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# Carbon Market Sensitive Green Supply Chain Network Design

**Amin Chaabane, jr. eng., Ph.D. Student**

Supervised by

Prof. **Amar Ramudhin** and Prof. **Marc Paquet**

**Department of Automated Manufacturing Engineering**
**École de Technologie Supérieure**
**Montreal, Quebec, Canada**

# Outline

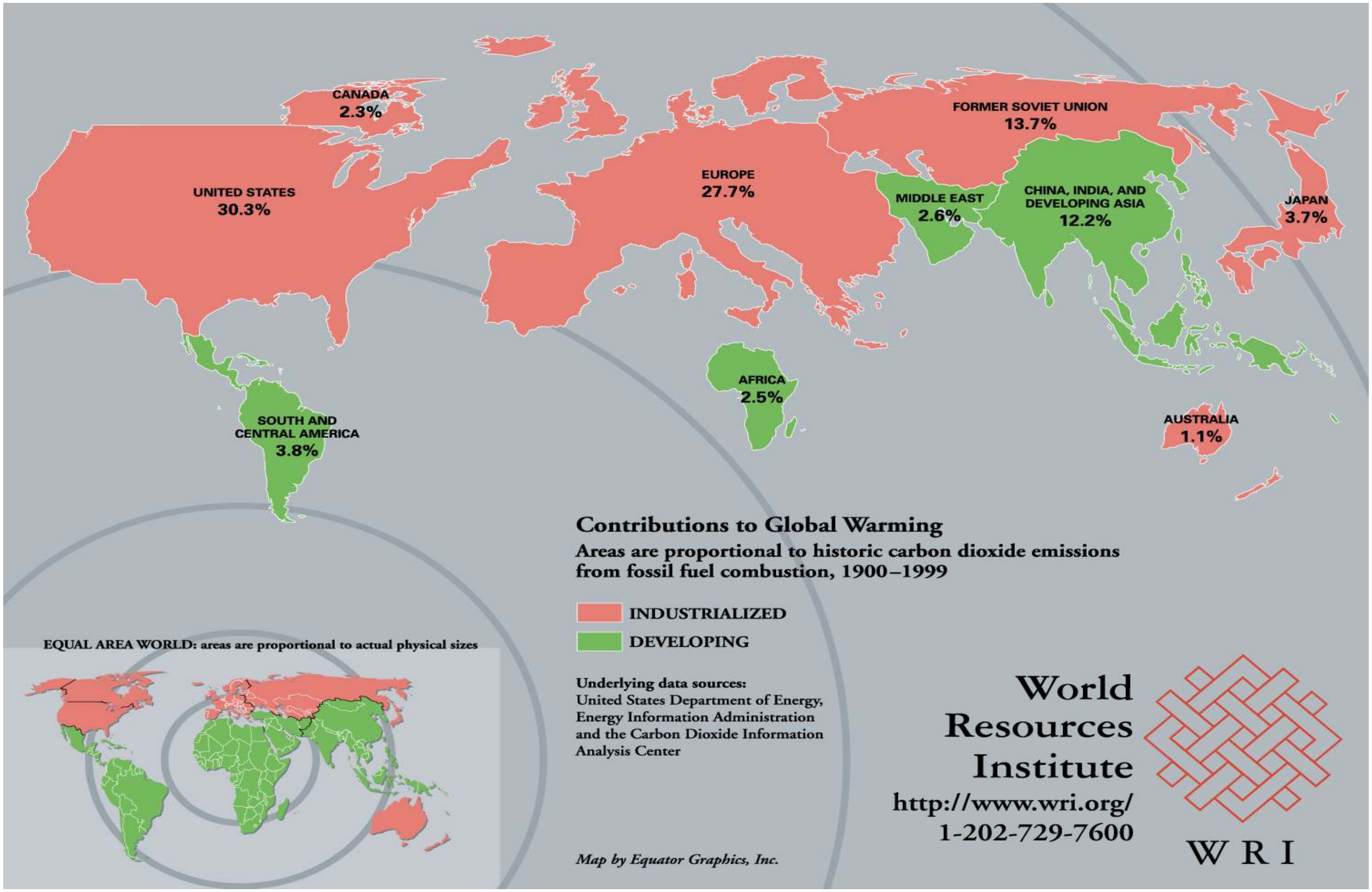
- Introduction
  - Context
  - Motivation and objective
  - Kyoto protocol
  - Carbon Market
- Literature
  - Limitations
- Model formulation
- Experimentation
  - Managerial insights
- Conclusion

