A carbon sensitive supply chain network problem with green procurement

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Abstract—Faced with growing concerns over the environmental impact of human activities and increasing regulatory pressure, companies are beginning to recognize the importance of greening their supply chains by minimizing carbon emissions of their activities. An original equipment manufacturer that is concerned with minimizing the environmental impact of its activities should choose its suppliers based on the trade off between costs and respective emissions. In this paper, we develop an MIP model for the carbon-sensitive supply chain that minimizes emissions throughout the supply chain by taking into consideration green procurement. A sensitivity analysis of our model and results on several small problems are included.

I. INTRODUCTION

Anthropogenic Green house gases (GHG) are rapidly warming the earth and are causing changes in the global climate that will lead to severe environmental, economic and social impacts over the coming decade. Global GHG emissions increased around 70% between 1970 and 2004 due to the increases in population, energy demand, and human activities, [1]. This provides strong evidence for the effect of GHG on global warming as eleven of the last twelve years (1995-2006) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850) [1]. Many scientists also believe that the increase in natural disasters is fueled by climate change, since atmospheric and oceanic patterns shift as the earth’s temperature increases [2].

In response to climate change challenge, the Kyoto protocol was signed in 1997 and came into force in 2005. The protocol sets emissions target for 37 industrialized countries (Annex B). As mentioned in article 3 of the protocol, most of these targets require an emissions reduction of greenhouse gases by an average of 5% from 1990s levels by 2012 [3]. The protocol sets more aggressive targets for developed nations for their responsibility for 150 years of industrialized activity. The Kyoto protocol does not only call for collaborative governmental action, but also sets legally binding conditions for the committing countries.

The protocol introduced various flexible mechanisms through which different countries can cooperate to meet their reduction targets and cutting down their costs. The Kyoto mechanisms are:

(i) Emissions trading known as “the carbon market”: as set out in article 17, allows countries that are below their targets to sell this excess capacity to countries that are over their targets. Since Carbon is the principle GHG, it is now tracked and traded like any other commodity in a “carbon market”;

(ii) Clean development mechanism (CDM): defined in Article 12, allows countries with greenhouse gas reduction commitments to invest in emission-reduction projects in developing countries. Such projects can earn salable certified emission reduction (CER) credits which can be counted towards the meeting of Kyoto targets;

(iii) Joint implementation (JI); defined in Article 6, allows a country with an emission reduction commitment to invest in emission-reduction projects in another developed country committed to its emissions reductions. Such projects, as well, can earn emissions reduction units (ERUs) from the host country which can be counted towards the meeting of Kyoto targets of the investing country.

The carbon trading mechanism is one of the great innovations in environmental policy [4]. The advantage of allowing a trade is that some firms can reduce their emissions more economically than others. It relieves the pressure on companies to reduce carbon emissions throughout their operations, by either greening its own activities or investing in other economical emissions reduction projects or through purchasing carbon credits. In any way, companies realize now that they will have to pay for their emissions under business as usual strategies. In addition, this mechanism increases the competition amongst firms to provide greener products and increase their appeal to the growing number of environmentally-conscious consumers.
This would force a change in the way companies manage their supply chains; they would have to find new and innovative means of optimizing the supply chain to reduce carbon emissions, across all its stages and implement green procurement to minimize its carbon footprint. The result is an economy where all suppliers and end-use products companies are competing to reduce GHG emissions, in order to increase their market share and meet reductions requirements.

This paper presents a novel optimization model for green supply chain management with green procurement that minimizes traditional supply chain location and transportation cost, in addition to the carbon emissions cost through carbon trading. The mixed-integer programming (MIP) model captures the impact of different emission caps on the supply chain cost, and helps reveal an optimal strategy for companies to meet their carbon cap, while minimizing the opportunity cost. The model assumes that the company’s emissions are directly affected by the carbon embedded in the raw materials procured from the suppliers. The paper is organized as follows: Section II presents the literature conducted on green supply chains; Section III presents the mathematical formulation of the model; Section IV presents the numerical analysis of the model; and Section V concludes with future research directions.

II. LITERATURE REVIEW

Since the early 1990s, manufacturers have been faced with pressure to integrate environmental management into their supply chains [5]. Srivastava defines green supply chain management 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 end-of-life management of the product after its useful life” [6]. Interested readers about end-of-life management are referred to [7],[8].

