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OPTIMIZATION AND EVALUATION OF SUSTAINABLE SUPPLY CHAINS

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ABSTRACT: *Increasing environmental concerns together with legislations are forcing industries to take a fresh look at the impact of their supply chain operations on the environment. This paper introduces a mixed-integer linear programming based framework for sustainable supply chain design that considers life cycle assessment (LCA) principles in addition to the traditional material balance constraints at each node in the supply chain. Indeed, the framework distinguishes between solid and liquid wastes, as well as gaseous emissions due to various production processes and transportation. The framework is used to evaluate the tradeoffs between economic and environmental objectives under various cost and operating strategies for an aluminum company. The results suggest that current legislation and Emission Trading Schemes (ETS) must be strengthened and harmonized at the global level in order to drive a meaningful environmental strategy.*

KEYWORDS: *Sustainable supply chain design, Environment, Greenhouse gases emissions, Life cycle assessment, Reverse logistics, Emission trading scheme, Carbon management.*

1 INTRODUCTION

Supply chain network design attempts to define the best supply chain configuration that enables an organization to maximize its long-term economic performance. Typically, the decisions cover two planning levels: (1) strategic decisions on sourcing, production (opening or closing of facilities), distribution and sales; (2) tactical decisions on supply network planning affecting the flow of goods trough the network. Flexibility, robustness and responsiveness are some of the strategies that have been used to adapt to dynamic changes in the supply chain environment (Sabri and Beamon, 2000). But, unfortunately the pursuit of short term profitability is still recognized as the one of the major drivers for managerial decisions and this, among other things, has contributed to the slowdown in the current global economy. Nowadays, given the constraints relative to the availability of non-renewable resources (metal, oil, etc.), enterprises are more than ever obliged to rethink their strategies to ensure the sustainability of their operations.

Closed-loop supply chains are one of the options that are being considered (Pochampally et al., 2009, Srivastava, 2008, Barker and Zabinsky, 2008, Lieckens and Vandaele, 2007). Other avenues being studied include different actions related to one or more phases of the product life cycle such as product design (Hugo and Pistikopoulos, 2005), production planning and control for remanufacturing (Jayaraman et al., 1999, Luo et al., 2001), inventory management (Ferretti et al., 2007), product recovery (Jayaraman, 2006), reverse logistics (Sheu et al., 2005, Sheu, 2008) and carbon emissions reduction (Ramudhin et al., 2008). However, these actions may not be enough to guarantee long term sustainability. Recovery of used products and reprocessing (remanufacturing, recycling, disposal, incineration, etc.) might not only increase operating costs but also contribute to an increase in greenhouse gases (GHG) emissions which defeats long-term sustainability by destroying the very geographical environment in which these supply chains operate. Sustainable development recognizes the interdependence between three dimensions: the economic, the environmental and the social performances of an organization. An integrated approach that links supply chain decisions to the three pillars of sustainability is advocated.

Sustainable supply chain design (Frota Neto et al., 2008) is a new emerging approach that arose in response to this situation and tries to embed economic, environmental as well as societal decisions in supply chains at design time. The objective of the methodology proposed in this paper is to present a formal model that considers the important dimensions of sustainability throughout the supply chain life cycle.

2 LITERATURE REVIEW

Traditionally, the main objective of optimization models used in strategic network design focused on the economic aspect of supply chains (Goetschalcks and Fleischmann, 2008). However, more recently there has been a growing awareness about environmental issues. The first proposals tried to integrate such considerations at the plant level. The main drawback of these approaches is that it may result in solutions that reduce the negative environmental impact somewhere in the supply chain at the expense of increasing it somewhere elsewhere. Life-Cycle Assessment (LCA) methodology has been proposed in response to this situation (De Benedetto and Klemes, 2009). LCA is a process for evaluating the environmental impacts associated with a product, process or activity. It identifies and quantifies the energy and materials used and the waste released to the environment, and evaluates and implements opportunities for environmental improvements. The assessment covers the entire life cycle of the product, process or activity, including extracting and processing raw materials, manufacturing, transportation and distribution, reuse and maintenance, recycling and final disposal.

