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A Carbon-Capped Supply Chain Network Problem

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***Abstract*—The Kyoto protocol was negotiated as a global effort to reduce greenhouse gas (GHG) emissions. The future standing of companies will be seriously affected by the steps they take today in regards to the environment. Perhaps, if vigilant actions are not taken by a firm then it could easily be left behind in today's highly competitive world. This paper presents a novel optimization model for green supply chain management, which integrates environmental management and its impact into the supply chain while taking carbon emissions into account. The model, which we formulate as a mixed-integer program (MIP), can help to reveal an optimal strategy for companies to meet their carbon cap, while minimizing opportunity cost. We demonstrate the viability of the model via a computational study.**

***Keywords*—Green supply chains, carbon emission, cap-and-trade, location problem, integer programming.**

I. INTRODUCTION

Among the wide range of problems facing our world today, there is global consensus that greenhouse gas (GHG) emissions have the largest negative impact on our environment. GHGs include carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons and perfluorocarbons [1]. These gases help to maintain the temperature of the earth at comfortable levels for organisms, and a decrease in their levels would result in a temperature that could be too low for us to live in. However, while GHGs allow sunlight to enter the atmosphere, they trap the heat radiated off the earth's surface, and an increase in these emissions would result in an increase in the planet's temperature, or global warming, to levels that could be detrimental to living organisms. 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. Even with the awareness of the dangers of GHG emissions, the concentration of carbon dioxide and GHGs has been rising over the years, along with the temperature of the earth, which increased by 0.8 degrees Celsius between 1900 and 2005. Over the past 150 years, the last decade was recorded to be hottest, while 2005 has been claimed to be the hottest year of the last 150 years [1, 2]. What first seemed to be a regional concern over global warming has now turned into a continental one. As a result, concern over global warming has made its way into all parts of our society, and the corporate/industrial world, which is responsible for a large part of the emissions, cannot turn a blind eye to what has become a social responsibility. However, to motivate firms to reduce GHG emissions and to fuel their research into clean energy technologies, a market pull has to be generated for them [3, 4]. The Kyoto protocol, a part of the United Nations Framework Convention on Climate Change[1], was negotiated as part of a global effort to reduce GHG emissions. The protocol establishes legally binding commitments on all member nations to reduce their GHG emissions. Emissions limits, or caps, force economies to consider their emissions. To allow economies to meet their emission restrictions, the protocol introduced three "flexible mechanisms". The first two of these are the Joint Implementation mechanism, which allows countries to carry out emission reduction projects in other countries to gain emission credits, and the Clean Development mechanism, which allows countries to gain emission credits by financing emission reduction projects in developing countries. The third mechanism is Emissions Trading (also known as carbon trading) [5, 6], which serves as an economic incentive for companies to reduce pollution and emissions. Governments set limits, or caps, on the amount of certain pollutants allowed to be emitted. Each company will have an emission allowance. If a company wishes to exceed that allowance, it will have to buy emission credits from companies that produce less GHGs, or are below their cap.

The carbon trading mechanism applies pressure on companies to reduce carbon emissions throughout their operations, to seek more environmentally friendly ways of conducting their business, and to contribute to emission-reducing projects worldwide. In addition, with a 'carbon market' created out of this mechanism, competition amongst firms to become more 'green' is fiercer, and a bigger effort has to be made by companies looking to make their products more appealing to the growing number of environmentally-conscious consumers in the market, and to a next generation workforce eager to make a positive impact on the world they live in [7]. Furthermore, a cap placed on emissions applies pressure on companies to change and optimize their internal and external processes in

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[1] Website: http://unfccc.int

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order to reduce their GHG emissions. This would force a change in the way companies run 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. Companies will now have one of two options: either to alter their processes and experiment with new technologies to keep their emissions under the cap, or leave the supply chain as it is and purchase emission credits from companies that have remained below their limit. Either way, this will have to be done while competing with other supply chains. The result is an economy where all companies are competing to reduce GHG emissions, in order to meet an overall reduction target.

Integrating environmental management into the supply chain is a complex process because of the numerous options supply chain managers have at different stages of the chain. However, with the current financial incentives and governmental pressures on companies to reduce their emissions and protect the environment, supply chain managers will have to find optimal methods for greening their supply chain, and this is now an area of intense ongoing research.