Green procurement is an important step towards greening the supply chain. Geffen and Rothenberg [9] used three case studies of US assembly plants to examine the role of Strategic partnership between manufacturers and their suppliers to achieve their desirable environmental performance targets. The study concluded that manufacturers and suppliers’ that were actively involved in each other plants achieved the greatest success. Simpson and Power [10] investigated the relationship between a supplier and firm’s level of environmental management activity and the structure of the customer-supplier manufacturing relationship. They concluded that the manufacturing system is where the greatest amount of pollution is generated and where the greatest amounts of resources are consumed. Hence, the supply-manufacture relationship has the ability to make significant strides towards a greener supply chain. Preuss [11] suggested five ways to green the supply chain. First, manufacturers should focus on the material procured from its suppliers. Second, manufacturers need to include environmental criteria in their assessments of suppliers. Third, the manufacturers should monitor the manufacturing processes of the its supply chain, e.g. by seeking accreditation to an environmental standard such as ISO 14001. Fourth, manufacturers should be involved in internal environmental protection initiatives such as the establishment of an environmental management systems. Finally, supply chain managers should be more involved in downstream activities like product recovery.

Sheu et al. [12] formulated a linear multi-objective that systematically optimizes the operations of both integrated logistics and corresponding reverse logistics in a given green-supply chain. Government subsidies for reverse logistics were considered during the formulation. A typical 5-layer manufacturing supply chain was proposed to characterize 5 respective forward functions in corresponding layers: raw material supply, manufacturing, wholesaling, retailing, and end-customers. Similarly, a 5-layer reverse logistics chain was specified: recycling plants, 1 disassembly plant, secondary material markets, and final disposal locations of wastes. Their results showed an increase of around 21.3 % in net profit by implementing the suggested integrated supply chain model.

Hugo and Pistikopoulos [13] presented a multi-objective mathematical programing that includes Life cycle analysis (LCA) in the decision process of the traditional supply chain network design. At the strategic level, the model determines the optimal location sites, optimum combination of processing technologies, the capacity expansions, and allocates demands with distribution links to the market demand. Also, at the operational level, the model determines optimal production quantities and their flow along the different components of the supply chain. Bojarski et al. [14] also presented a mixed integer program with LCA embedded in the formulation. However, their work included the decisions regarding the planning and design of a SC under economical and environmental impacts consideration. The goal was to determine the active links in the supply chain, the facilities capacity in each time period, the assignment of the manufacturing and distribution tasks to the network nodes, the amount of final products to be sold, and the environmental impact associated to each SC node. Ramudhin et al. [15] introduced the carbon market sensitive supply chain network problem. Their mixed integer program focuses on the impact of transportation, subcontracting, and production activities on the design of a green supply chain. They considered the multi-supplier, multi-plant, multi-product, and multi-retailer problem, but assume that the plant/DC locations and sizes are known in advance. Diabat and Simchi-Levi [16] presented the carbon capped supply chain where they consider the throughput capacity of the manufacturing site and storage capacity of the distribution centers as decision variables. However, they restricted the carbon emissions from the supply chain to the allocated carbon cap with out taking into consideration the flexible mechanism of emissions trading. In addition, they did not consider the effect of suppliers’ emissions on the overall emissions of the company. In this paper, we introduce a different MIP model in which carbon trading mechanism is realized where the company can decide to either sell or buy its credits while monitoring its carbon...
emissions. In addition, we introduce the green procurement concept where the decision on which supplier to choose affects the overall carbon footprint of the supply chain.

III. MODEL FORMULATION

A. Model Description

The carbon-sensitive supply chain with green procurement (CSSCGP) is a two-level multi-commodity facility location problem [17] with a trading price of carbon emissions and cost of procurement. The company might either incur costs if the carbon cap, normally assigned by regulatory agencies, is lower than the current emissions or gain profit from selling excess credits. The network consists of a set of candidate suppliers for raw materials, a set of potential plants of different production capacities, a set of distribution centers (DCs) of different throughput capacities, a set of retailers, and a set of product types. The problem is to decide which suppliers to deliver the raw materials, how the plants distribute the products to the candidate DCs, and how the retailers’ demand is satisfied from the DCs, in such a way that the total facility opening, products distribution and carbon emissions costs are minimized. This supply chain considers the green procurement problem by holding the original equipment manufacturer accountable for the emissions embedded in the raw materials procured in addition to the carbon emissions incorporated with the transportation of these materials. Retailers’ demands are assumed to be deterministic, and the plants and DCs have limited production and throughput capacities to be determined.

In our model, we assume that carbon emissions come from five main sources:

(i) the raw materials of the suppliers, where the manufacturer is held accountable for the carbon embedded in the raw material supplied;
(ii) the delivery of the raw materials, where the emissions level is based on traveled distance;
(iii) the plants, where the amount of emissions is proportional to the power consumption of these products;
(iv) the DCs, and the amount of emissions is proportional to the volume of these DCs; and
(v) the distribution of the products, where the emissions level is based on the traveled distance.