Hugo et Pistikopoulos (2005) present a mathematical programming-based methodology with explicit inclusion of life cycle assessment (LCA) criteria as part of the strategic investment decisions related to the design and planning of supply chain networks. Nagurney et al. (2006) develop a supply chain model in which the manufacturers can produce homogeneous product in different manufacturing plants with distinct environmental emissions. Frota Neto et al. (2008) develop a framework for the design and evaluation of sustainable logistic networks where activities affecting the environment and cost efficiency in logistic networks are considered. Guillen-Gosalbez and Grossmann (2009) present a supply chain network design model to determine the supply chain configuration along with the planning decisions that maximizes the net present value and minimizes environmental impact. The model includes structural and planning decisions.

While the LCA principle has been successfully applied to design new products and processes that minimize environmental damage (global warming, ozone depletion, acidification, toxicity, etc.), limited work has been conducted on the development of decision making models that integrate both LCA principles and supply chain management principles (Seuring and Muller, 2008). In addition, few studies have addressed the impact of integrating external control mechanisms (government regulation, take-back legislation, GHG emissions, and carbon taxes, carbon markets, etc.) on sustainable supply chain management practices.

For instance, Nagurney et al. (2006) is one of the first studies that addresses carbon taxes in the electric power supply chains (Nagurney et al., 2006). Subramanian et al. (2008) propose an approach to integrate environmental consideration within a managerial decision making framework (Subramanian et al., 2008). A non-linear mathematical programming model is introduced that allows the incorporation of traditional operations planning considerations (capacity, production and inventory) with environmental considerations (design, production, and end-of-life). Decisions on the number of carbon credits purchased and sold in different periods are added under the limitation of carbon emissions.

Ramudhin et al. (2009) are the first to propose a carbon market sensitive strategic planning model for sustainable supply chain network design. They show that considerations of internal and external control mechanisms are of great importance to decision makers when designing sustainable supply chains (Ramudhin et al., 2009). This paper extends the model presented in Ramudhin et al. (2009) by consideration of the LCA methodology to establish successful sustainable supply chains over time. The capability of the model is illustrated by an example of strategic planning in the aluminum supply chain.

3 PROBLEM STATEMENT

Among the different approaches available to assess the environmental impact of processes and organizations, the LCA method seems to be the most promising. It aggregates the results of different aspects of environmental studies including GHG emissions that are recognized as the most harmful elements to the environment and responsible for climate change. GHG emissions are calculated based on emission factors and converted to carbon dioxide equivalent quantity (CO_2e).

Many countries are implementing various mechanisms to reduce GHG emissions including incentives or mandatory targets to reduce carbon footprint. Carbon taxes and carbon markets (emissions trading) are recognized as the most cost-effective mechanisms. The basic idea is to put a price tag on carbon emissions and create a new investment opportunities to generate a fund for green technology development (Bayon et al., 2007, Labatt and White, 2007). There is already a number of active carbon markets for GHG emissions such as the European Union Emission Trading Scheme (or EU ETS) in Europe, the largest multi-national GHG emissions trading scheme in the world, the New Zealand Emissions Trading Scheme (NZ ETS) in New Zealand, the Chicago Climate Exchange in United State (Peace and Juliani, 2009, Johnson and Heinen, 2004), and more recently the Montreal Climate Exchange in Canada.

Measuring and assessing carbon emissions becomes then an important step that can be achieved by LCA techniques and software (Rice et al., 1997). However, compliance with the environmental regulation of carbon emissions in a cost-effective manner is challenging. Thus, supply chain network design model have been revised to include the additional cost due to GHG emissions at all levels of the supply chain and social variables affecting the quality of life of the community in which the supply chain operates. As shown in Figure 1, an LCA based approach is necessary in order to establish the link between the critical inputs (raw material, energy, human, used product, etc.) and the output (products, GHG emissions, waste) at each node of the network over its entire life cycle.