This paper presents a novel optimization model for green supply chain management that integrates a mixed-integer programming (MIP) model with carbon emission considerations. The 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 opportunity cost. The remainder of the paper is organized as follows: Section II surveys the literature on green supply chain management; Section III presents the mathematical formulation of the model; Section IV provides a numerical analysis of the model; and Section V concludes the paper.

II. LITERATURE REVIEW

A supply chain is traditionally defined as a group of organizations that perform the various processes that are required to make a finished product. The chain begins with materials and ends with the finished product that is delivered to the customers. The supply chain includes the manufacturer, transporters, warehouses, retailers, and customers themselves. Within each organization, the supply chain includes all functions involved in satisfying customer demand. A very simple definition of a supply chain is due to Simchi-Levi et al. [8]:

> *Supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service level requirements.*

Green supply chains (GSCs), or environmentally conscious supply chains, involve the design and implementation of supply chains that incur minimal environmental impact [9]. Environmental awareness and legislation have successfully pushed companies to aim for the manufacture of greener products that would have less impact on the environment through all stages of their manufacturing and distribution [10]. Reducing the supply chain's emissions has become a necessary obligation, and the "trade-offs in the supply chain are no longer just about cost, service and quality — but cost, service, quality and carbon," [11]. Integrating the environment into companies' processes by limiting their emissions has made companies evolve their waste control from "end-of-pipe control" to emission and pollutant prevention at the source, by altering or redesigning their products and production processes [12]. The chain will no longer only consist of processes like raw material extraction, manufacturing, distribution and directing waste flows. Green Supply Chain Management brings a new dimension to the chain, by adding processes such as reverse logistics (reuse, disposal, recycling, etc.). Srivastava [13] has conducted a thorough literature review on green supply chain. Some of the different facets introduced by the management of GSCs are discussed below.

Green design is one of the rising issues that have attracted researchers to the field. Hugo and Pistikopoulos [14] introduced a mathematical programming-based methodology that integrated life cycle assessment criteria into the design and planning decisions of supply chain networks. Multiple environmental concerns were considered along with financial criteria in formulating the planning task as an optimization problem. Strategic decisions involving the selection, allotment and capacity expansion of technologies along with the appointment of appropriate transportation routes that would satisfy market demand were addressed using MIP. Another aspect of Green Supply Chain Management that has attracted growing attention is reverse logistics, which refers to the moving of products from their point of consumption or final destination to capture value (e.g. recycling) or for proper disposal. The importance of recoverable products for the industry-push towards environmentally considerate manufacturing is shown by Jayaraman et al. [15], who emphasize the importance of a recoverable product environment, which is made possible through a recoverable manufacturing system that extends the life of a product by recovering it, then remanufacturing or repairing it. Materials and products in this environment flow from both the consumer to the remanufacturer, and from the remanufacturer to the consumer. The authors then present a model using 0-1 mixed integer programming, which is solved for the location of remanufacturing and distribution plants, and the optimal amounts of remanufactured products to produce and store. The model was also shown to be useful for management in their logistics decision-making. Furthermore, Lu et al. [16] studied inventory management and production planning for remanufacturing. They stressed the importance of all players in the supply chain (the companies, suppliers and customers) for making it greener. Ramudhin et al. [17] introduce a MIP formulation of the green supply chain network problem. Their model focuses on the impact of transportation, subcontracting, and production activities on the design of a green supply chain. They consider the multi-supplier, multi-plant, multi-product, and multi-retailer problem, but they assume that the plant/DC locations and sizes are known in advance. In this paper, we introduce a different MIP model in which the sizes and locations of facilities are not fixed.

III. MODEL FORMULATION

A. Model Description

The carbon-capped supply chain network (CCSCN) is a two-level multi-commodity facility location problem [18, 19], with a carbon emission constraint. The network consists of a set of plants of various production capacities, a set of distribution centers (DCs) of various throughput capacities, a set of retailers, and a set of product types. The problem is to decide which plants and DCs to open, how the DCs are assigned to the plants, and how the DCs distribute multiple types of products to satisfy retailers' demands, in such a way that the total facility opening and products distribution costs are minimized and total carbon emission is not more than a predetermined emission cap. Retailers' demands are assumed to be deterministic, and the plants and DCs have limited production and throughput capacities. Throughout this paper, we use the words warehouse and DC interchangeably, while we use the word facility to refer to a plant, warehouse, or retailer. Figure 1 shows a schematic representation of the CCSCN's structure.