# Introduction – *Context*

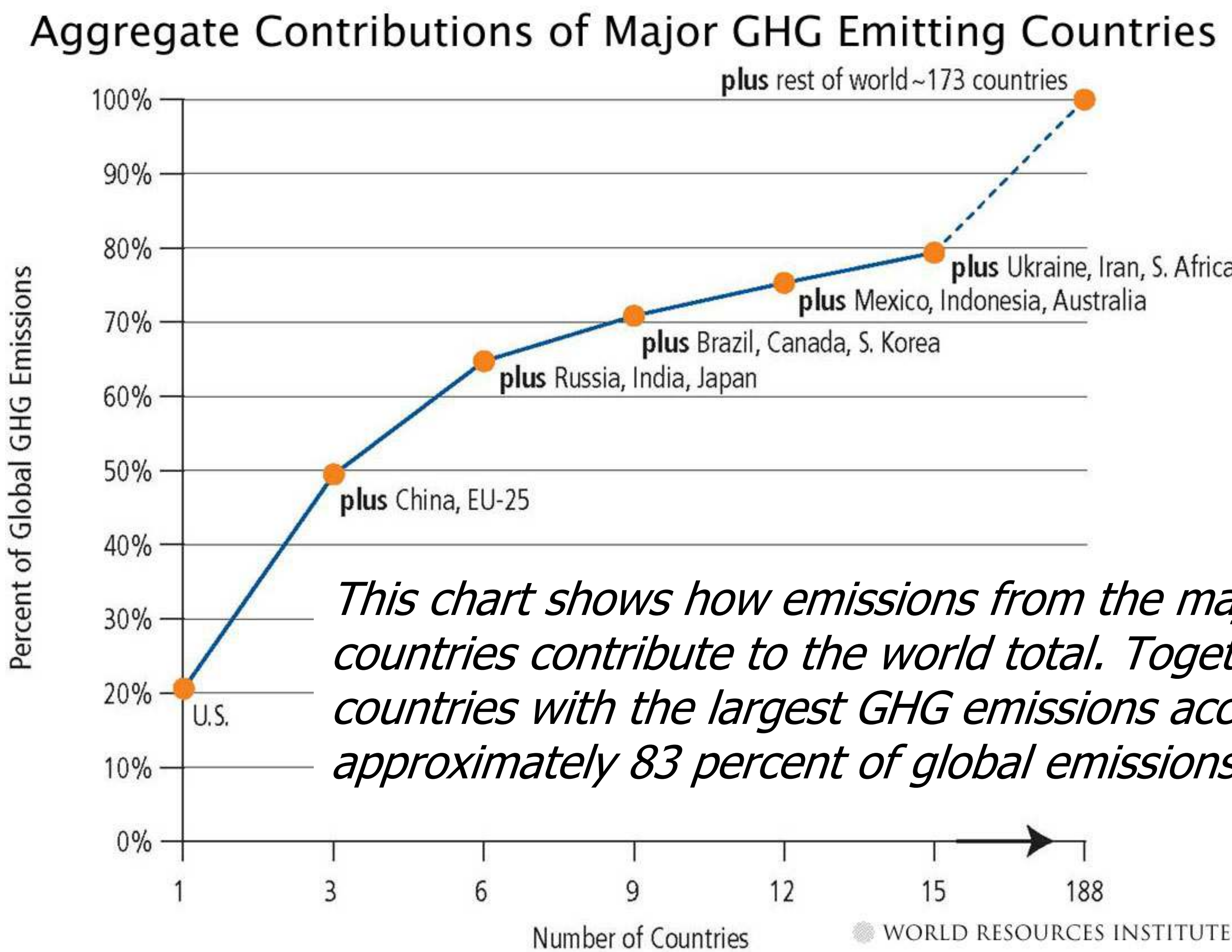
- Supply chain strategies of last decade :
  - Warehouse consolidation
  - Lean and agile supply chains
  - Just in time
  - Offshore manufacturing
  - Low cost country sourcing

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

*Climate Change : who is the responsible !!!*



# Introduction – *Context*




*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

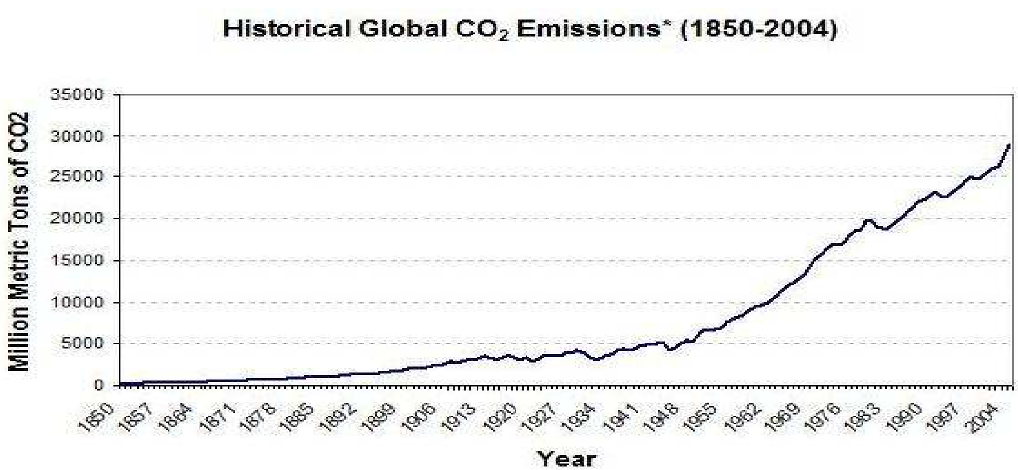
- Entry into force: February 16, 2005
  - US and Australia did not ratify
- Differentiated commitments:
  - Developed countries and countries with economies in transition agree to quantified legally-binding targets (overall objective leads to a 5% reduction from 1990 levels by 2008-2012)
- **Six gases**,:
  - 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

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




*from Fuel Burning, Cement Manufacture, and Gas Flaring
Source: Marland et. al (2007) Global, Regional, and National $CO_2$ Emissions. In Trends: A Compendium of Data on Global Change. CDIAC U.S.A.