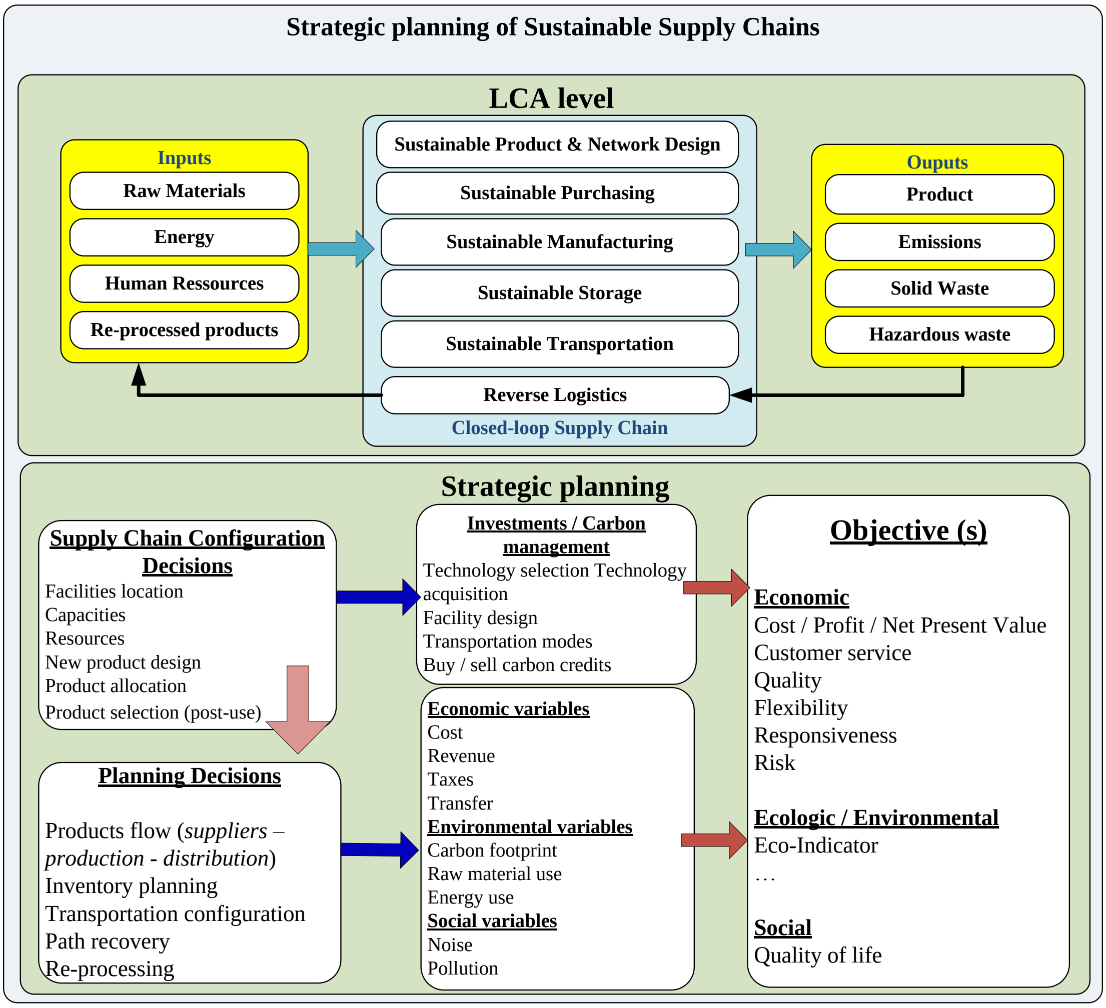

Figure 1: An LCA approach to support sustainable supply chain design

4 OPTIMIZATION MODEL

This section describes a generic mathematical model to help decision makers in the design and planning of sustainable supply chain based on the LCA methodology. The model establishes the link with the emission trading scheme to achieve sustainability objectives in a cost effective manner.

4.1 Notations

Figure 2 shows the structure of the supply chain. A set of potential suppliers (S) can supply raw materials to a set of sub-contractors and plants (F) for the manufacturing of products. The latter can be distributed through a set of potential distribution centers (D). Final products are shipped from the distribution centers to different customers or markets (C). Also available are different recycling centers for the processing of used products that can be returned to different stages in the supply chain. At each production or recycling center, a set of potential technologies, $h \in H$, is available for use. Each of these technologies need some inputs (energy, liquid, solid, gazes, etc.), $i \in I$, other than materials and generate different outputs (liquid, solid, gazes), $o \in O$. Different transportation modes, $m \in M$, are used for the shipment of products between nodes (suppliers, production units, distribution centers, and recycling units). Each transportation technology need some inputs (e.g. energy) and may generate some wastes (output). The main objective of the model is to support sustainable supply chain network design over a long-term period of time, $t \in T$.

