An integrated logistics model for environmental conscious supply chain network design

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ABSTRACT

Operations Research has addressed a variety of environmental problems outside the traditional supply chain management area such as remanufacturing, reverse logistics, and waste management. Supply chain sustainability, which includes designing green supply chains, will gain much more attention in the future. Indeed, most companies are still in the early stage of considering a green initiative. Traditionally, optimization models for supply chain network design looked to different strategic network alternatives, and analyze the trade-offs between logistics costs and service requirements. Today, with the strong emphasis in reducing greenhouse gas footprint, the integration of such consideration into the supply chain network design phase will provide to companies much more visibility on how to manage efficient, effective, and green supply chains.

In this paper, a mathematical programming model for environmental conscious supply chain network design is introduced with the explicit inclusion of carbon emission cost. By considering the greenhouse gases emissions cost together with traditional logistics costs, the problem is formulated as a single objective optimization program. The methodology uses mixed integer linear programming modeling technique to deal with different strategic decisions, including supplier and subcontractor selection, product allocation, capacity utilization, and assignment of transportation links required to satisfy market demand. This new formulation provides decision makers with a quantitative decision support system to understand the tradeoffs between the total logistics cost and the carbon footprint reduction.

Keywords

Supply chain management, network design, greenhouse gas (GHG) emission, CO_2 emission, mixed integer programming.

INTRODUCTION

Climate change and the environment are some of the biggest issues facing the world today. Greenhouse gases (GHG) emissions, particularly carbon dioxide (CO_2), are the main contributing factor of global warming (Intergovernmental Panel on Climate Change, 2007). The Intergovernmental Panel on Climate Change (IPCC), a scientific body tasked to evaluate the risk of climate change, reported in the "Fourth Assessment Report" that: "*global GHG emissions due to human activities have grown since pre-industrial times with an increase of 70% between 1970 and 2004*" (Intergovernmental Panel on Climate Change, 2007). The annual emission of CO_2 grew about 80% between 1970 and 2004 (see Figure 1). Also, the environment has been a constant preoccupation in the global media, and now governments are taking real actions in response to the emergence of green and environmental conscious strategies and international regulations (Kyoto protocol). Indeed, in 2002, the president of United States (U.S) announced a climate policy to reduce GHG intensity by 18 percent over the next decade. The Environmental Protection Agency (EPA), an agency of the federal government of the U.S, is charged for helping to achieve this goal, and collaborate with private and public organizations. In the recent EPA's strategic plan, the agency announced that by 2012, 160 Million Metric Tons of Carbon Equivalent (MMTCE) of emission will be reduced through EPA's voluntary climate protection programs (99 MMTCE will be reduced in the industry sector and 15 MMTCE will be reduced in the transportation sector) (U.S. Environmental Protection Agency's (EPA), 2006). Moreover, the government of Canada plans to regulate both GHG emissions and air pollutants. The action will impose mandatory targets in terms of GHG emissions reduction for some industries to achieve a goal of an absolute reduction of 150 mega tons in GHG emissions by 2020 (ecoAction, 2007).

So, it is not surprising to see that Corporate Social Responsibility (CSR) and green initiatives are on the rise (from 45% of Global fortune 250 companies in 2002 to 67% in 2005)[1]. A number of organizations have already made the move and they are lessening their harmful impact on the environment while reducing different logistics costs. For example, Texas Instruments saved USD 8 million each year by reducing its transit packaging budget for its semiconductor business through source reduction, recycling, and use of reusable packaging systems.

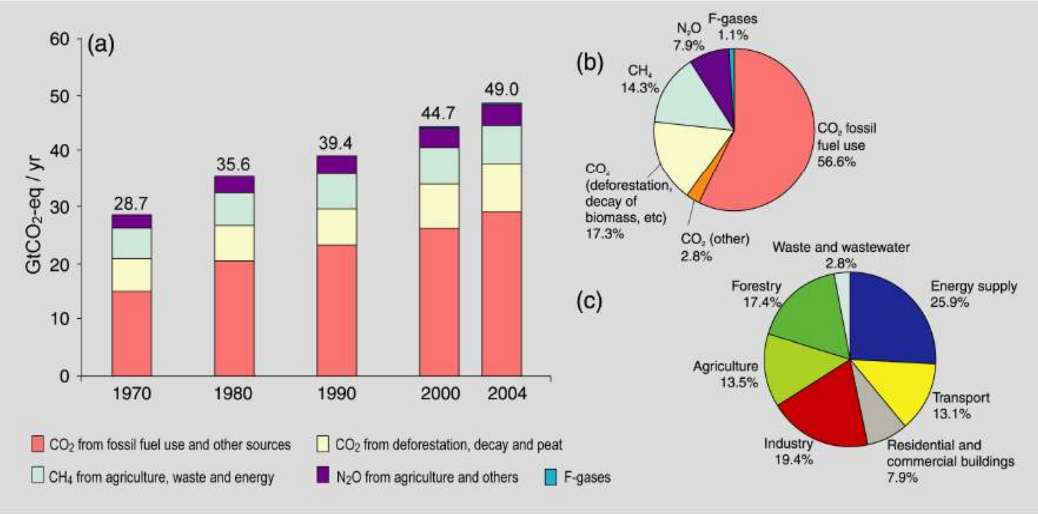

Figure SPM.3. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.[5] (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation). {Figure 2.1}