MCeX – Montréal Climate Exchange

*13$ per ton*
*30 may 2008, launched*

CCX – Chicago Climate Exchange

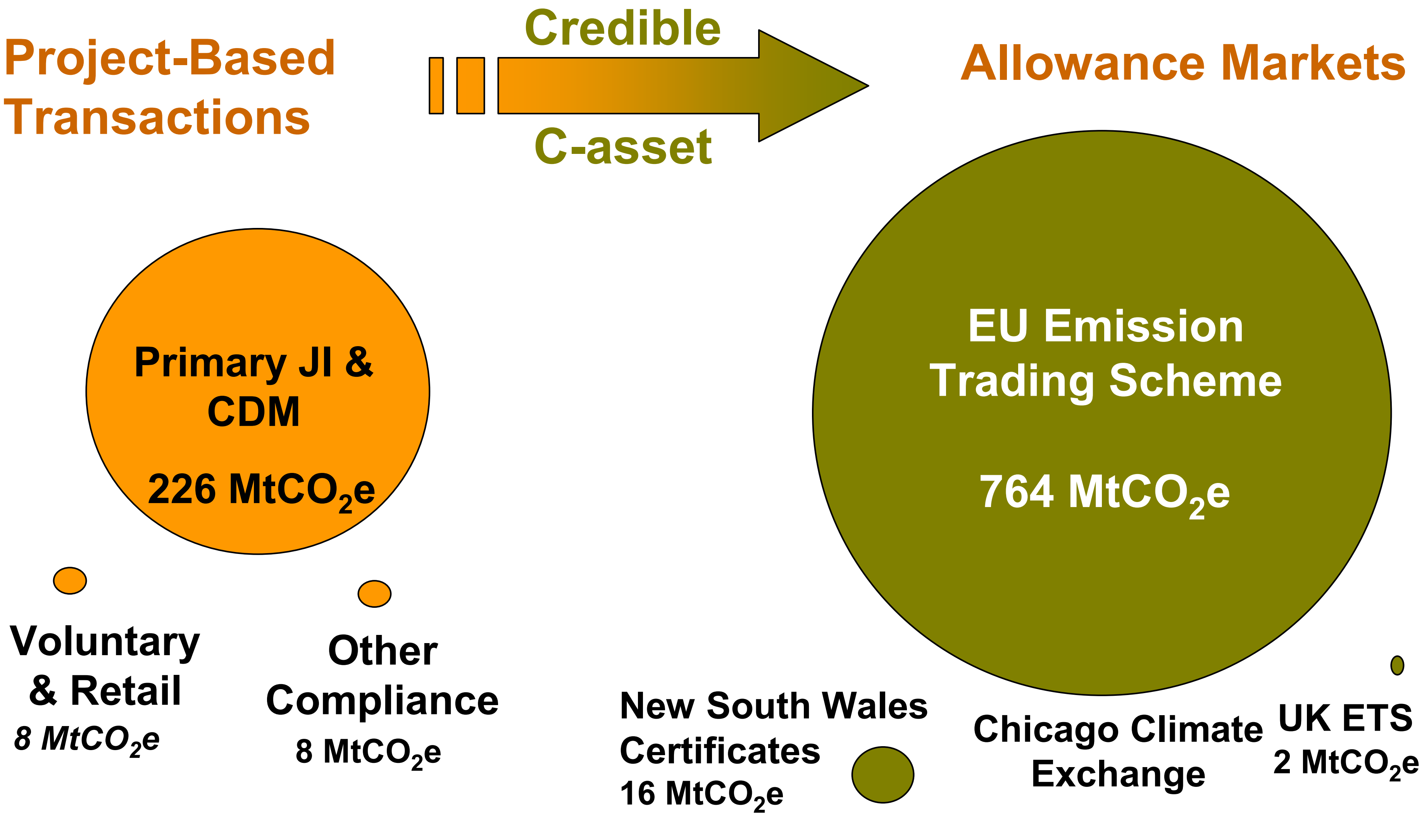
*6$ per ton*

ECX – European Climate Exchange

*25€ per ton*

# Structure of the Carbon Market 2006

(worth close to \$22 billion in 2006)



# 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] *Source : KPMG "International Survey of Corporate Responsibility reporting in 2005"*

- 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"*

# 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

*Srivastava, S.K. (2007) Green supply-chain management: A state-of-the-art literature review, International Journal of Management Reviews, 9, 1, 53-80.*

# 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

*Srivastava, S.K. (2007) Green supply-chain management: A state-of-the-art literature review, International Journal of Management Reviews, 9, 1, 53-80.*