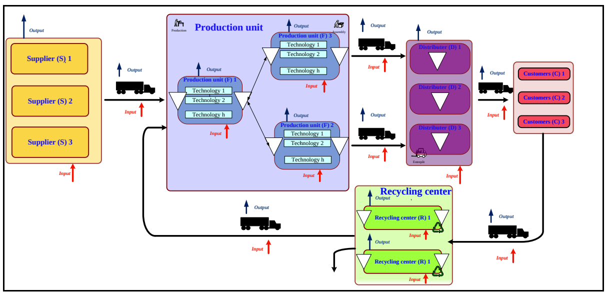

Figure 2: Closed-loop Supply chain network structure

Before the description of the detailed model, some basic elements about modeling techniques that have been used based are explained. Generally, we define two types of nodes (production unit and recycling center). For a production unit, one or several technologies will be available for manufacturing activities. The production is based on a bill of material that indicate the quantity of raw material or component $p\in P^{MP}\cup P^{SF}$ necessary to manufacture product $p'\in P^{SF}\cup P^{PF}$. The potential technologies available differ in terms of acquisition and operation costs as well as inputs consumption and outputs emissions. Figure 3 summarize the situation.

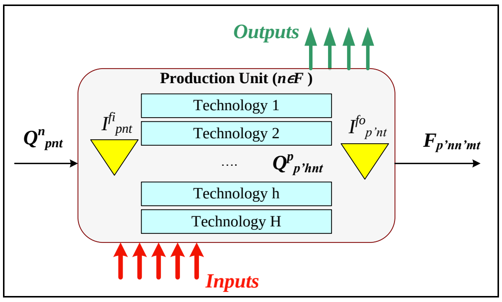

Figure 3: Characteristics of a production unit

For a recycling center, we consider that a certain percentage of products is recovered by the company. To simplify the calculation, we consider that is proportional to the demand at each period. Thus, we assume that for each period, there is a quantity of used products collected and delivered to recycling centers. Using a bill of material of disassembly, the product is disassembled. Good recycled components and raw materials are reintegrated in production units. The non usable ones are destroyed thorough the disposal process.

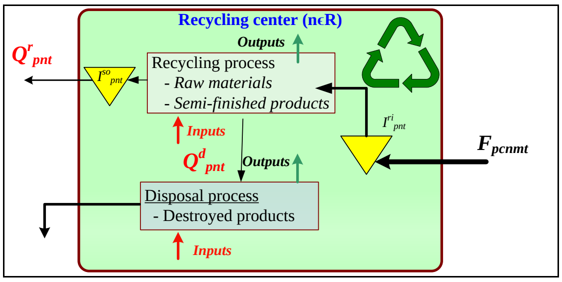

Figure 4: Characteristics of a recycling center

4.2 Decision variables

To achieve the objective of sustainability and understand the impact of different control parameters on the decision process, several decisions at touching various aspects of the supply chain must be taken into account. They are:

(a) Decisions as to production units

Q^n_{pnt} = Quantity of material $p\in P^{MP}$ necessary in production unit $n\in F$ during time period $t\in T$

Q^p_{phnt} = Quantity of product $p\in P^{SF}\cup P^{PF}$ manufactured / assembled using technology $h\in H$ at production unit $n\in F$ during time period $t\in T$

I^{fi}_{pnt} = The inventory level of input product $p\in P^{MP}\cup P^{PF}$ at unit production $n\in F$ during time period $t\in T$

I^{fo}_{pnt} = The inventory level of output product $p\in P^{SF}\cup P^{PF}$ at unit production $n\in F$ during time period $t\in T$

Y^s_{pnt} = Binary variable takes a value of *1* if supplier $n\in S$ is selected for supplying raw material $p\in P^{MP}$ during time period $t\in T$, *0* otherwise

Y^f_{nt} = Binary variable takes a value of *1* if production unit $n\in F$ is operational during time period $t\in T$, *0* otherwise

Y^h_{phnt} = Binary variable takes a value of *1* if technology $h\in H$ is selected at production unit $n\in F$ during time period $t\in T$, *0* otherwise

Y^p_{phnt}= Binary variable takes a value of 1 if product $p\in P^{SF}\cup P^{PF}$ is manufactured/assembled using technology $h\in H$ at production unit $n\in F$ during time period $t\in T$, 0 otherwise

(b) Decisions as to distribution centers

I^d_{pnt}= The inventory level of product $p\in P^{PF}$ at distribution centre n∈D during time period $t\in T$

Y^d_{nt} = Binary variable takes a value of 1 if distribution center $n\in D$ is operational during time period $t\in T$, 0 otherwise

(c) Decisions as to recycling centers

Y^r_{nt} = Binary variable takes a value of *1* if recycling center $n\in R$ is operational during time period $t\in T$, *0* otherwise

Q^a_{pnt} = Quantity of product $p\in P^{PF}$ recycled at recycling center $n\in R$ during time period $t\in T$