Seven major cost components are considered in the objective function of the model. They are as follows:

(i) DC fixed-location cost: the cost to establish and operate a distribution center;
(ii) DC-retailer unit-shipping cost: the cost to ship one unit of a commodity from a DC to a retailer;
(iii) plant fixed-location cost: the cost associated with establishing and operating a plant;
(iv) plant-DC unit-shipping cost: the cost to ship one unit of a product from a plant to a DC;
(v) unit cost of raw material: the cost of procuring one unit of raw material;
(vi) supplier-plant unit-shipping cost: the cost to ship one unit of raw material from a supplier to a plant; and
(vii) carbon trading cost: the cost of purchasing carbon credits;

B. Notation

To formulate the problem, the following notation is used:

Sets

\[ I \triangleq \text{set of retailers, indexed by } i \]
\[ J \triangleq \text{set of potential DC sites, indexed by } j \]
\[ K \triangleq \text{set of potential plant locations, indexed by } \kappa \]
\[ N \triangleq \text{set of potential suppliers, indexed by } n \]
\[ \Omega \triangleq \text{set of raw materials, indexed by } \rho \]
\[ \hat{J} \triangleq \text{set of DC sizes, in ft}^3, \text{indexed by } \hat{j} \]
\[ \hat{K} \triangleq \text{set of plant production capacities in kilowatt hour (KWh), indexed by } \hat{k} \]
\[ L \triangleq \text{set of products, indexed by } \iota \]

Parameters

\[ f_{\kappa} \triangleq \text{fixed-cost to run a plant of size } \hat{k} \text{ at location } \kappa \]
\[ g_{j} \triangleq \text{fixed cost to open and operate a DC of size } \hat{j} \text{ at location } j \]
\[ \alpha_{i\iota} \triangleq \text{demand of retailer } i \text{ for product type } \iota \]
\[ c_{\iota} \triangleq \text{distribution cost of product type } \iota \text{ per unit distance} \]
\[ c_{\rho} \triangleq \text{distribution cost of raw material type } \rho \text{ per unit distance} \]
\[ \bar{c}_{n\rho} \triangleq \text{unit cost of procuring raw material type } \rho \text{ from supplier } n \]
\[ \beta_{\rho} \triangleq \text{amount of raw material type } \rho \text{ needed to manufacture one unit of product } \iota \]
\[ \theta_{n\rho} \triangleq \text{threshold amount of raw material } \rho \text{ required by supplier } n \text{ to establish a contract} \]
\[ w_{j} \triangleq \text{throughput capacity, in ft}^3, \text{ of a DC } \hat{j} \]
\[ p_{\kappa} \triangleq \text{production capacity, in KWh, of plant } \hat{k} \]
\[ q_{\iota} \triangleq \text{capacity, in KWh, required to produce one unit of product type } \iota \text{ at any plant} \]
\[ s_{\iota} \triangleq \text{capacity, in ft}^3, \text{ required to store a unit of product type } \iota \text{ at any warehouse} \]
\[ d_{ij} \triangleq \text{distance, in miles, between retailer } i \text{ and a DC at location } j \]
\[ d_{j\kappa} \triangleq \text{distance, in miles, between a plant at location } \kappa \text{ and a DC at location } j \]
\[ d_{kn} \triangleq \text{distance, in miles, between a supplier at location } n \text{ and a plant at location } \kappa \]
\[ e_{j\kappa} \triangleq \text{distance, in miles, from a DC at location } j \text{ and a plant at location } \kappa \]
\[ CO_{2}^{\rho} \triangleq \text{maximum amount (in tons) of carbon dioxide (CO}_2) \text{ that can be emitted} \]
\[ \alpha_{p} \triangleq \text{CO}_2 \text{ emissions factor of a plant, in ton per KWh of operation} \]
\[ \alpha_{w} \triangleq \text{CO}_2 \text{ emissions factor of a warehouse, in ton per ft}^3 \]
\[ \alpha_{s} \triangleq \text{CO}_2 \text{ emissions factor per unit distance, in ton per mile} \]
C. The Model