# Literature – *Limitations*

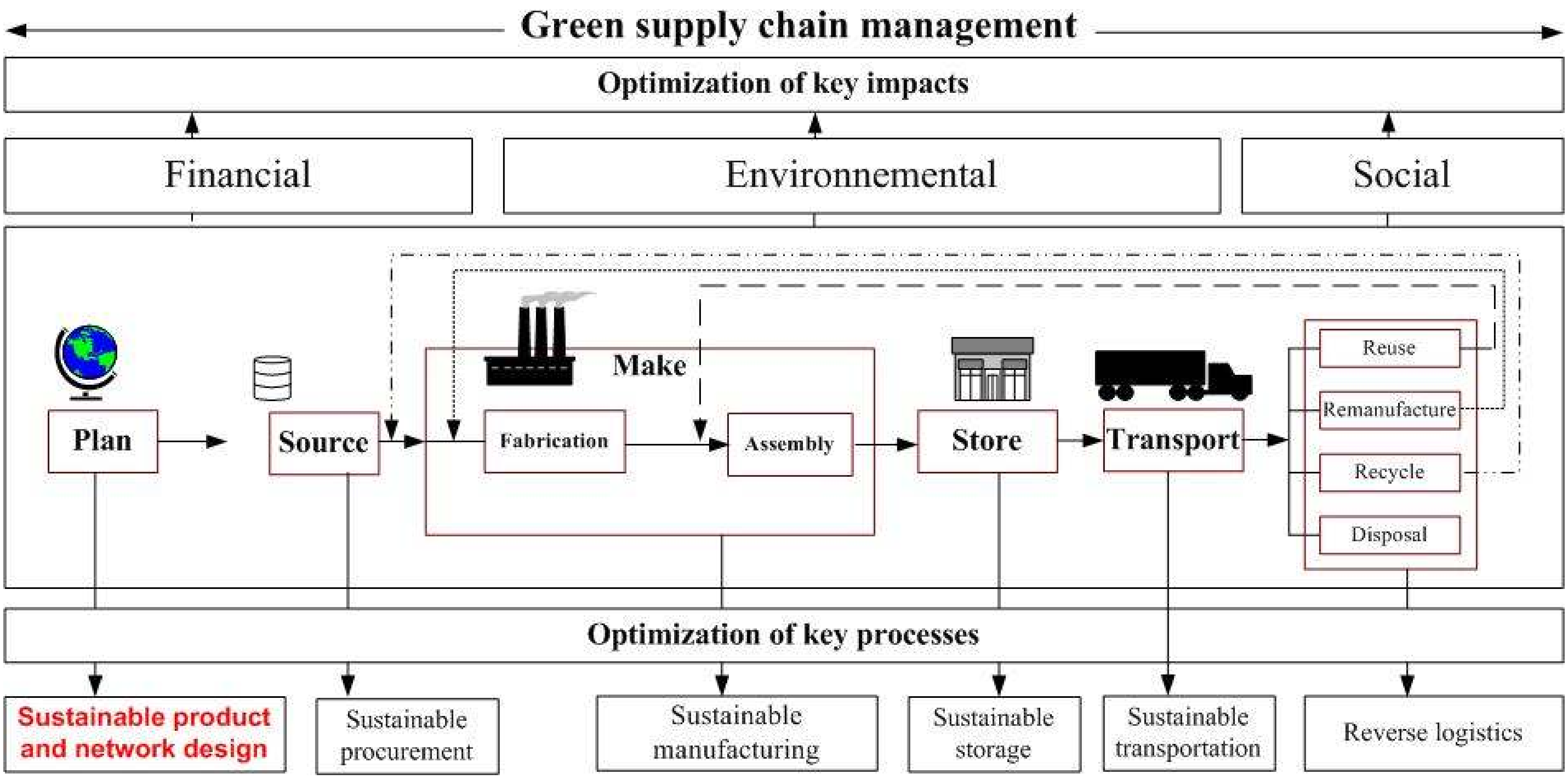
- GSCM studied  supply chain problems much more form operational point of view

- For the green supply chain network design
  - The problem is not studied enough
  - Research stress 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

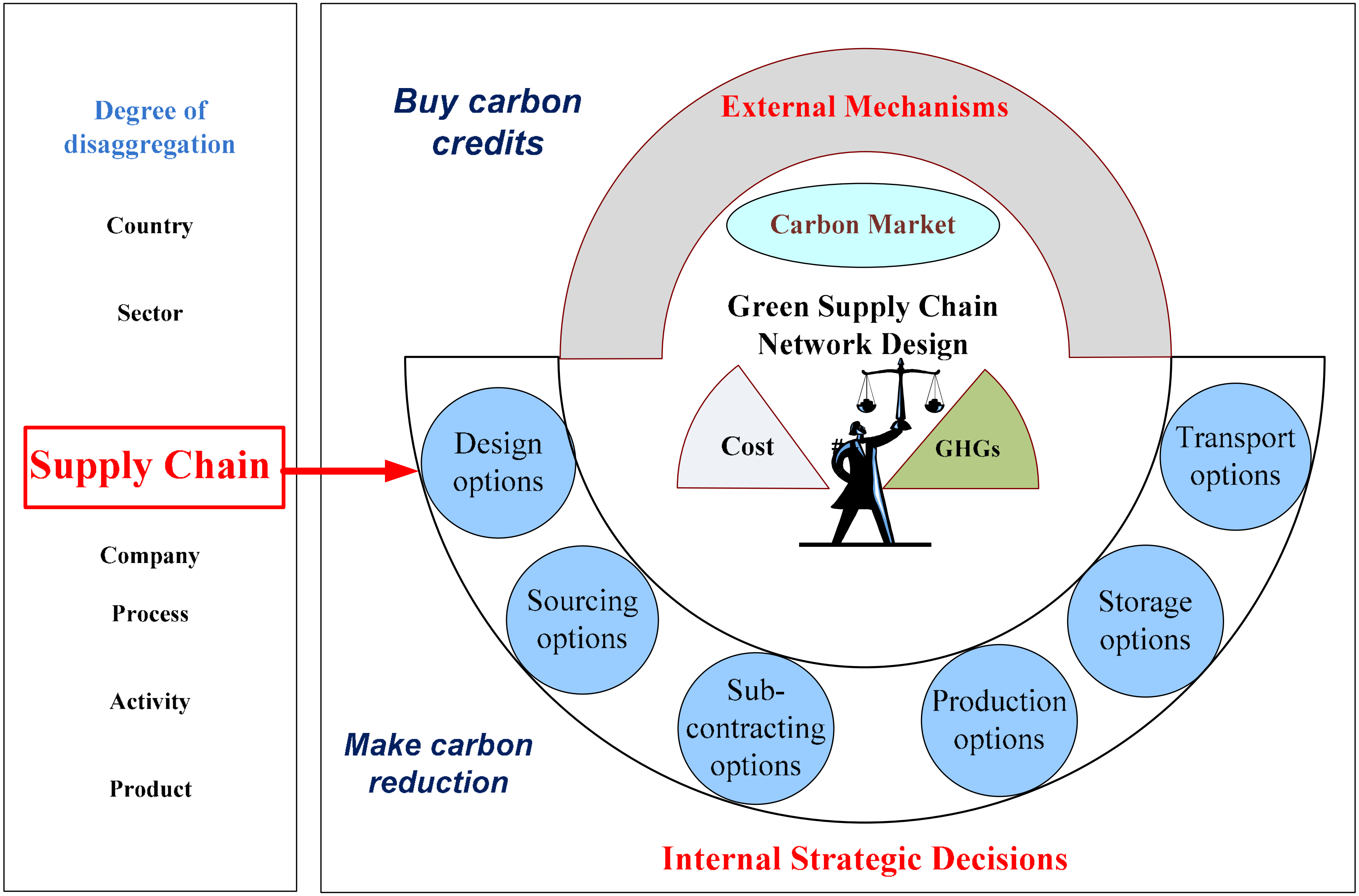
**Environmental conscious supply chain network design**