Q^r_{pnt} = Quantity of raw material $p\in P^{MP}$ recycled at recycling center $n\in R$ during time period $t\in T$

Q^d_{pnt} = Quantity of product $p\in P^{PD}$ destroyed at recycling center $n\in R$ during time period $t\in T$

I^{ri}_{pnt} = The inventory level of input of product $p\in P^{PF}$ at recycling center $n\in R$ during time period $t\in T$

I^{so}_{pnt} = The inventory level of output of product $p\in P^{MP}$ at recycling center $n\in R$ during time period $t\in T$

(d) Decisions as to transportation

$F_{pnn'mt}$ = Quantity of product $p\in P$ processed from node $n\in N$ to node $n'\in N$ using transportation mode $m\in M$ during time period $t\in T$

$Y^t_{nn'mt}$= Binary variable takes a value of *1* if transportation mode $m\in M$ is selected between node $n\in N$ and node $n'\in N$ during time period $t\in T$, *0* otherwise

(e) Decisions as to carbon management

CC^+_t= Allowances purchased during time period $t\in T$

CC^-_t = Allowances sold during time period $t\in T$

Decisions on (a), (b), (c) and (d) are related to the supply chain network design while decisions on (e) will determine the strategy to put in place for GHG emissions control. The problem can be viewed as a multi-objective model where the economic objective function, denoted by $\mathbf{F_1}$, evaluates the total logistic cost and the environmental objective function, denoted by $\mathbf{F_2}$, evaluates GHG emissions resulting from operation strategies manufacturing and transportation activities.

Using the Intergovernmental Panel for Climate Change (IPCC) guidelines and other environmental data, the global warming potential (GWP) for each activity of the supply chain is expressed in terms of carbon dioxide equivalent quantity (CO_2e). Emissions are assumed to be linearly proportional to manufacturing, transportation and usage.

4.3 Parameters

4.3.1 *Monetary parameters*

a^s_{pnt} = Fixed cost due to acquisition of raw material $p \in P^{MP}$ from supplier $n \in S$ during period $t \in T$. This represents the cost of development of long term partnership with the supplier to guarantee a good service level (e.g. investing on information technology and communication)

c^a_{pnt} = Purchasing cost of one unit of raw material $p \in P^{MP}$ from supplier $n \in S$ during time period $t \in T$

$c^{a'}_{pnt}$ = Purchasing cost of one unit of recycled raw material $p \in P^{MP}$ from recycling centre $n \in R$ during time period $t \in T$

a^f_{nt} = Fixed cost associated with the operation of production unit $n \in F$ during time period $t \in T$

a^h_{hnt} = Fixed cost associated with the implementation of a new technology $h \in H$ in production unit $n \in F$ during time period $t \in T$

a^p_{phnt} = Production cost of one unit of product $p \in P^{SF} \cup P^{PF}$ using technology $h \in H$ in production unit $n \in F$ during time period $t \in T$

c^p_{phnt} = Fixed cost associated with the configuration of technology $h \in H$ used in production unit $n \in F$ to manufacture/assemble product $p \in P^{SF} \cup P^{PF}$ during time period $t \in T$

c^{fi}_{pnt} = Inventory carrying cost of input product $p \in P^{MP} \cup P^{SF}$ at production unit $n \in F$ during time period $t \in T$

c^{fo}_{pnt} = Inventory carrying cost of output product $p \in P^{SF} \cup P^{PR}$ form production unit $n \in F$ during time period $t \in T$

a^d_{nt} = Fixed cost associated with the operation of distribution centre $n \in D$ during time period $t \in T$

c^d_{pnt} = Inventory carrying cost of product $p \in P^{PF}$ at distribution centre $n \in D$ during time period $t \in T$

a^r_{nt} = Fixed cost associated with the operation of recycling centre $n \in R$ during time period $t \in T$

c^{ri}_{pnt} = Inventory carrying cost of product $p \in P^{PF}$ at recycling centre $n \in R$ during time period $t \in T$

c^{ro}_{pnt} = Inventory carrying cost of raw material $p \in P^{MP}$ at recycling centre $n \in R$ during time period $t \in T$

c^r_{pnt} = Recycling cost of one unit of used product $p \in P^{PF}$ at recycling centre $n \in R$ during time period $t \in T$

c^d_{pnt} = Destruction cost of used product $p \in P^{PF}$ at recycling centre $n \in R$ during time period $t \in T$

c^{rc}_{pnt} = Purchasing cost of one unit of used product $p \in P^{PF}$ at recycling centre $n \in R$ during time period $t \in T$