Figure 1. Global anthropogenic GHG emissions (source : (Intergovernmental Panel on Climate Change, 2007))

With all this global attention, the concept of green supply chain management (GSCM) is gaining increasing interest among researchers and practitioners of supply chain management area. The scope of GSCM ranges from reactive monitoring of the general environment programs to more proactive practices implemented through various operations practices: reduce, reuse, rework, refurbish, reclaim, recycle, remanufacture, and reverse logistics. A recent good review can be seen in the paper of (Srivastava, 2007). It is important to notice that green and environmental supply chain management literature had been largely developed with integration of reverse logistics and waste management activities. Nevertheless, until now we are not able to quantify clearly the real impact of such improvements relative to GHG emissions reduction. Some recent articles had addressed the problem (Ferretti et al., 2007; Hugo et al., 2005). This was motivated especially by the major advancement of practical methodologies to estimate precise GHG emissions of several supply chain activities and relative to different industrial contexts (Intergovernmental Panel on Climate, 2006). Five years ago, GHG footprints measurement may have seemed strange, but today it is commonplace. Many sources of information including databases are now available for estimating GHG emissions such as the IPCC Emission Factor Data Base (EFDB), the EMEP/CORINAIR Emission Inventory Guidebook, the International Emission Factor Database (OECD), etc.

In the same direction, we focus in this article on developing an integrated logistics mathematical model for green supply chain network design with GHG emissions considerations. The environmental impact is measured through CO_2 emissions caused by transportation activities within the supply chain. The problem is mathematically formulated as a mixed integer linear program (MILP). Indeed, to be considered environmentally responsible, the supply chain has to include a new cost related to the quantity of GHG emissions. This cost can represent taxes or cost to buy carbon credits from a carbon market.

The remaining of the article is as follows. After an introduction to the problem context, the literature review about GSCM is detailed in section 2. An integrated framework for sustainable supply chain management is proposed in section 3. Section 4 presents the mathematical model formulation for environmental conscious supply chain network design. The sets, indices, parameters, major decision variables, objective function and the different constraints are also explained in details. Section 5 demonstrates via an illustrative numerical example how the model can be used to evaluate potential reduction of GHG emissions and the direct impact on supply chain configuration and costs. Finally, the conclusion and future extensions to the model are discussed.

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[1] Source : KPMG "International Survey of Corporate Responsibility reporting in 2005"

LITTERATURE REVIEW

Traditional supply chain management practices identify certain performance measures which are the drivers in the evaluation of supply chain effectiveness and efficiency. Typically, they were concerned with: (1) customer satisfaction, service level, or responsiveness and (2) cost/profit. But today, in response to more rigid environmental regulations and changes in environmental supply chain conscious, there has been a need to develop guidelines and standards to assist supply chain mangers to consider the impact of their decisions on the environment, known as Green Supply Chain Management (GSCM). Different studies available on this subject are summarized in a recent review by Srivastava (2007). It is not surprising to see that mathematical modeling based methodologies are the most common approaches used to tackle GSCM problems (Srivastava, 2007). Indeed, these models can be embedded as decision support systems (DSS) for GSCM. DSS proved their efficiency to manage traditional supply chain networks known today as advanced planning and scheduling systems (APS) provided bye companies such as i2, Manugistics, ILOG, and SAP. We believe that analytical methods will continue to contribute actively for the development of GSCM practices.

A variety of mathematical tools and techniques have been used to tackle problems related to GSCM such dynamic programming, non-linear programming, Markov chains, and multi-criteria decision making. Different solution procedures were proposed and vary from exact solutions using linear programming (LP) solver such as LINGO to heuristic based solutions. Here, we give a detailed review about LP methodologies applied to different GSCM contexts.

Very early, Bloemhof-Ruwaard et al. (1996) studied the problem of paper recycling and how it reduces the environmental impact of the European pulp and paper sector. They used a model based on LP to analyze scenarios with different recycling strategies. Spengler et al. (1997) developed two mathematical models for two planning problems: recycling of industrial by-products and dismantling and recycling of products at the end of their lifetime. The models have been applied to large industrial case studies in the fields of recycling of demolition waste and by-product management in the steel industry. Barros et al. (1998) propose a two-level location mathematical model for the recycling of construction waste. The model was solved using a heuristic procedure. The model was applied for the sand recycling network in the Netherlands and shows the utility of this approach. Giannikos (1998) presented a multi-objective linear model for locating disposal or treatment facilities and transporting hazardous waste of a transportation network. Jayaraman et al. (1999) developed a mixed integer programming model for the supply chain network design problem while incorporating the location of remanufacturing/distribution facilities, the transshipment, production and stocking of the optimal quantities of remanufactured products.

