Introduction
- Context
- Motivation and objective
- Kyoto protocol
- Carbon Market

Literature
- Limitations

Model formulation

Experimentation
- Managerial insights

Conclusion
Introduction – **Context**

- Supply chain strategies of last decade:
  - Warehouse consolidation
  - Lean and agile supply chains
  - Just in time
  - Offshore manufacturing
  - Low cost country sourcing

- How green are these strategies?
- How relevant are they if the carbon trading market became a reality (*a price tag for carbon emissions*)?
Introduction – Context

Climate Change: who is the responsible!!!
Introduction – **Context**

Aggregate Contributions of Major GHG Emitting Countries

This chart shows how emissions from the major emitting countries contribute to the world total. Together, the 25 countries with the largest GHG emissions accounted for approximately 83 percent of global emissions in 2000.
The Kyoto Protocol: key features

- **Entry into force:** February 16, 2005
  - US and Australia did not ratify
- **Differentiated commitments:**
  - Developed countries and countries with economies in transition agree to quantified legally-binding targets (overall objective leads to a 5% reduction from 1990 levels by 2008-2012)
- **Six gases,**:
  - carbon dioxide (CO2),
  - methane (CH4),
  - nitrous oxide (N2O),
  - Sulphur hexafluoride (SF6),
  - Per fluorocarbons (PFC) and
  - Hydro fluorocarbons (HFC).
The Kyoto Protocol: key features

- Target should be achieved through:
  - **Domestic Reductions**
  - **Carbon Sinks**: direct human-induced land use change and forestry activities
  - **International Credits** (Kyoto Mechanisms):
    - International Emissions Trading
    - Project – Based: Joint Implementation (in industrialized countries)
    - Project – Based: Clean Development Mechanism (in developing countries)

- Negotiations on next period (post-2012) to start in 2005
Introduction – **Context**

- **Carbon trading markets: a new reality for Green Supply Chain Management**

  - **Montréal Climate Exchange**
    - 13$ per ton
    - 30 May 2008, launched
  - **Chicago Climate Exchange**
    - 6$ per ton
  - **European Climate Exchange**
    - 25€ per ton

*Historical Global CO₂ Emissions* (1850-2004)

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Structure of the Carbon Market 2006
(worth close to $22 billion in 2006)

Project-Based Transactions

Credible C-asset

Allowance Markets

Primary JI & CDM
226 MtCO₂e

Voluntary & Retail
8 MtCO₂e

Other Compliance
8 MtCO₂e

New South Wales Certificates
16 MtCO₂e

Chicago Climate Exchange

EU Emission Trading Scheme
764 MtCO₂e

UK ETS
2 MtCO₂e

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Introduction – *Context*

**Trends:**
- ‘Corporate Responsibility’ reporting (green accounts) is on the rise (from 45% of Global fortune 250 companies in 2002 to 67% in 2005)[1]
  - *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* [1]

**Regulations:**
- The government of Canada (ecoAction, 2007) plans to regulate both GHG emissions and air pollutants
  - “impose mandatory targets on industry to achieve a goal of an absolute reduction of 150 mega tons in GHG emissions by 2020”
- The U.S. Environmental Protection Agency’s (EPA, 2006) announced that by 2012, 160 Million Metric Tons of Carbon Equivalent (MMTCE) of emission will be reduced
  - “99 MMTCE will be reduced in the industry sector and 15 MMTCE will be reduced in the transportation sector”

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Introduction – Objective

- Develop a decision support system (DSS) for strategic and environmental supply chain network design analysis:
  - Calculate a supply chain’s existing carbon footprint (calculation of GHG emissions) based on the current supply chain network structure
  - Determine the most cost effective supply chain network design based on user-defined GHG reduction targets
  - Incorporate carbon offsets into cost and footprint calculations to optimize where carbon credits should be purchased and applied: Environmental Cost
Literature – *Problem context*

- Green supply chain management (GSCM) and problems context:
  - **Green design**
    - Environmentally conscious design (ECD)
    - Life-cycle assessment/analysis (LCA)
  - **Green operations**
    - Supplier selection
    - Green manufacturing and remanufacturing
    - Reverse logistics and network design
    - Waste management
    - Minimize the use of energy


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Literature – Methodology

- Green supply chain management (GSCM) based methodology / approach:
  - Empirical studies
    - Case studies
    - Interviews and surveys
    - Though papers
  - Simulation and game theory
  - Mathematical modelling
    - Non Linear Programming (LP)
    - Multi-criteria decision making
    - LP and Mixed Integer LP


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Literature – Limitations

- GSCM studied supply chain problems much more from an operational point of view.