*Adapted from the SCOR Model*

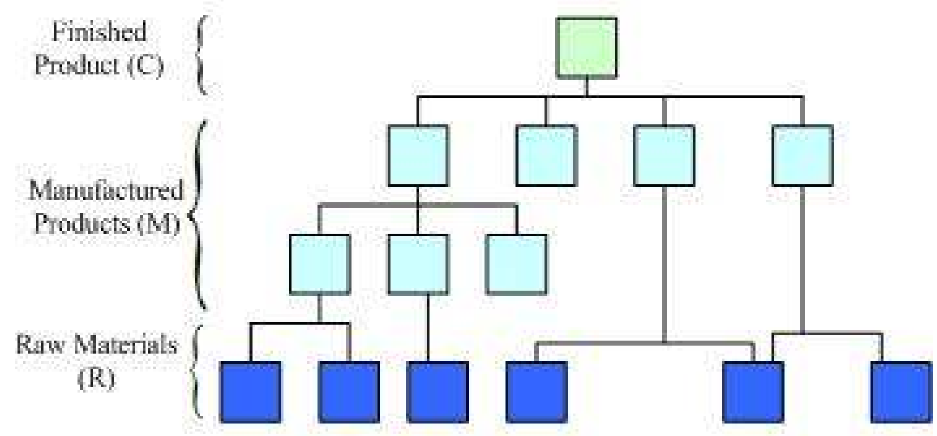
*http://www.supply-chain.org/cs/root/scor_tools_resources/scor_model/scor_model*

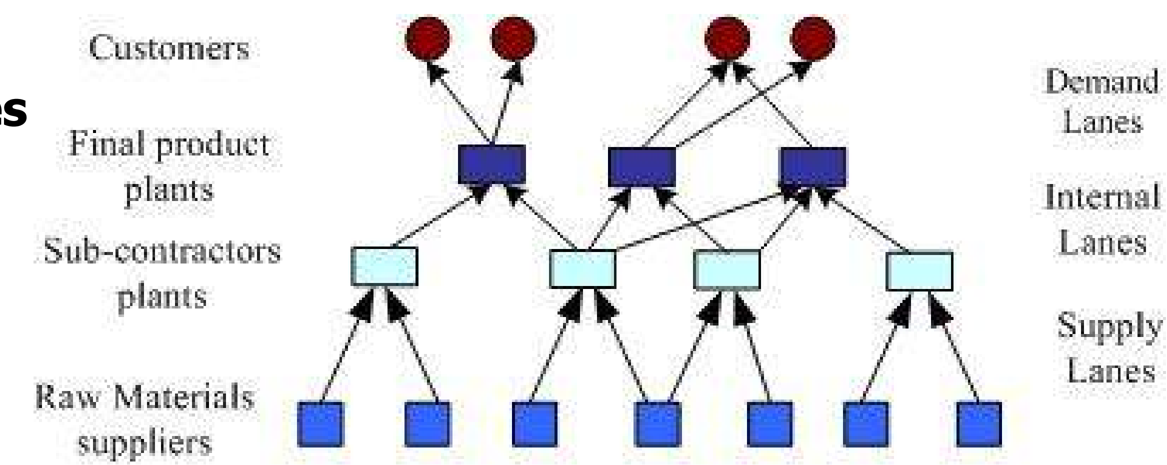
# Methodology: Mathematical programming



# 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 ($CO_2$)



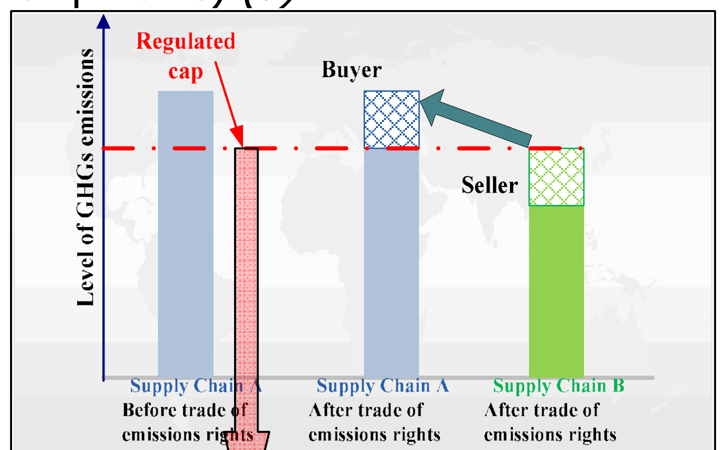



# Model formulation

- 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)*




$$\text{Min } \mathbf{F}_1 = \underbrace{\sum_{i\in V\cup S} \lambda_i A_i}_{(a)} + \underbrace{\sum_{p\in M\cup R}\sum_{i\in S_p\cup V_p} a_{ip}Y_{ip}}_{(b)} + \underbrace{\sum_{p\in M\cup R}\sum_{i\in S_p\cup V_p} c_{ip}X_{ip}}_{(c)}$$

$$+ \underbrace{\sum_{i\in S\cup V}\sum_{j\in S\cup D}\sum_{k\in K} l_i^k U_{ij}^k}_{(d)} + \underbrace{\sum_{p\in M\cup R}\sum_{i\in S_p\cup V_p}\sum_{j\in S(Suc(P))\cup D}\sum_{k\in K} t_{ijp}^k F_{ijp}^k}_{(e)}$$

$$+ \underbrace{\delta\left(\sum_{p\in M\cup R}\sum_{i\in S_p\cup V_p}\sum_{j\in S(Suc(P))\cup D}\sum_{k\in K} \alpha^k \pi_p d(i,j) F_{ijp}^k + \sum_{p\in M}\sum_{i\in S_p} \beta_p \pi_p X_{ip} - \underbrace{L}_{\substack{Emission\\ Cap}}\right)}_{(f)}$$