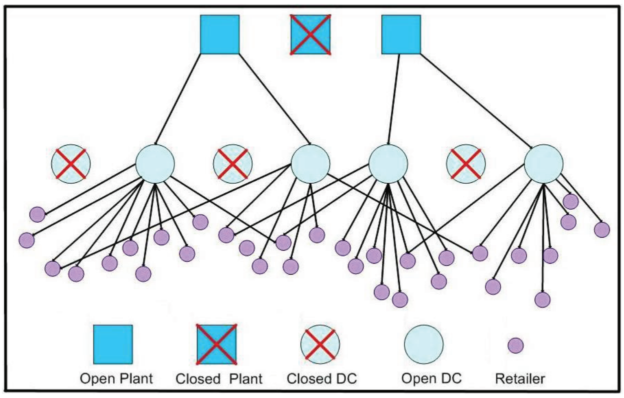

Fig. 1. A schematic representation of the CCSCN.

We assume that carbon emissions come from three sources:

(i) from the plants, and the amount of emissions is proportional to the power consumption of these plants;
(ii) from the warehouses, and the amount of emissions is proportional to the volume of these warehouses;
(iii) from the distribution of the products, and the emissions level is based on the traveled distance between facilities.

Four 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; and
(iv) plant-DC unit-shipping cost: the cost to ship one unit of a commodity from a plant to a DC.

B. Notation

To formulate the problem, the following notation is used:

Sets

$I \triangleq$ set of retailers, indexed by i
$J \triangleq$ set of potential warehouses sites, indexed by j
$K \triangleq$ set of potential plant locations, indexed by κ
$\widehat{J} \triangleq$ set of warehouse sizes (in ft^3), indexed by $\hat{j}$
$\widehat{K} \triangleq$ set of plant production capacities in kilowatt hour (KWh), indexed by $\hat{\kappa}$
$L \triangleq$ set of products, indexed by ι

Parameters

$f_{\kappa}^{\hat{\kappa}} \triangleq$ fixed-cost to run a plant of size $\hat{\kappa}$ at location κ
$g_{j}^{\hat{j}} \triangleq$ fixed cost to open and operate a warehouse of size $\hat{j}$ at location j
$a_{i\iota} \triangleq$ demand of retailer i for product type ι
$c_{ij\iota} \triangleq$ cost to distribute a unit of product type ι from a warehouse at location j to retailer i
$h_{j\kappa\iota} \triangleq$ cost to distribute a unit of product type ι from a plant at location κ to warehouse j
$w^{\hat{j}} \triangleq$ throughput capacity of warehouse $\hat{j}$ in ft^3
$p^{\hat{\kappa}} \triangleq$ production capacity in kWh of plant $\hat{\kappa}$
$q_{\iota} \triangleq$ capacity (in kWh) required to produce one unit of product type ι at any plant
$s_{\iota} \triangleq$ capacity, in cubic feet , required to store a unit of product type ι at any warehouse
$d_{ij}^{w} \triangleq$ distance, in miles, between retailer i and a warehouse at location j
$d_{j\kappa}^{p} \triangleq$ distance, in miles, between a plant at location κ and a warehouse at location j
$e_{j\kappa} \triangleq$ distance (in mi) from a warehouse at location j and a plant at location κ
$CO_2^{\text{CAP}} \triangleq$ maximum amount (in tons) of carbon dioxide (CO_2) that can be emitted
$\alpha_p \triangleq$ CO_2 emissions factor of a plant, in tons per KWh of operation
$\alpha_w \triangleq$ CO_2 emissions factor of a warehouse, in tons per ft^3
$\alpha_s \triangleq$ CO_2 emissions factor per unit distance, in tons per mile

Decision Variables

$X_{ij\iota} \triangleq$ total number of units of product type ι distributed to retailer i from warehouse j
$Y_{j\kappa\iota} \triangleq$ total number of units of product type ι shipped from plant κ to warehouse j

$$U_{j}^{\hat{j}} \triangleq \begin{cases} 1 & \text{if we open a warehouse of size } \hat{j} \text{ at location } j \\ 0 & \text{otherwise} \end{cases}$$

$$V_{\kappa}^{\hat{\kappa}} \triangleq \begin{cases} 1 & \text{if we run a plant with production capacity } \hat{\kappa} \text{ at location } \kappa \\ 0 & \text{otherwise} \end{cases}$$