Fleischmann et al. (2001) presented a facility location model while considering a closed-loop supply chain. The proposed model shows how product return flows have a real impact on the logistics network and depend largely from the context studied. Luo et al. (2001) presented a mathematical model to design and optimize supply chains in terms of different performance indices such as product cost, cycle time, quality, energy and environmental impact in the context of global and Internet-based manufacturing. A multi-objective optimization model was formulated and solved for a personal computer manufacturer. Sheu et al. (2005) presented a linear multi-objective programming model that optimizes the operations of an integrated supply chain while incorporating reverse logistics activities for used-product. Appling the proposed approach for a notebook computer manufacturer supply chain, analysis report an improvement of the net profit by 21.1%. Hugo and Pistikopoulos (2005) presented a mathematical model for designing and planning the supply chain. They include life cycle assessment (LCA) principles in the classical plant location and capacity expansion problem. The environmental performance was monitored using the Eco-Indicator 99 method.

Jayaraman (2006) presented a mathematical linear programming model for aggregate production planning and control. The major decisions are the determination of the number of units of core type with a nominal quality level that is disassembled, disposed, remanufactured and acquired in a given time period. Data from a company that remanufactures mobile telephones are used to validate the model. Lu et al. (2007) presented, in a recent study, a method using some procedures to evaluate the effectiveness of projects supplying green supply chain concept. A multi-objective decision making process for green supply chain management is considered to help the supply chain manager in measuring and evaluating suppliers' performance based on an Analytical Hierarchy Process (AHP) method. Ferretti et al. (2007) proposed a model to evaluate the economic and environmental effects of the industrial practice case study. The output of the model was the determination of the supply aluminum mix capable of balancing the economic benefits versus the environmental requirements. Finally, Sheu (2008) builds on the concepts of GSCM and presents a multi-objective optimization programming approach to address the issue of nuclear power generation. A linear multi-objective optimization model is formulated to optimize the operations of the nuclear power generation and the reverse logistic flows of the produced waste.

As we see, GSCM has been studied much more from recycling and waste management perspective rather than a global and integrated supply chain network design point of view. However, increased regulations and governmental pressure in many countries to reduce their carbon footprints associated with the introduction of the carbon trading market have motivated companies to measure their emission and redesign the supply chain. As a consequence, it is clear that there is a real need for an integrated methodology to be able to measure carbon footprints and identify different scenario to analyze by mangers in order to minimize costs while considering a green business strategy. The development of advanced decision support systems that integrate strategic and operational decisions with the carbon footprint emission measurement as an additional key performance indicator is important. This will help supply chain managers to trade-off the impact of environmental impact decisions on both cost and service level when planning supply chain operations. Traditional studies on strategic supply chain management concept treat such consideration in the supply chain network design phase. We believe that efficient GSCM must begin with environmental conscious supply chain network design and this is the subject of the proposed approach.

TOWARDS A GREEN SUPPLY CHAIN MANAGEMENT FRAMEWORK

Supply chain management is better understood within the context of end-to-end key process depicted in Figure 2 and adapted form the Supply-Chain Operations Reference-model (SCOR Model) (Supply Chain Council, 2006). The whole activities can be aggregated into different critic areas: plan, source, make, store, transport, and reverse logistics. GSCM begins with an optimization of these major key processes and targets sustainable supply chain planning, sustainable procurement, sustainable manufacturing, sustainable storage, sustainable transportation, and sustainable reverse logistics. GSCM has to consider explicitly financial, environmental and social impacts of supply chain activities. Financial benefits can be measured via revenue increase, cost reduction, increased asset utilization and customer service enhancement. Environmental benefits can be monitored via the reduction in fuel consumption, reduction in GHG and water emissions, increase of energy efficiency use and waste reduction. For the social benefits, this can be seen by the reduction of noise, traffic congestion and improvement of quality of life (health and safety). It is clear that considering all processes in the same model is impossible. But it is essential to take into account the key impacts when tackling any process.