- For the green supply chain network design:
  - The problem is not studied enough.
  - Research stresses on reverse logistics activities:
    - Unable to quantify clearly the real impact of such improvement relative to GHG emission reduction and the supply chain configuration.

- Lack of standardized, comprehensive, and up-to-date data:
  - Industry is struggling to find the right trade-off between:
    - Green supply chains
    - Lean supply chains
    - Agile supply chains
A GSCM framework

Environmental conscious supply chain network design

Green supply chain management

Optimization of key impacts

Financial

Environnamental

Social

Plan → Source → Fabrication → Make → Assembly → Store → Transport

Optimization of key processes

Sustainable product and network design
Sustainable procurement
Sustainable manufacturing
Sustainable storage
Sustainable transportation
Reverse logistics

Adapted from the SCOR Model

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Methodology: Mathematical programming

Supply Chain

- Degree of disaggregation
  - Country
  - Sector

- Make carbon reduction
  - Design options
  - Sourcing options
  - Sub-contracting options
  - Production options
  - Storage options
  - Transport options

- Buy carbon credits
- Internal Strategic Decisions
  - Cost
  - GHGs
  - Carbon Market
  - External Mechanisms

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Supply Chain Configuration

- **Products : Bill-Of-Materials**
  - Raw materials
  - Sub-assemblies
  - Finished products

- **Supply Chain Configuration**
  - Potential Suppliers
  - Potential Subcontractors
  - Production plants

- **Transportation modes**
  - Road
  - Rail
  - Air

- **GHG emission**
  - Carbon dioxide (CO₂)
Model formulation

- Minimize the total supply chain cost
- Majors decisions are:
  - Select
    - Suppliers, sub-contractors and production centers
    - Transportation modes to use between nodes
  - Assign
    - Raw materials to suppliers
    - Sub-assemblies to sub-contractors
  - Determine
    - Products flow between nodes
    - GHG emissions (carbon dioxide equivalent)
- Subject to
  - Technological constraints
Formulation – **Objective Function**

- The total cost includes fixed and variable costs
  - Fixed costs are:
    - Fixed costs for facilities \((a)\)
    - Assignment of raw materials to suppliers and manufactured products to subcontractors \((b)\)
  - Variable costs are of five types:
    - Supply of raw materials and manufacturing products \((c)\)
    - Shipment costs (related to the number of shipments) \((d)\)
    - Transportation costs \((e)\)
    - GHG emissions credits \((f)\)

\[
\begin{align*}
\text{Min } F_i &= \sum_{a \in (\mathcal{P} \cup \mathcal{S})} \lambda_a A_a + \sum_{p \in \mathcal{M} \cap R} \sum_{i \in \mathcal{S}_p} a_{ip} Y_{ip} + \sum_{p \in \mathcal{M} \cap R} \sum_{i \in \mathcal{S}_p} c_{ip} X_{ip} \\
&+ \sum_{i \in \mathcal{S} \cap \mathcal{V}} \sum_{j \in \mathcal{S}_p} \sum_{k \in \mathcal{K}} U_{ij}^k + \sum_{p \in \mathcal{M} \cap R} \sum_{i \in \mathcal{S}_p} \sum_{j \in \mathcal{S}(\text{Suc}(p)) \cap \mathcal{D}} \sum_{k \in \mathcal{K}} t_{ijp}^k F_{ijp}^k \\
&+ \delta \left( \sum_{p \in \mathcal{M} \cap R} \sum_{i \in \mathcal{S}_p} \sum_{j \in \mathcal{S}(\text{Suc}(p)) \cap \mathcal{D}} \sum_{k \in \mathcal{K}} \alpha_{ip} d(i, j) F_{ijp}^k + \sum_{p \in \mathcal{M}} \sum_{i \in \mathcal{S}_p} \beta_{ip} \pi_p X_{ip} - L \left( \text{Emission Cap} \right) \right)
\end{align*}
\]
## Formulation – Constraints

- **Number of operational sites**
  \[ \sum_{i \in S_p \cup V_p} Y_{ip} \leq m_p \quad (\forall p \in R \cup M) \quad (2) \]

- **Node capacity**
  \[ X_{ip} - b_{ip} Y_{ip} \leq 0 \quad (\forall p \in R \cup M, \forall i \in S_p \cup V_p) \quad (3) \]