Decision Variables

\[ X_{ijt} \triangleq \text{total number of units of product type } t \text{ distributed to retailer } i \text{ from warehouse } j \]
\[ Y_{jkt} \triangleq \text{total number of units of product type } t \text{ shipped from plant } k \text{ to warehouse } j \]
\[ Z_{kn} \triangleq \text{total number of units of raw material } \rho \text{ shipped from supplier } n \text{ to plant } k \]
\[ \bar{Z}_{kn} \triangleq \begin{cases} 1 & \text{if supplier } n \text{ supplies raw material } \rho \text{ to plant at location } k \\ 0 & \text{otherwise} \end{cases} \]
\[ U_{j} \triangleq \begin{cases} 1 & \text{if we open a warehouse of size } \hat{j} \text{ at location } j \\ 0 & \text{otherwise} \end{cases} \]
\[ V_{\hat{k}} \triangleq \begin{cases} 1 & \text{if we run a plant with production capacity } \hat{k} \text{ at location } \kappa \\ 0 & \text{otherwise} \end{cases} \]
\[ CO_2^{\text{CUR}} \triangleq \text{amount (in tons) of carbon dioxide (CO}_2\text{) that is currently emitted} \]

The objective function equation (1) minimizes the sum of the fixed costs, distribution costs, procurement costs and carbon emissions cost with carbon trading. Constraint set equation (2) ensures that the demand of each retailer is satisfied by the open DCs. Constraint set equation (3) ensures that all the raw material requirements are met from the assigned suppliers. Constraint set equation (4) states that every retailer has a minimum number of raw material order requirement to establish a contract. Constraint set equation (5) ensures that no contract is established unless a supplier provides the raw material. Constraint set equation (6) ensures that no raw material is shipped unless a contract is established. Constraint set equation (7) ensures that the demands of retailers that are supplied by open DCs do not exceed the throughput capacity of any of those DCs. Constraint set equation (8) ensures that total flow of product \( t \) that enters DC \( j \) from all plants does not exceed the flow that leaves the DC to all retailers. Constraint set equation (9) represents the capacity restriction of plant \( \kappa \) of size \( \hat{k} \) in terms of the amount of product it can handle. Constraint set equation (10) calculates the carbon dioxide emissions across the supply chain. Constraint set equations (11)-(13) and (14)-(16) enforce the non-negativity and the binary restrictions on the decision variables.

IV. EXPERIMENTAL ANALYSIS

Our analysis was based on the 49-node dataset presented in Daskin(1995) [17]. The 49-nodes represent candidate plants locations, DCs locations, and current retailers locations. Nodes 1 – 16 represent candidate supplier locations. We used a hypothetical product which consists of 4 raw materials procured from different suppliers. Nodes 1 – 4 are candidate suppliers of raw material one, nodes 5 – 8 are candidate suppliers of raw material two and so on. Each supplier has different emissions, costs, and minimum demand requirements generated using a random number. We assume there are 5 possible plant throughput capacities (in KWh) and DC sizes (in ft^3) (5000, 10000, 20000, 40000, 80000). The fixed location costs for the lowest size of plants and DCs were calculated by multiplying the fixed cost given by Daskin by 10. This cost was multiplied by 1.3 for incremental change in size. The
distance between the nodes were set to the euclidean distance between them. The value of the other parameters are used in the analysis are provided in Tab. I.

### TABLE I
VALUES OF PARAMETERS USED IN THE ANALYSIS

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<td>αₗ</td>
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<td>αₜ</td>
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We performed sensitivity analysis based on different expected prices for the carbon credits. We used ILOG CPLEX 11.0 MIP solver in the GAMS modeling language.

Fig. 1 shows that as the carbon credits cost increases the total CO₂ emissions will decrease. At lower prices the total cost would increase due to purchasing of credits, but once the cost of abatement is lower than the price of the credit, the total cost decreases since the supply chain becomes carbon efficient which allows the company to shift from a carbon credits purchaser to seller.

Fig. 2 shows that as the price of carbon credits increases the carbon trading cost decreases. In fact, the company as it becomes more carbon efficient it starts generating profit by selling its excess carbon credits.

Fig. 3 shows that as the carbon credits price increase the number of DCs opened increases in order to minimize the carbon emissions due to transportation. Also the average size of the DCs will eventually decrease as less products are allocated to the DCs (note that the case “min carbon” represents an objective function that minimizes only the carbon emissions).

### V. CONCLUSION

In this paper, a novel approach to greening the supply chain through consideration of the carbon emissions along the supply chain and introduction of the green procurement concept is presented. The problem was formulated as a MIP and solved using ILOG CPLEX 11.0 MIP solver in GAMS. The experimental analysis shows that companies will tend to reduce their carbon emissions significantly with the introduction of carbon price by decentralizing the supply chain and multi-sourcing to reduce the transportation and production emissions. This model can help supply chain managers to devise their strategy based on their future expectations of a binding carbon trading scheme and the cost of carbon credits. We are now considering to work with the carbon management unit at Masdar City (the world first carbon neutral city) to devise a case strategy to minimize the carbon footprint of several supply chains at Masdar City and implementing Life cycle analysis to quantify the improvement in the sustainability index of the products.

1. www.masdar.ae
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