$c^t_{pnn'mt}$ = Transportation cost of one unit of product $p \in P$ between node $n \in N$ and node $n' \in N$ using transportation mode $m \in M$ during time period $t \in T$

$a^t_{nn'mt}$ = Fixed cost associated with the establishment of a transportation link using mode $m \in M$ between node $n \in N$ and node $n' \in N$ during time period $t \in T$

u_{ot} = Emission cost of output $o \in O$ during time period $t \in T$

v_{it} = Usage cost of input $i \in I$ during time period $t \in T$

A^{CC}_t = The market price of buying an allowance during time period $t \in T$

V^{CC}_t = The market price of selling an allowance during time period $t \in T$

4.3.2 *Technical parameters*

λ_{pnt} = Capacity of supplier $n \in S$ for raw material $p \in P^{MP}$ during time period $t \in T$

q^p_{pnt} = Upper bound on product $p \in P^{SF} \cup P^{PF}$ manufactured / assembled a production unit $n \in F$ during time period $t \in T$

$\varphi_{pp'}$ = Utilisation factor of product $p \in P^{MP} \cup P^{SF}$ used in product $p' \in P^{SF} \cup P^{PF}$

EF^p_{oph} = Emission inventory of output $o \in O$ to manufacture /assemble product $p \in P^{SF} \cup P^{PF}$ using technology $h \in H$

CF^p_{iph} =Utilisation factor of input $i \in I$ to manufacture /assemble $p \in P^{SF} \cup P^{PF}$ using technology $h \in H$

χ_{pnt} = Distribution capacity of product $p \in P^{PF}$ at distribution center $n \in D$ during time period $t \in T$

d_{pnt} = Demand of product $p \in P^{PF}$ for customer $n \in C$ during time period $t \in T$

δ_{pnt} = Return rate of product $p \in P^{PF}$ from customer $n \in C$ during time period $t \in T$

q^r_{pnt} = Capacity of recycling centre $n \in R$ for product $p \in P^{MP}$ during time period $t \in T$

$\Phi_{pp'}$ = Conversion factor of recycled raw material $p \in P^{MP}$ from product $p' \in P^{PF}$

$\theta_{pp'}$ = Conversion factor of destroyed product $p \in P^{PD}$ from product $p' \in P^{PF}$

EF^r_{opn}= Emission inventory of output $o \in O$ during the recycling process of product $p \in P^{PF}$ at recycling center $n \in R$

CF^r_{ipn} = Utilisation factor of input $i \in I$ during the recycling process of product $p \in P^{PF}$ at recycling center $n \in R$

EF^d_{opn}= Emission inventory of output $o \in O$ during the destruction process of product $p \in P^{PF}$ at recycling center $n \in R$

CF^d_{ipn}= Utilisation factor of input $i \in I$ during the destruction process of product $p \in P^{PF}$ at recycling center $n \in R$

c_{pm} = Capacity of transportation mode $m \in M$ for product $p \in P$

EF^t_{opm} = Emission inventory of output $o \in O$ for using transportation mode $m \in M$ for handling product $p \in P$

CF^t_{ipm}= Utilisation factor of input $i \in I$ for using transportation mode $m \in M$ for handling product $p \in P$

4.3.3 Carbon management parameters

CO^{in}_i = Characterization factor used to convert used input $i \in I$ to carbon dioxide equivalent (CO_2e)

CO^{out}_o= Characterization factor used to convert used output $o \in O$ to carbon dioxide equivalent (CO_2e)

$L^{CO2\acute{e}q}_t$ = Aggregated limit in term of carbon dioxide equivalent (CO_2e) during compliance time period $t \in T$

4.4 Model formulation

This section describes the linear programming model that considers the critical aspects for the design and strategic planning of sustainable supply chains.

The choice of multi-objective linear programming (MOLP) as a methodology to investigate this problem is basically because it helps to find the different strategic decisions (explained in the previous framework) of linear objective functions and a single decision maker or a decision making body (the focal company) that guarantee a trade-off with respect to some linear constrains. Different parameters are necessary to describe the model. Here we limit the description to monetary and carbon management parameters. Some technological and technical parameters are also necessary but not described in details.

4.4.1 Economic objective (F_1)

The strategic sustainable supply chain network design described before has the objective to find a trade-off solution between the economic and the environmental performance. The economic objective is evaluated by the total logistic cost. The environmental performance is evaluated by the total emission of GHG.