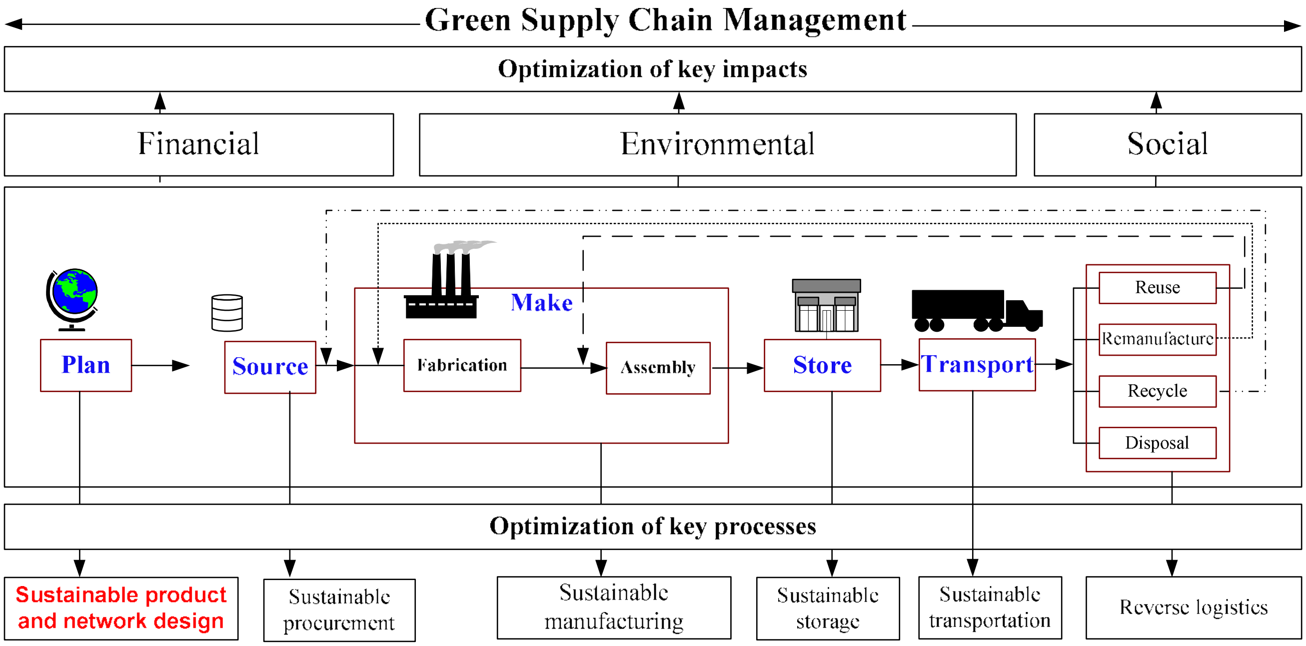

Figure 2. A strategic framework for green supply chain management practices

The "plan" process contains activities performed at the strategic level. It includes product lifecycle management (PLM) and supply chain network design optimization. In one hand, life cycle management takes into account that products need to be managed through design, production, operation, maintenance and end of life reuse or disposal. Product design and packaging influence the efficiency and effectiveness of the supply chain activities, and later logistics cost, waste and GHG emissions. In the other hand, Supply chain network design, which is the scope of the proposed mathematical model, is the second important decision in the plan process. Indeed, competitive markets, pressure to reduce inventory and costs, merger activities, rising energy and fuel costs are the most common incentives for a corporate to examine the supply chain network and define the number, type, location of manufacturing and distribution facilities and the transportation channels and modes used to serve customers. Including environmental and social impacts with the traditional financial impact allow companies to reduce the harmfulness to the environment while still achieving the strategic financial targets.

MATHEMATICAL MODEL FORMULATION FOR GREEN SUPPLY CHAIN NETWORK DESIGN

Model description

Green supply chain network design must integrate the additional key factors described before. In this paper we concentrate on the integration of CO_2 emission when designing the supply chain. With this new formulation, the aim is to introduce a generic DSS for environmental conscious supply chain network design. In addition to the basic logistics costs (raw material cost, fixed and variable facilities costs, and transportation cost), decision makers have to add a new cost due to the greenhouse gas emission. CO_2 emission can be caused by different supply chain activities. In this model, we basically focus on studying the impact of transportation activities on green supply chain performance. But, it is easy to extend the same methodology in order to include sourcing, manufacturing and reverse logistics activities. The introduced model for environmental conscious supply chain network design is generic and can be applied to different manufacturing contexts.

Fundamental to the model is the use of mixed integer linear programming (MILP) technique to capture the interaction between the supply chain structure and its environmental impact. The Bill Of Material (BOM) and the supply chain structure considered are presented respectively in Figure 3 and Figure 4.