# Formulation – *Constraints*

- Number of operational sites

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

- Node capacity

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

- Capacity constraints
  - Maximum time capacity use for subcontractors

$$\sum_{p \in M_i} X_{ip} te_{ip} - T_i A_i \le 0, \forall i \in S \qquad (4)$$

  - Minimum time capacity use for subcontractors

$$\sum_{p \in M_i} X_{ip} te_{ip} - \rho_i T_i A_i \ge 0, \forall i \in S \qquad (5)$$

  - Maximum capacity for suppliers

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

- Conservation of flow

$$X_{ip} - \sum_{j \in S(Suc(p)) \cup D} \sum_{k \in K} F_{ijp}^{k} \ge 0 \quad (\forall p \in P, \forall i \in V_p \cup S_p) \qquad (7)$$

# Formulation – *Constraints*

- BOM constraints

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

- Demand constraints

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

- Transportation capacity constraints
  - Maximum number of transportation modes that can be used

$$\sum_{k \in K} Z_{ij}^{k} \le \tau_{ij} \quad (\forall i \in V \cup S, \forall j \in S \cup D) \qquad (11)$$

  - Volume capacity

$$\sum_{p \in R_i \cup M_i} \delta_p F_{ijp}^{k} - \kappa^k U_{ij}^{k} \le 0 \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (12)$$

  - Weight capacity

$$\sum_{p \in R_i \cup M_i} \pi_p F_{ijp}^{k} - \psi^k U_{ij}^{k} \le 0 \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (13)$$

# Formulation – *Constraints*

- Logical constraints
  - The number of shipments between two nodes is not nil only if the transportation mode is actually used

$$U_{ij}^{k} - MZ_{ij}^{k} \leq 0 \quad (\forall\, i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (14)$$

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

$$Z_{ij}^{k} \leq U_{ij}^{k} \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (15)$$

  - The number of shipment between two nodes using a transportation mode is nil if there is no flow of products

$$U_{ij}^{k} \leq \sum_{p \in R_i \cup M_i} F_{ijp}^{k} \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (16)$$

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

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

# Formulation – *Constraints*

- Integer, binary, and non-negativity constraints
  - Transport variables and the quantities supplied are non negative

$$F_{ijp}^{k} \geq 0 \quad (\forall p \in R \cup M, \forall i \in V_p \cup S_p, \forall j \in S(suc(p)) \cup D, \forall k \in K) \qquad (17)$$

$$X_{ip} \geq 0 \quad (\forall (p,i) \in R \times V_p \cup M \times S_p) \qquad (18)$$

  - Binary variables:

$$Y_{ip} \in \{0,1\}, \forall (p,i) \in R \times V_p \cup M \times S_p \qquad (19)$$

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

$$Z_{ij}^{k} \in \{0,1\} \quad (\forall i \in V \cup S, \forall j \in S \cup D, \forall k \in K) \qquad (21)$$

  - The number of shipments must be integer:

$$U_{ij}^{k} \text{ integer} \quad (\forall p \in P, \forall i \in V_p \cup S_p, \forall j \in S(Suc(p)) \cup D, \forall k \in K) \qquad (22)$$

# Parameters – *Data input*

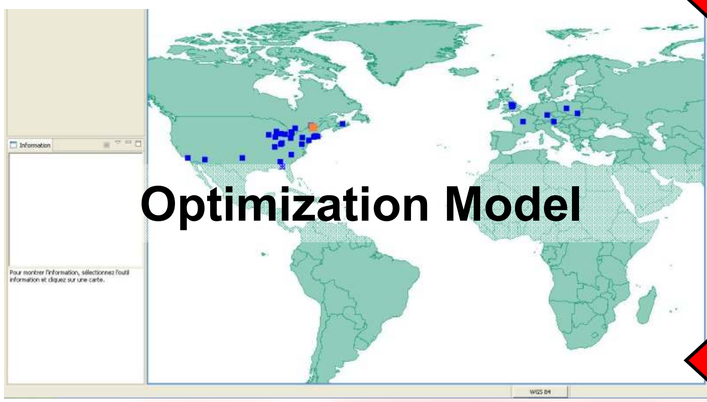
- How to find Emission Factors ?
  - Example: IPCC Emission Factor Database (EFDB)

    *http://www.ipcc-nggip.iges.or.jp/EFDB/main.php*

| Supply Chain Activity | Data Required |
|---|---|
| Transportation | ▪ Carbon Emission factor (kg $CO_2$ per gallon) or **$CO_2$ per Freight (kg $CO_2$ per ton-mile)** |
| Production | ▪ Carbon Conversion Factor per kg of Product produced **(kg $CO_2$ per kg)** |
| Plant | ▪ 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). |
| Warehouses | ▪ 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) |