C. The Model

The MIP formulation of the the CCSCN problem can be stated as follows:

$$\min \quad \left\{ \begin{array}{l} \sum_{j\in J}\sum_{\hat{j}\in\widehat{J}} g_j^{\hat{j}} U_j^{\hat{j}} + \sum_{i\in I}\sum_{j\in J}\sum_{\iota\in L} c_{ij\iota} X_{ij\iota} + \\ \sum_{\kappa\in K}\sum_{\hat{\kappa}\in\widehat{K}} f_\kappa^{\hat{\kappa}} V_\kappa^{\hat{\kappa}} + \sum_{j\in J}\sum_{\kappa\in K}\sum_{\iota\in L} h_{j\kappa\iota} Y_{j\kappa\iota} \end{array} \right\} \tag{1}$$

$$s.t. \quad \sum_{j\in J} X_{ij\iota} = a_{i\iota}, \qquad \forall\, i\in I,\ \iota\in L \tag{2}$$

$$\sum_{i\in I}\sum_{\iota\in L} s_\iota X_{ij\iota} \le w_j^{\hat{j}} U_j^{\hat{j}}, \qquad \forall\, j\in J,\ \hat{j}\in\widehat{J} \tag{3}$$

$$\sum_{i\in I} X_{ij\iota} \le \sum_{\kappa\in K} Y_{j\kappa\iota}, \qquad \forall\, j\in J,\ \iota\in L \tag{4}$$

$$\sum_{j\in J}\sum_{\iota\in L} q_\iota Y_{j\kappa\iota} \le p_\kappa^{\hat{\kappa}} V_\kappa^{\hat{\kappa}}, \qquad \forall\, \kappa\in K,\ \hat{\kappa}\in\widehat{K} \tag{5}$$

$$\begin{aligned} &\sum_{\kappa\in K}\sum_{\hat{\kappa}\in\widehat{K}} \alpha_p p^{\hat{\kappa}} V_\kappa^{\hat{\kappa}} + \sum_{j\in J}\sum_{\hat{j}\in\widehat{J}} \alpha_w w^{\hat{j}} U_j^{\hat{j}} \\ &+ \sum_{i\in I}\sum_{j\in J}\sum_{\kappa\in K} \alpha_s \left(d_{j\kappa}^{p} \widehat{Y}_{j\kappa} + d_{ij}^{w} \widehat{X}_{ij} \right) \le CO_2^{\text{CAP}} \end{aligned} \tag{6}$$

$$X_{ij\iota} \le M\widehat{X}_{ij}, \qquad \forall\, i\in I,\ j\in J,\ \iota\in L \tag{7}$$

$$Y_{j\kappa\iota} \le M\widehat{Y}_{j\kappa}, \qquad \forall\, j\in J,\ \kappa\in K,\ \iota\in L \tag{8}$$

$$X_{ij\iota} \ge 0, \qquad \forall i\in I,\ j\in J,\ \iota\in L \tag{9}$$

$$Y_{j\kappa\iota} \ge 0, \qquad \forall j\in J,\ \kappa\in K,\ \iota\in L \tag{10}$$

$$U_j = \{0,1\}, \qquad \forall j\in J \tag{11}$$

$$V_\kappa = \{0,1\}, \qquad \forall \kappa\in K \tag{12}$$

$$\widehat{X}_{ij} = \{0,1\}, \qquad \forall\, i\in I,\ j\in J \tag{13}$$

$$\widehat{Y}_{j\kappa} = \{0,1\}, \qquad \forall\, j\in J,\ \kappa\in K. \tag{14}$$

The objective function equation (1) minimizes the sum of the fixed costs and distribution costs. Constraint set equation (2) ensures that the demand of each retailer is satisfied by the open DCs. Constraint set equation (3) ensures that the demands of retailers that are supplied by open DCs do not exceed the throughput capacity of any of these DCs. Constraint set equation (4) ensures that total flow of product ι that enters DC j from all plants does not exceed the flow that leaves the DC to all retailers. Constraint set equation (5) represents the capacity restriction of plant κ of size $\hat{\kappa}$ in terms of the amount of product it can handle. Constraint set equation (6) ensures that the total carbon dioxide emission does not exceed an emission cap, which is usually determined by environmental regulations. The two new variables ($\widehat{X}_{ij}$ and $\widehat{Y}_{j\kappa}$) that are used in constraint set equations (6)-(8) are auxiliary binary variables that take value one with positive flow between facilities, which is guaranteed by equations (7)-(8), where M refers to a satisfactorily large number. Constraint set equations (9)-(10) and (11)-(14) enforce the nonnegativity and binary restrictions on the decision variables.