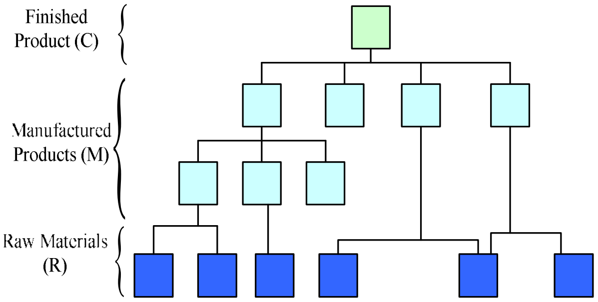

Figure 3. Bill Of Material (BOM)

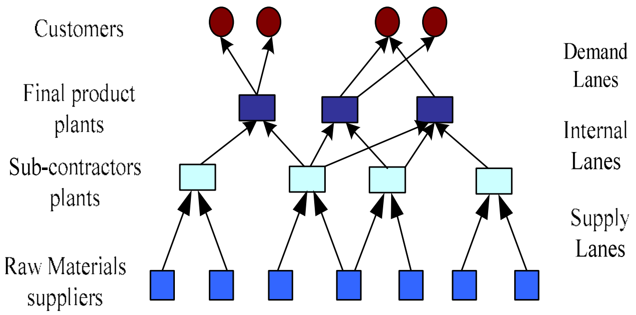

Figure 4. Supply chain structure

Sets and indices

In this study, the following sets and indices are used:

P	Set of all products
$R \subset P$	Set of raw materials
$M \subset P$	Set of manufactured products
$C \subset M$	Set of finished products
N	Set of all nodes
$D \subset N$	Set of customer zones
$S \subset N$	Set of all subcontractors
$S_p \subset S$	Set of subcontractors of product $p \in M$
$V \subset N$	Set of suppliers of raw materials
$V_r \subset V$	Set of suppliers of raw material $r \in R$
Suc(p)	Set of immediate successors of product $p \in P / C$ in the BOM
S(Suc(p))	Function that returns all subcontractors for the set of immediate successors of product $p \in P / C$
M_i	Set of products that can be manufactured by subcontractor $i \in S$
R_i	Set of raw materials that can be supplied by supplier $i \in V$
K	Set of all transportation modes $k \in K$

It is important to notice that we use the term "supplier" for raw materials' providers. "Subcontractor" is used for entities that make manufactured products.

Parameters

The strategic mathematical model requires the following cost parameters:

λ_i	Fixed cost associated with the use of site $i \in S \cup V$
a_{ip}	The start-up cost associated with the assignment of product $p \in M \cup R$ to site $i \in S_p \cup V_p$
c_{ip}	Unit cost of product $p \in M \cup R$ at site $i \in S_p \cup V_p$
t_{ijp}^k	Unit transportation cost of product $p \in P$ from node $i \in V_p \cup S_p$ to node $j \in S(Suc(p)) \cup D$ using transportation mode $k \in K$
l_{ij}^k	Cost of a single shipment between nodes $i \in V \cup S$ and $j \in S \cup D$ using transportation mode $k \in K$
δ	Cost per ton of GHG emissions

The following data are also needed:

α^k	Greenhouse gases emission factor per weight unit and per distance unit due to the use of transportation mode $k \in K$
$g_{pp'}$	Number of products $p \in P / C$ required to manufacture one unit of product $p' \in Suc(p)$
m_p	Maximum number of sites that can be opened for product $p \in M \cup R$
b_{ip}	Capacity of node $i \in S_p \cup V_p$ for product $p \in M \cup R$
te_{ip}	Processing time on product $p \in M$ at node $i \in S_p$
d_{pd}	Number of product $p \in C$ required by demand node $d \in D$
ρ_i	Lower bound (in %) on the aggregated capacity to be used if subcontractor or supplier $i \in S \cup V$ is chosen
T_i	Total time available at the assembly line of subcontractor $i \in S$
τ_{ij}	Maximum number of transportation modes that can be used between nodes $i \in V \cup S$ and $j \in S \cup D$
κ^k	Volume capacity of transportation mode $k \in K$
ψ^k	Weight capacity of transportation mode $k \in K$
π_p	Weight of product $p \in P$
δ_p	Volume of product $p \in P$
$d(i,j)$	Distance between nodes $i \in V \cup S$ and $j \in S \cup D$

Decision variables

To find the optimal configuration of the network, the following decision variables are required:

F_{ijp}^k	Number of units of product $p \in P$ shipped from node $i \in V_p \cup S_p$ to node $j \in S(Suc(p)) \cup D$ using transportation mode $k \in K$
X_{ip}	Number of units of product $p \in M \cup R$ manufactured or supplied by node $i \in S_p \cup V_p$
Y_{ip}	Binary variable equals 1 if product $p \in M \cup R$ is assigned to node $i \in V_p \cup S_p$ and 0 otherwise

A_i	Binary variable equals 1 if node $i \in V \cup S$ is open and operational for at least one product and 0 otherwise
U_{ij}^k	Number of shipments between nodes $i \in V \cup S$ and $j \in S \cup D$ using transportation mode $k \in K$
Z_{ij}^k	Binary variable equals 1 if transportation mode $k \in K$ is used between nodes $i \in V \cup S$ and $j \in S \cup D$ and 0 otherwise

Mathematical formulation

The objective function

The total cost of the supply chain includes fixed and variable costs. Fixed costs are:

- fixed costs for facilities;
- assignment of raw materials to suppliers;
- assignment of manufactured products to subcontractors.