Supply costs (*denoted SC*)

Fixed cost to establish contracts with suppliers:

$$\sum_{p \in P^{MP}} \sum_{n \in S} \sum_{t \in T} a^s_{pnt} Y^s_{pnt}$$

Variable cost for raw materials acquisition:

$$\sum_{p \in P^{MP}} \sum_{n \in S} \sum_{t \in T} c^a_{pnt} \sum_{n' \in F} \sum_{m \in M} F_{pnn'mt}$$

Recycled materials acquisition:

$$\sum_{p \in P^{MP}} \sum_{n \in R} \sum_{t \in T} c^{a'}_{pnt} \sum_{n' \in F} \sum_{m \in M} F_{pnn'mt}$$

Production costs (*denoted PC*)

Fixed cost for operating production units:

$$\sum_{n \in F} \sum_{t \in T} a^f_{nt} Y^f_{nt}$$

Fixed cost for technology acquisition:

$$\sum_{n \in F} \sum_{h \in H} \sum_{t \in T} a^h_{hnt} Y^h_{hnt}$$

Fixed cost for production line configuration:

$$\sum_{p \in P^{SF} \cup P^{PF}} \sum_{n \in F} \sum_{h \in H} \sum_{t \in T} a^p_{phnt} Y^p_{phnt}$$

Variable cost for manufacturing:

$$\sum_{p \in P^{SF} \cup P^{PF}} \sum_{n \in F} \sum_{h \in H} \sum_{t \in T} c^p_{phnt} Q^p_{phnt}$$

Inventory cost of raw materials:

$$\sum_{p \in P^{MP} \cup P^{SF}} \sum_{n \in F} \sum_{t \in T} c^{fi}_{pnt} I^{fi}_{pnt}$$

Inventory cost for products:

$$\sum_{p \in P^{SF} \cup P^{PF}} \sum_{n \in F} \sum_{t \in T} c^{fo}_{pnt} I^{fo}_{pnt}$$

Distribution costs (*denoted DC*)

Fixed cost for operating distribution centers:

$$\sum_{n \in D} \sum_{t \in T} a^d_{nt} Y^d_{nt}$$

Variable cost for material handling products:

$$\sum_{p \in P^{PF}} \sum_{n \in D} \sum_{t \in T} c^d_{pnt} I^d_{pnt}$$

Reverse logistics costs (*denoted* RC)

Fixed cost for operating distribution centers:

$$\sum_{n \in R} \sum_{t \in T} a^r_{nt} Y^r_{nt}$$

Variable cost of recycling used products:

$$\sum_{p \in P^{PR}} \sum_{n \in R} \sum_{t \in T} c^r_{pnt} Q^r_{pnt}$$

Variable cost for disposal of used products:

$$\sum_{p \in P^{PR}} \sum_{n \in R} \sum_{t \in T} c^d_{pnt} Q^d_{pnt}$$

Inventory cost for recovered used products:

$$\sum_{p \in P^{PF}} \sum_{n \in R} \sum_{t \in T} c^{ri}_{pnt} I^{ri}_{pnt}$$

Inventory cost for recycled products:

$$\sum_{p \in P^{MP} \cup P^{SF}} \sum_{n \in R} \sum_{t \in T} c^{ro}_{pnt} I^{ro}_{pnt}$$

Cost of recovery of used product:

$$\sum_{p \in P^{PR}} \sum_{n \in R} \sum_{t \in T} \left(c^{rc}_{pnt} \sum_{n' \in C} \sum_{m \in M} F_{pn'nmt} \right)$$

Transportation cost (*denoted* TC)

Fixed cost for transportation links between nodes

$$\sum_{n \in N} \sum_{n' \in N} \sum_{m \in M} \sum_{t \in T} a^t_{nn'mt} Y^t_{nn'mt}$$

Variable cost for transportation

$$\sum_{p \in P^{PR}} \sum_{n \in N} \sum_{n' \in N} \sum_{m \in M} \sum_{t \in T} c^t_{pnn'mt} F_{pnn'mt}$$

LCA based cost (*denoted LC*)