- **Capacity constraints**
  - **Maximum time capacity use for subcontractors**
    \[ \sum_{p \in M_i} X_{ip} t_e_{ip} - T_i A_i \leq 0, \forall i \in S \quad (4) \]
  - **Minimum time capacity use for subcontractors**
    \[ \sum_{p \in M_i} X_{ip} t_e_{ip} - \rho_i T_i A_i \geq 0, \forall i \in S \quad (5) \]
  - **Maximum capacity for suppliers**
    \[ \sum_{p \in R_i} X_{ip} - \left( \rho_i \sum_{p \in R_i} b_{ip} \right) A_i \geq 0 \quad (\forall i \in V) \quad (6) \]

- **Conservation of flow**
  \[ X_{ip} - \sum_{j \in S(Suc(p)) \cup D} \sum_{k \in K} F_{jp}^{ik} \geq 0 \quad (\forall p \in P, \forall i \in V_p \cup S_p) \quad (7) \]
Formulation – **Constraints**

- **BOM constraints**
  \[
  \sum_{j \in V_p \cup S_p} \sum_{k \in K} F_{jp}^k - \sum_{p' \in \text{Suc}(p)} g_{pp'} X_{ip'} = 0 \quad (\forall p \in M \cup R, \forall i \in S(\text{Suc}(p)))
  \]  
  \(8\)

- **Demand constraints**
  \[
  \sum_{i \in S_p} \sum_{k \in K} F_{ip}^k = d_{pd} \quad (\forall p \in C, \forall d \in D)
  \]  
  \(10\)

- **Transportation capacity constraints**
  - Maximum number of transportation modes that can be used
    \[
    \sum_{k \in K} Z_{ij}^k \leq \tau_{ij} \quad (\forall i \in V \cup S, \forall j \in S \cup D)
    \]  
    \(11\)
  - **Volume capacity**
    \[
    \sum_{p \in R_i \cup M_i} \delta_p F_{ijp}^k - \kappa^k U_{ij}^k \leq 0 \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
    \]  
    \(12\)
  - **Weight capacity**
    \[
    \sum_{p \in R_i \cup M_i} \pi_p F_{ijp}^k - \psi^k U_{ij}^k \leq 0 \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
    \]  
    \(13\)
Formulation – *Constraints*

- **Logical constraints**
  - The number of shipments between two nodes is not nil only if the transportation mode is actually used:
    \[
    U_{ij}^k - MZ_{ij}^k \leq 0 \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
    \]  
    (14)
  - A transportation mode is used between two nodes only if the number of shipments is not nil:
    \[
    Z_{ij}^k \leq U_{ij}^k \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
    \]  
    (15)
  - The number of shipment between two nodes using a transportation mode is nil if there is no flow of products:
    \[
    U_{ij}^k \leq \sum_{p \in R_i \cup M_i} F_{ijp}^k \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
    \]  
    (16)
  - A site is operational if it is open for one product at least:
    \[
    Y_{ip} - A_i \leq 0 \quad (\forall i \in S \cup V, \forall p \in M_i \cup R_i)
    \]  
    (9)
Formulation – Constraints

- Integer, binary, and non-negativity constraints
  - Transport variables and the quantities supplied are non negative
    \[
    F_{ip}^k \geq 0 \quad (\forall p \in R \cup M, \forall i \in V \cup S_p, \forall j \in S(suc(p)) \cup D, \forall k \in K)
    \]
    (17)

    \[
    X_{ip} \geq 0 \quad (\forall (p,i) \in R \times V \cup M \times S_p)
    \]
    (18)

- Binary variables:
  \[
  Y_{ip} \in \{0,1\}, \forall (p,i) \in R \times V \cup M \times S_p
  \]
  (19)

  \[
  A_i \in \{0,1\}, \forall i \in S \cup V
  \]
  (20)

  \[
  Z_{ik}^k \in \{0,1\} \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K)
  \]
  (21)

- The number of shipments must be integer:
  \[
  U_{ij}^k \text{ integer} \quad (\forall p \in P, \forall i \in V \cup S_p, \forall j \in S(suc(p)) \cup D, \forall k \in K)
  \]
  (22)
Parameters – *Data input*

- **How to find Emission Factors?**
  - **Example: IPCC Emission Factor Database (EFDB)**