IV. EXPERIMENTAL ANALYSIS

The analysis was based on data derived from the 88-node dataset, which is described in Daskin (1995) [18]. We used 7 (nodes 1-7) candidate plants, 18 (nodes 8-25) candidate DCs, 63 (nodes 26-88) retailers, and a single type of product. We assume that there is only one type of plant and one type of DC, i.e., $|\widehat{J}| = |\widehat{K}| = 1$. We computed the demand for each retailer by dividing the average population given by Daskin by 10^5. Fixed location costs for the DCs were obtained by dividing the fixed costs given by Daskin for nodes 8-25 by 10, and fixed location costs for the plants were set equal to the fixed costs for nodes 1-7. The unit shipping costs between facilities (plants, DCs, and retailers) were proportionally set to the distances between these facilities, which were set to the great-circle distances between different locations. The throughput capacity of each DC was set to 400 units, and the production capacity of each plant was set to 1000 units. The capacity required to produce and store one unit of the product were respectively set to 1 Kw/unit and 1 ft^3/unit. The values of the other parameters used in the analysis are provided in Table I. All parameter values were chosen so as to provide a large range of tradeoffs between location costs (first and third terms in equation (1)) and distribution costs (second and forth terms in equation (1)).

TABLE I
VALUES OF PARAMETERS USED IN THE ANALYSIS.

$Parameter$	$Value(s)$
α_p	0.3
α_w	0.5
α_s	0.7
$p^{\hat{k}}$	400
$w^{\hat{j}}$	550
CO_2^{CAP}	160000-250000

To solve these instances, we used the ILOG CPLEX 11.0 MIP solver in the GAMS© modeling language [20].

Figure 2 shows the change in the fixed-location costs, distribution costs, and total cost (the sum of the location and distribution costs) for different values of emission cap (CO_2^{CAP}). As the figure shows, as the cap increases the total cost decreases. This can be explained by noting that while the distribution costs may increase as the cap is raised, this tends to be offset by a reduction in fixed costs due to the fact that as the cap is raised, the right hand side of constraint equation (6) increases, which in turn tends to increase the size of the solution space for the integer program equations (1)-(14), and this tends to reduce the optimal objective function value, since a lower minimum can often be attained over a larger solution space; the result is that the reduction in fixed costs may more than offset the increase in distribution costs, resulting in a lower total cost.

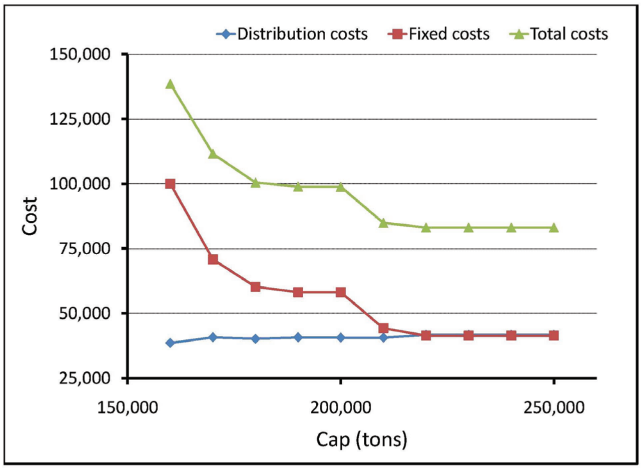

Fig. 2. Location, distribution, and total costs as a function of emission cap.

V. CONCLUSION

In this paper, we introduced a new supply chain network problem with a carbon emission constraint. The problem was formulated as a MIP and solved using the ILOG CPLEX 11.0 MIP solver in GAMS©. We conducted an experimental study on instances of small sizes, and found that as carbon emission allowance decreases, supply chain total cost increases. Supply chain managers should therefore consider taking a long-term view and take into account possible future carbon emission allowance decreases when setting target carbon footprints so as to remain competitive under a wide range of scenarios.

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