Variable costs are of five types:

- supply of raw materials;
- supply of manufactured products;
- shipment costs (related to the number of shipments);
- transportation costs;
- GHG emissions cost due to transportation activities.

Therefore, the objective function to be minimized is given by:

$$\begin{aligned} MinZ = & \sum_{i \in V \cup S} \lambda_i A_i + \sum_{p \in M \cup R} \sum_{i \in S_p \cup V_p} a_{ip} Y_{ip} + \sum_{p \in M \cup R} \sum_{i \in S_p \cup V_p} c_{ip} X_{ip} + \sum_{i \in S \cup V} \sum_{j \in S \cup D} \sum_{k \in K} l_{ij}^k U_{ij}^k + \\ & \sum_{p \in M \cup R} \sum_{i \in S_p \cup V_p} \sum_{j \in S(Suc(P)) \cup D} \sum_{k \in K} t_{ijp}^k F_{ijp}^k + \delta \sum_{p \in M \cup R} \sum_{i \in S_p \cup V_p} \sum_{j \in S(Suc(P)) \cup D} \sum_{k \in K} \alpha^k \pi_p d(i,j) F_{ijp}^k \end{aligned} \tag{1}$$

Model constraints

For the MILP supply chain network design model, there are many constraints to be considered. These constraints are of many kinds including the balance constraints of all products, the capacity limit constraints, the minimum capacity occupation constraints, and the demand satisfaction constraint. The BOM constraints are implicitly taken into account in the balance constraints. These elements are discussed below.

For each raw material and for each manufactured product, the number of operational sites should not exceed the maximum number allowed of suppliers and subcontractors:

$$\sum_{i \in S_p \cup V_p} Y_{ip} \leq m_p \; (\forall p \in R \cup M) \tag{2}$$

If a product (manufactured product or raw material) is assigned to a node, then the number of products supplied by this node must not exceed its capacity for this product:

$$X_{ip} - b_{ip} Y_{ip} \leq 0 \quad (\forall p \in R \cup M, \forall i \in S_p \cup V_p) \tag{3}$$

If a subcontractor is chosen for at least one product, then the overall processing time used must not exceed the total available time at its assembly line or manufacturing facility:

$$\sum_{p \in M_i} X_{ip} te_{ip} - T_i A_i \leq 0, \forall i \in S \tag{4}$$

There is usually a minimum amount of the aggregate capacity of a subcontractor that should be consumed to justify the establishment of a contract. This consideration leads to constraints (5) where the first term is the total time used at the assembly line or manufacturing facility of subcontractor *i* in order to manufacture all the products. The second term of the left hand side of the inequality is the minimum time to be used if subcontractor *i* is chosen:

$$\sum_{p \in M_i} X_{ip} te_{ip} - \rho_i T_i A_i \geq 0, \forall i \in S \tag{5}$$

To make a deal with a supplier, the minimum capacity can also be considered. Here, the minimum capacity to be used is a percentage of the total weight of all maximum quantities of raw materials that can be supplied by the supplier:

$$\sum_{p \in R_i} X_{ip} - \left(\rho_i \sum_{p \in R_i} b_{ip} \right) A_i \geq 0 \ \ (\forall i \in V) \tag{6}$$

The constraints of flow out of subcontractors'/ suppliers' nodes are given by the inequalities below:

$$X_{ip} - \sum_{j \in S(Suc(p)) \cup D} \ \sum_{k \in K} F^k_{ijp} \geq 0 \ \ (\forall p \in P, \forall i \in V_p \cup S_p) \tag{7}$$

For each product, the quantity that arrives to a node must equal the quantity needed to manufacture next higher assemblies:

$$\sum_{j \in V_p \cup S_p} \sum_{k \in K} F^k_{jip} - \sum_{p' \in Suc(p)} g_{pp'} X_{ip'} = 0 \ \ (\forall p \in M \cup R, \forall i \in S(Suc(p))) \tag{8}$$

The following are logical constraints.

A site is operational if it is open for one product at least:

$$Y_{ip} - A_i \leq 0 \ \ (\forall i \in S \cup V, \forall p \in M_i \cup R_i) \tag{9}$$

The quantity of finished products shipped from all its subcontractors to the demand node must equal the demand of that product:

$$\sum_{i \in S_p} \sum_{k \in K} F^k_{idp} = d_{pd} \ \ (\forall p \in C, \forall d \in D) \tag{10}$$

For each couple of nodes, there is a maximum number of transportation modes that can be used. That leads to the following constraint:

$$\sum_{k \in K} Z^k_{ij} \leq \tau_{ij} \ \ \ (\forall i \in V \cup S, \forall j \in S \cup D) \tag{11}$$

