m} X1_{ni}^{rm} . CO2RM_n^{r} = CO2^{CUR} \tag{18}$$

$$\sum_{k,h,l,m} X4_{kh}^{lm} = \sum_{j,k,l,m} ROR_l . X3_{jk}^{lm} \tag{19}$$

$$\sum_{h,i,m} X5_{hi}^{m} = \sum_{k,h,l,m} RORCP_l . X4_{kh}^{lm} \tag{20}$$

$$\sum_{h,v,m} X6_{hv}^{m} = \sum_{k,h,l,m} RORCD_l . X4_{kh}^{lm} \tag{21}$$

$$CO2^{CUR} > CO2^{CAP} * Z1 \tag{22}$$

$$CO2^{CUR} \leq CO2^{CAP} + M * Z1 \tag{23}$$

$$\sum_{b} Y1_i^{b} \leq 1 \tag{24}$$

$$Y1_i^{b} = \{0 , 1\}, \forall\ i,b \tag{25}$$

$$Y2_j = \{0 , 1\}, \forall\ j \tag{26}$$

$$Y3_h = \{0 , 1\}, \forall\ h \tag{27}$$

$$Y4_v = \{0 , 1\}, \forall\ v \tag{28}$$

$$W_{ni}^{r} = \{0 , 1\}, \forall\ n,i,r \tag{29}$$

$$Z1 = \{0 , 1\} \tag{30}$$

$$X1_{ni}^{rm}, X2_{ij}^{lm}, X3_{jc}^{lm}, X4_{ch}^{l\,m}, X5_{hi}^{m}, X6_{hv}^{m} \geq 0 \tag{31}$$

Objective Function (1) minimizes the total costs within the supply chain. Relation (2) determines the fixed cost of the supply chain based on opened facilities. Equation (3) computes the transportation cost according to the distance and amount of the transported product by each transportation mode. Relation (4) computes the energy consumption cost according to the distance and amount of the transported product by each transportation option and energy consumption in plants according to amount of produced and recovered products. (5) computes purchasing cost of raw materials and (6) computes CO2 emission cost in throughout the supply chain according to amount of emission in transportation and plants and co2 embedded in raw materials. Constraint (7) ensures that the demand of each customer is satisfied by the open DCs. Constraint (8) ensures that all the raw material requirements are met from the assigned suppliers. Constraint (9) states that every supplier has a minimum raw material order requirement to establish a contract. Constraint (10) describes that no contract is established unless a supplier provides the raw material. (11) ensures that no raw material is shipped unless a contract is established. Constraints (12)-(16) are defined to guarantee the capacity of different sites. Relation (17) ensures that the total flow of product l that enters DC j from all plants does not exceed the flow that leaves the DC to all customers. (18) calculates the carbon dioxide emissions across the supply chain. Constraint (19) states that there is a rate for return of end of life products from customers. (20) describes that after inspection in the collection centers only number of collected products that are recyclable ship to plant for recovery or recycling. Constraint (21) states that non-recyclable collected products send to disposal centers. Relations (22) and (23) define Z1 binary variable which should be one if and only if $CO2^{CUR}$ is bigger than $CO2^{CAP}$. Constraint (24) ensures that only one type of building technology is selected for opened plant i. Constraints (25)-(30) enforce the binary restriction of some variables and (31) enforce the non-negativity restriction of other variables respectively.

4 EXPERIMENTAL RESULTS

In this section the results of some numerical examples carried out to evaluate the performance of the proposed model. To do so the developed model is coded and solved using Lingo 8.0 software. All experiments are performed using a computer with an Intel Core 2duo 2.2 GHz CPU and 2GB of RAM. We generate four different instances randomly and in each case the optimal solution of the problem is gained and the running CPU time is reported. Since the problem is NP-complete the optimal solution will be achievable just for reasonable size problems. These experiments are summarized in tables 1 and 2.

Table 1: Dimensions of tests

	Test 1	Test 2	Test 3	Test 4
# of Suppliers	2	4	4	6
# of Raw material types	2	2	2	3
# of Plants	2	3	3	4
# of Distribution centers	2	4	4	5
# of Customers	2	8	15	30
# of Collection centers	2	3	3	5
# of Disposal centers	2	2	3	5
# of Transportation options	2	2	2	3
# of Products	2	3	4	5
CO2 Capacity	100000	200000	2000000	400000

Table 2: optimal solutions and solution times

	Optimal solution	Solution time (s)
Test 1	405680.0	10
Test 2	3852382.0	13
Test 3	7694819.0	106
Test4	60816060.0	314

As can be seen from table 2 by increasing the size of the problem, the solution time will increase exponentially and thus the optimization software are useful just for limited dimension.

5 SUMMARY AND CONCLUSIONS

Pace of Climate change is increasing in recent years and greenhouse gases emission is one of the most important factors that contribute to this change. Green supply chain design is one of the areas that has been considered for this problem by many researchers. Green supply chain approach is a new attitude where supply chains can reduce their environmental effects, collecting their end of products to recover them. We utilized the srivastava definition of green supply chain that mentioned above, in our proposed model. The developed mixed integer non-linear programming model is based on fixed cost of opened facilities, energy consumption cost, supply chain operational costs and carbon dioxide emission cost for extra emission that considering these elements is innovations of this model. The problem was solved using the LINGO 8.0 optimization solver on four tests with different dimensions and the optimal solutions are gained. However for large size problems optimization software cannot achieve to optimal solution. Future studies may develop heuristic methods solving this problem with bigger dimensions in acceptable times, define other objectives and also perform the model on real-world cases.

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