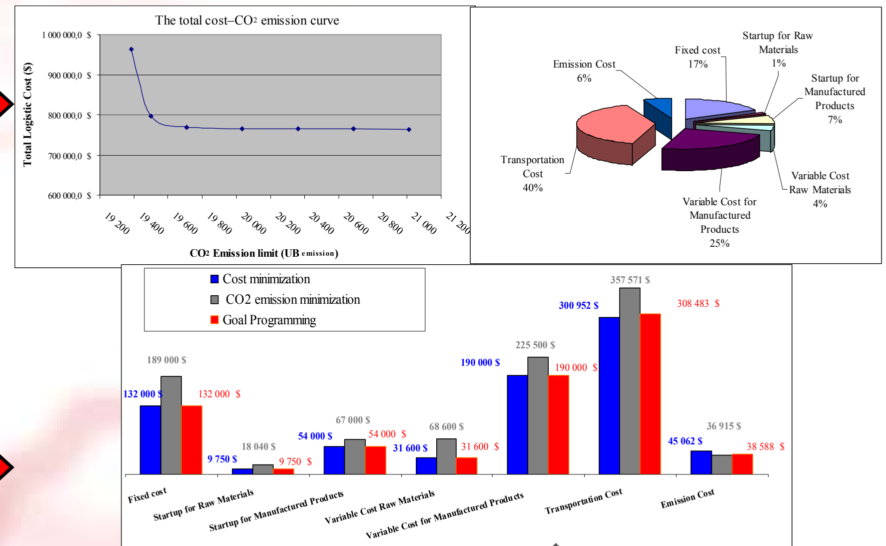
# Summary of the model (DSS)