The quantity of products shipped between two nodes is limited by the capacity of transportation mode and the number of shipments. While the first set of constraints (12) expresses the volume capacity and the second set (13) expresses the weight capacity:

$$\sum_{p \in R_i \cup M_i} \delta_p F^k_{ijp} - \kappa^k U^k_{ij} \leq 0 \ \ (\forall\, i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \tag{12}$$

$$\sum_{p \in R_i \cup M_i} \pi_p F^k_{ijp} - \psi^k U^k_{ij} \leq 0 \ \ (\forall\, i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \tag{13}$$

The number of shipments between two nodes for a given transportation mode is not nil only if the transportation mode is actually used. This yields to the following constraint:

$$U^k_{ij} - M Z^k_{ij} \leq 0 \ \ (\forall\, i \in V \cup S, \forall j \in S \cup D, \forall k \in K), \ M \text{ is a big number} \tag{14}$$

A transportation mode is used between two nodes only if the number of shipments is not nil:

$$Z^k_{ij} \leq U^k_{ij} \ \ \ (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \tag{15}$$

The transport variables and the quantities supplied by sites are non negative:

$$F_{ijp}^{k} \geq 0 \quad (\forall p \in R \cup M, \forall i \in V_p \cup S_p, \forall j \in S(suc(p)) \cup D, \forall k \in K) \tag{16}$$

$$X_{ip} \geq 0 \quad (\forall (p,i) \in R \times V_p \cup M \times S_p) \tag{17}$$

Binary variables:

$$Y_{ip} \in \{0,1\}, \forall (p,i) \in R \times V_p \cup M \times S_p \tag{18}$$

$$A_i \in \{0,1\}, \forall i \in S \cup V \tag{19}$$

$$Z_{ij}^{k} \in \{0,1\} \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \tag{20}$$

The number of shipments must be integer:

$$U_{ij}^{k} \text{ integer } \quad (\forall p \in P, \forall i \in V_p \cup S_p, \forall j \in S(Suc(p)) \cup D, \forall k \in K) \tag{21}$$

AN ILLUSTRATIVE EXAMPLE

In this section, we show the experimentation with an illustrative example composed of one finished product given its BOM. When solving the problem, we assumed that the locations of all subcontractors and suppliers are known and that transportation costs include taxes and duties. Three freight transportation modes are considered: rail, air, and road. Rail and air transportation costs are assumed to include intermodal consideration, in the sense that they take into account the costs related to the use of other transportation modes for shipping between the rail stations or the airports and the different sites. The BOM contains a certain number of levels and components. It is illustrated in Figure 5. We assumed that all parts at the lowest level (RM001, RM002, RM003 and RM004) are raw materials. In this simple example, there are only two semi finished products (SF001 and SF002). All the parts have two potential subcontractors or suppliers as shown in Figure 5. The aggregated demand during the planning horizon is 4,900 units of finished product FP001.

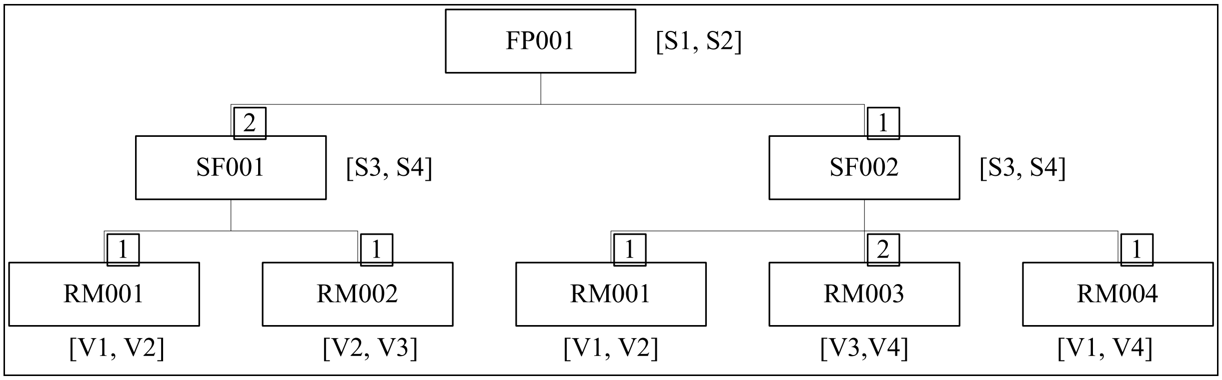

Figure 5. Bill of materials: Example

GHG emissions are limited to carbon dioxide (CO_2) caused by transportation activities. The quantity of CO_2 is calculated using emission factors for the three freight transportation modes considered in this example and detailed in Table 1. An emission factor can be defined as the average emission rate of a given pollutant for a given source, relative to units of activity. Emission factors can be used to derive estimates of GHG emissions based on the amount of fuel combusted or on industrial production levels. The level of precision of the resulting estimates depends significantly on the activity in question. Different studies on how to calculate CO_2 emission factors for transportation activities are available. Emission factors considered in this example are based on the recent study published in (Facanha and Horvath, 2007). The authors quantify emission factors associated with road, rail, and air transportation. Due to the complexity of such assessment, some basic assumptions related to equipment capacity, equipment utilization, empty miles and fuel used were considered.