<table>
<thead>
<tr>
<th>Supply Chain Activity</th>
<th>Data Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>■ Carbon Emission factor (kg CO₂ per gallon) or <strong>CO₂ per Freight (kg CO₂ per ton-mile)</strong></td>
</tr>
<tr>
<td>Production</td>
<td>■ Carbon Conversion Factor per kg of Product produced <strong>(kg CO₂ per kg)</strong></td>
</tr>
<tr>
<td>Plant</td>
<td>■ By plant location, the user enters the Energy Consumption per Space (e.g. kWh per sq. ft.), the Energy Consumption per Capacity (e.g. kWh per production hr) and a Carbon Conversion Factor (kg CO2 per kWh).</td>
</tr>
<tr>
<td>Warehouses</td>
<td>■ By warehouse location, the user enters the Energy Consumption (e.g. kWh per sq ft.), the Carbon Conversion Factor (kg CO2 per kWh) and the Area to Apply (entire size of warehouse, or average inventory volume)</td>
</tr>
</tbody>
</table>
Environmental Conscious and Carbon Market Sensitive Supply Chain Network Design

Optimization Model

GHG Emissions and cost analysis

The total CO2 emission curve

CO2 Emission limit (UB emission) vs. Total Logistic Cost ($)

Fixed cost

Startup for Raw Materials

Startup for Manufactured Products

Variable Cost Raw Materials

Variable Cost for Manufactured Products

Transportation Cost

Emission Cost

Cost minimization

CO2 emission minimization

Goal Programming

Environmental data

Actual information system

SAP

Excel

CRM

CATIA

MY SAP SCM

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Experimentation – Example

- Environmental supply chain network design example

<table>
<thead>
<tr>
<th>Transportation mode</th>
<th>Type</th>
<th>Payload (tons)</th>
<th>CO₂ (grams/ton-mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road</td>
<td>Class 8b</td>
<td>12.5</td>
<td>187</td>
</tr>
<tr>
<td>rail</td>
<td>Intermodal rail</td>
<td>2,093</td>
<td>40</td>
</tr>
<tr>
<td>air</td>
<td>Boeing 747-400</td>
<td>70</td>
<td>1,385</td>
</tr>
</tbody>
</table>

Freight transportation emission factors (grams/ton-mile)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Number of variables</th>
<th>Binary variables</th>
<th>Integer variables</th>
<th>Continuous variables</th>
<th>Number of constraints</th>
<th>Inequality constraints</th>
<th>Equality constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILP statistics</td>
<td>207</td>
<td>64</td>
<td>42</td>
<td>101</td>
<td>232</td>
<td>210</td>
<td>22</td>
</tr>
</tbody>
</table>
Experimentation – **Results**

- The MILP problem is solved by CPLEX Interactive Optimizer

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GHG emission limit ($UP_{Emission}$) (in tons)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base scenario</td>
<td>21 012</td>
<td>763 364 $</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>20 687</td>
<td>764 421 $</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>20 361</td>
<td>764 421 $</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>20 035</td>
<td>764 421 $</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>19 710</td>
<td>768 802 $</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>19 709</td>
<td>768 802 $</td>
</tr>
<tr>
<td>Scenario 7</td>
<td>19 500</td>
<td>796 032 $</td>
</tr>
<tr>
<td><strong>Scenario 8</strong></td>
<td>19 383</td>
<td><strong>962 626 $</strong></td>
</tr>
</tbody>
</table>
Some managerial insights

- Tradeoffs between cost and CO$_2$ emissions
- Cost analysis
- GHG emissions assessment
Some managerial insights

Cost minimization versus CO₂ emissions minimization

<table>
<thead>
<tr>
<th>Category</th>
<th>Base scenario- Cost minimization</th>
<th>Scenario 8 - CO₂ emission minimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed cost</td>
<td>132 000 $</td>
<td>357 571 $</td>
</tr>
<tr>
<td>Startup for Raw Materials</td>
<td>189 000 $</td>
<td></td>
</tr>
<tr>
<td>Variable Cost Raw Materials</td>
<td>9 750 $</td>
<td>36 915 $</td>
</tr>
<tr>
<td>Variable Cost for Manufactured Products</td>
<td>18 040 $</td>
<td></td>
</tr>
<tr>
<td>Transportation Cost</td>
<td>54 000 $</td>
<td>225 500 $</td>
</tr>
<tr>
<td>Emission Cost</td>
<td>67 000 $</td>
<td>190 000 $</td>
</tr>
<tr>
<td></td>
<td>31 600 $</td>
<td>68 600 $</td>
</tr>
<tr>
<td></td>
<td>190 000 $</td>
<td>300 952 $</td>
</tr>
<tr>
<td></td>
<td>45 062 $</td>
<td></td>
</tr>
</tbody>
</table>
Thank you

References


Questions?

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