**Environmental Conscious and Carbon Market Sensitive Supply Chain Network Design**



**Optimization Model**

**GHG Emissions and cost analysis**




**Environmental data**

Actual information system

**SAP**

**Excel**

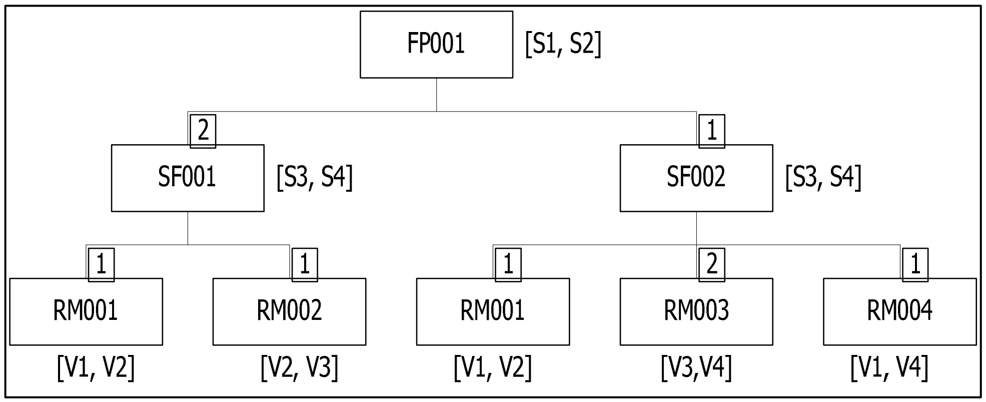
**CRM**

**CATIA**

**MY SAP SCM**

# Experimentation – *Example*

- Environmental supply chain network design example




| 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 |

**Freight transportation emission factors (grams/ton-mile)**

| | 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 |

**MILP model characteristics**

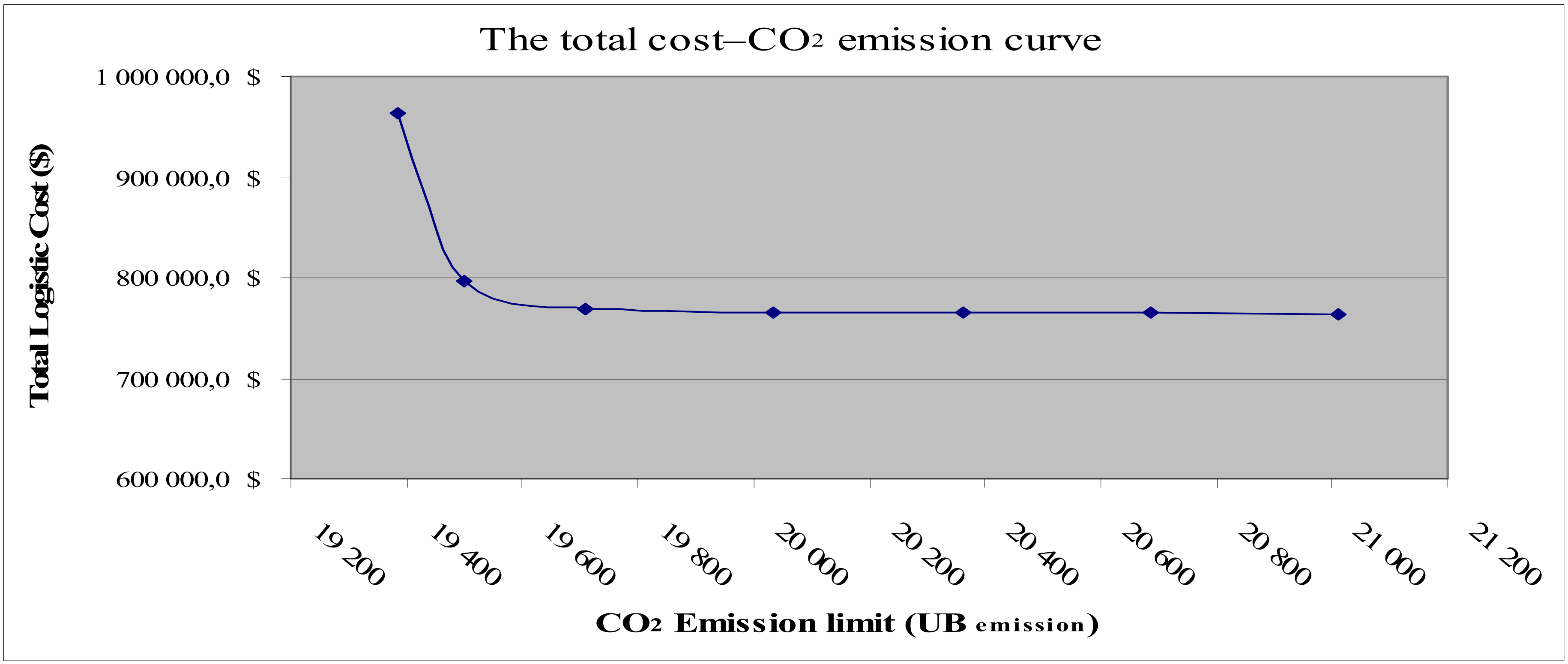
# Experimentation – *Results*

- The MILP problem is solved by CPLEX Interactive Optimizer

| | GHG emission limit ($UP_{Emission}$) *(in tons)* | Total Cost ($) |
|---|---|---|
| Base scenario | 21 012 | 763 364 $ |
| Scenario 2 | 20 687 | 764 421 $ |
| Scenario 3 | 20 361 | 764 421 $ |
| Scenario 4 | 20 035 | 764 421 $ |
| Scenario 5 | 19 710 | 768 802 $ |
| Scenario 6 | 19 709 | 768 802 $ |
| Scenario 7 | 19 500 | 796 032 $ |
| Scenario 8 | 19 383 | 962 626 $ |

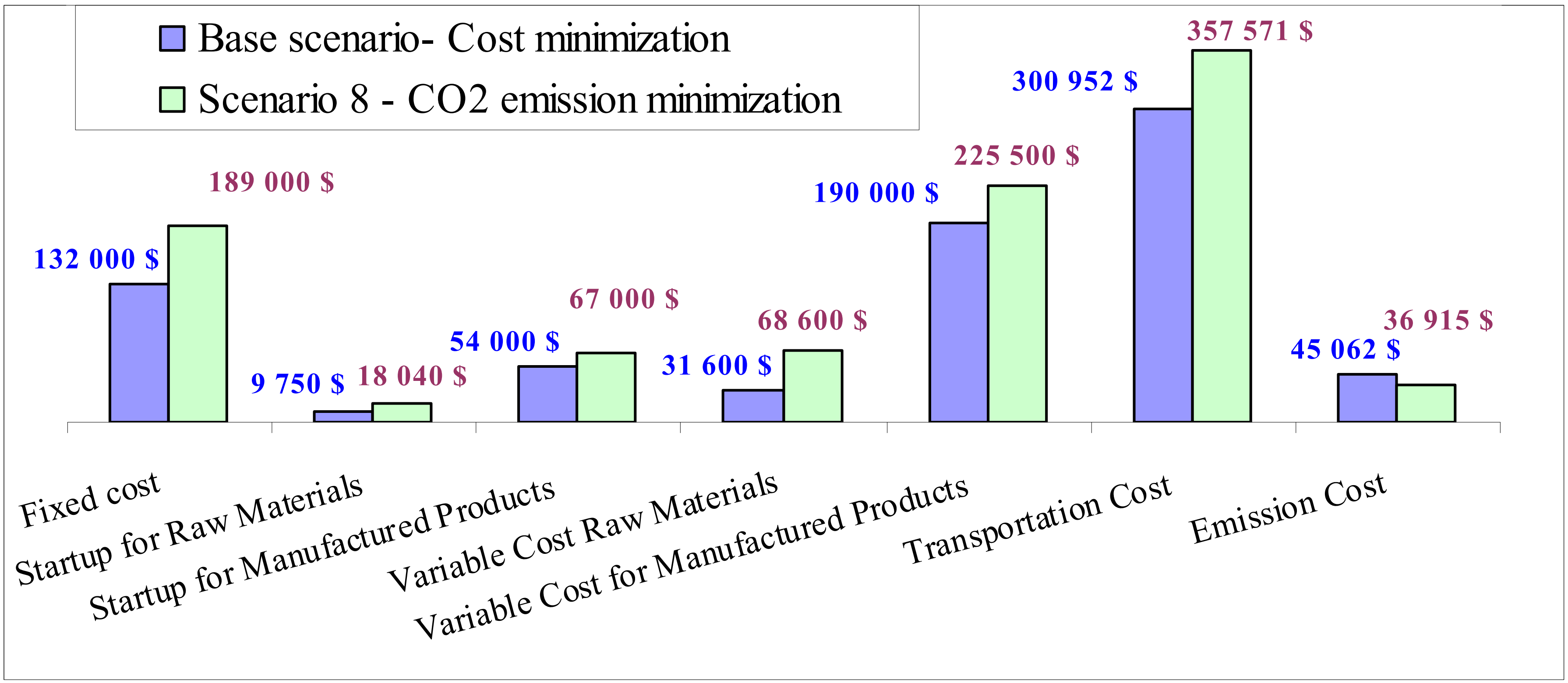
# Some managerial insights

- Tradeoffs between cost and $CO_2$ emissions
- Cost analysis
- GHG emissions assessment



# Some managerial insights

## Cost minimization versus $CO_2$ emissions minimization



# Thank you

## References


1. A. Ramudhin, A. Chaabane, M. Kharoune, and M. Paquet. "Carbon Market Sensitive Green Supply Chain Network Design". In Proceeding of the IEEE International conference on Industrial Engineering and Engineering Management (IEEM), Singapore, December 8-11, 2008.

2. A. Chaabane, A. Ramudhin, M. Kharoune, and M. Paquet. "Trade-offs Model for Carbon Market Sensitive Green Supply Chain Network Design". In Proceeding of the Sixth Annual International Symposium On supply Chain Management, Calgary, Alberta, Canada, October 15th – 17th 2008.

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# Questions ?



**For more information:**
**E-mail:** amin.chaabane.1@ens.etsmtl.ca