Transportation mode	Type	Payload (tons)	CO_2 (grams/ton-mile)
Road	Class 8b	12.5	187
rail	Intermodal rail	2,093	40
air	Boeing 747-400	70	1,385

Table 1. Freight transportation emission factors (grams/ton-mile)

Table 2 summarizes the MILP model characteristics obtained for this simple example.

	Number of variables	Binary variables	Integer variables	Continuous variables	Number of constraints	Inequality constraints	Equality constraints
MILP statistics	207	64	42	101	232	210	22

Table 2. MILP model characteristics

The MILP problem is solved by CPLEX Interactive Optimizer 10.0 in 0.03 seconds. For this example, the optimal cost is 984,455 $. To observe the sensitivity of the total supply chain cost, we analyzed different scenarios where the quantity of CO_2 emission is reduced by a step of 5%. Table 3 summarizes the different results obtained for the set of data used in the model. It shows particularly that the supply chain cannot go further a reduction of 17% compared to the base case.

	Percentage of GHG reduction	GHG emissions (in kg)	Total Cost ($)	Percentage of cost increase
Base scenario	0%	1 635 477	$ 984 455	0%
Scenario 2	5%	1 553 703	$ 986 452	0.203%
Scenario 3	10%	1 471 929	$1 003 336	1.918%
Scenario 4	15%	1 390 155	$1 056 476	7.316%
Scenario 5	16%	1 373 801	$1 070 167	8.707%
Scenario 6	17%	1 357 446	$1 083 857	10.097%
Scenario 7	18%	1 341 091	infeasible	

Table 3. Result for different scenario of GHG emissions reduction

The results show also that the percentage of cost change increases exponentially with potential GHG emissions reduction (Figure 6). Targeting higher percentages of GHG emissions reduction will injure the total supply chain cost. From a managerial perspective, considering GHG reduction suggests that companies within the supply chain network should look for new alternatives in order to absorb the additional logistics cost.

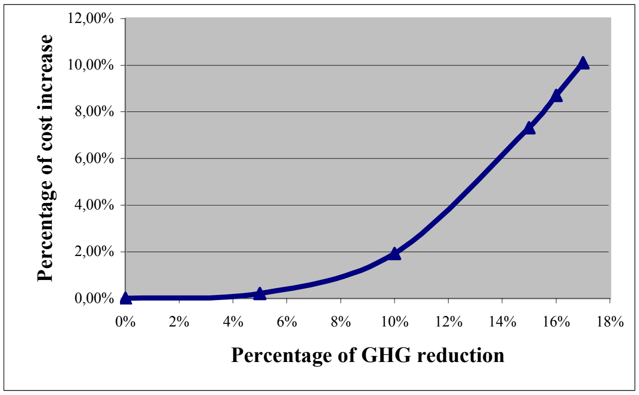

Figure 6. Percentage cost increase as function of GHG emissions reduction

Regarding decisions of transportation modes selection, we observe that lowest-cost's transportation modes are selected for the base scenario. As soon as we increase the percentage of GHG reduction, less pollutant transportation modes are selected.

CONCLUSION

The proposed decision framework for green supply chain network design is the first model in nature that integrates carbon cost explicitly in the model. The example demonstrated the potential of introduction of green practices in supply chain network design. It may help managers to analyze the impact of GHG emissions reduction on the supply chain configuration beyond the traditional financial approach. In fact, they may quantify the cost to add if they decide to go beyond a green initiative. The application of the model shows how the supply chain may balance carbon emission and total costs in a more effective way. Here, we take only into account CO_2 emission caused by transportation activities, but the model can be easily extended to add procurement; manufacturing and reverse logistics activities. The same approach and methodology can be applied to different real supply chain cases and the evaluation of their current positioning, in terms of total logistics cost and GHG emissions levels, may be assessed and compared thanks to the efficiency Pareto-frontier curve (Figure 6). In this model the delivery lead times were not in concern. But, we believe that additional constraints related to that such as service level and delivery lead time to customers may influence the solution characteristics and the supply chain configuration.

It is clear that green and environmental supply chain management has reached a level that requires a coherent and long term supply chain strategy. Regulations are coming soon and will affect all industries. There is going to be carbon legislation that puts price on carbon and creates carbon markets. As such, supply chain decision makers should establish the GHG footprints of their operations. This is not going to be a just a “feel good” or corporate culture initiative, it’s going to be driven by business requirement. Assessing GHG emissions may have seemed strange five years ago, but now it is a reality. This issue will change the DSS framework for supply chain management in the future and this is the first step.

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