We consider that the company will identify some strategic inputs cost (water, oil, energy, etc.) that need to be considered in economic objective function. Also, some outputs (waste, co-products, etc.) need further treatment and there are also some related costs. Let's denote C_{it} the consumption of the input $i \in I$ during period $t \in T$:

$$C_{it} = (\sum_{p\in P^{SF}\cup P^{PF}} \sum_{h\in H} \sum_{n\in F} CF^p_{iph} Q^p_{phnt}) + (\sum_{p\in P^{MP}\cup P^{SF}} \sum_{n\in R} CF^r_{ipn} Q^r_{pnt}) + (\sum_{p\in P^{PD}} \sum_{n\in R} CF^d_{ipn} Q^d_{pnt}) + (\sum_{p\in P} \sum_{n\in N} \sum_{n'\in N} \sum_{m\in M} CF^t_{ipm} F_{pnn'mt})$$

Let's denote E_{ot} the emission of the output $o \in O$ during period $t \in T$:

$$E_{ot} = (\sum_{p\in P^{SF}\cup P^{PF}} \sum_{h\in H} \sum_{n\in F} EF^p_{oph} Q^p_{phnt}) + (\sum_{p\in P^{MP}\cup P^{SF}} \sum_{n\in R} EF^r_{opn} Q^r_{pnt}) + (\sum_{p\in P^{PD}} \sum_{n\in R} EF^d_{opn} Q^d_{pnt}) + (\sum_{p\in P} \sum_{n\in N} \sum_{n'\in N} \sum_{m\in M} EF^t_{opm} F_{pnn'mt})$$

Thus, the cost of using inputs is: $\sum_{i\in I} \sum_{t\notin T} v_{it} C_{it}$

The cost of treating generated outputs is: $\sum_{o\in O} \sum_{t\in T} u_{ot} E_{ot}$

Carbon credit component (denoted CC)

For many organizations and industrial sectors, the main emissions are greenhouse gases. Many companies have set voluntary targets in term of GHG emissions attributable to their supply chain or are subject to a new regulation that "caps" GHG emissions. Under an Emission trading Scheme (ETS), carbon dioxide (CO_2) is tradable. This system is based on the allocation of units to a company for exceeding its intensity-based GHG emissions reduction targets [1 credit = right to emit one metric ton of carbon dioxide equivalent (CO_2e)]. At the end of each compliance period, the emissions of the company will be verified. Each emitter must then offset its GHG emissions against its intensity-based GHG emissions reduction target established by the government. The discrepancy between the imposed target and the actual emissions may be offset by, among other things, the purchase of units on the domestic market. In addition to internal reductions, large emitters will be able to buy units from the carbon market in order to ensure compliance with their GHG emissions reductions obligations. On the other hand, those companies with emissions less than the cap will have the possibility to sell allowances in the carbon market and generate profit.

Thus, "carbon management" consists of taking the decision on the most cost-effective strategy to be in compliance either with environmental regulation or with voluntary targets. Thus, the decision is to determine the number of allowances purchased (A^{CC}_t) in period $t \in T$ and the number of allowances sold (V^{CC}_t) in period $t \in T$.

$$CC = \sum_{t\in T} CC^-_t A^{CC}_t - \sum_{t\in T} CC^+_t V^{CC}_t$$

In summary, the economic performance is measured by the objective function ($\mathbf{F_1}$) that should be minimized to ensure economic sustainability.

$$\mathbf{F_1} = SC + PC + DC + RC + LC + TC + CC \quad (1)$$

4.4.2 Environmental objective (F_2)

The second key objective to achieve sustainable supply chains is the evaluation and the optimization of the environmental impact. The determination of the environmental performance of a supply chain is not easy and might be different form one industry sector to another. However, the use of an LCA approach helps in the evaluation of the environmental performance of product, process and service. To make it general, we aggregate the different impacts in term of GHG emissions (objective function $\mathbf{F_2}$) which is very important in our case (due to the link with ETS). Thus, GHG emissions should be minimized to ensure environmental sustainability:

$$\mathbf{F_2} = \sum_{t\in T} \sum_{o\in O} (E_{ot} CO^{out}_o + \sum_{i\in I} C_{it} CO^{in}_i) \quad (2)$$

4.4.3 Constraints

Suppliers

Supplier's capacity:

$$\sum_{n'\in F} \sum_{m\in M} F_{pnn'mt} \le \lambda_{pnt} Y^s_{pnt} \quad \forall p \in P^{MP}, \forall n \in S, \forall t \in T$$

If the supplier is selected, it will stay operational for the whole planning horizon:

$$Y^s_{pnt} \ge Y^s_{pn(t-1)} \quad \forall n \in S, \forall t \in T$$

Production units

Raw material and semi-finished products usage

$$Q^n_{pnt} = \sum_{p'\in P^{SF}\cup P^{PF}} \sum_{h\in H} \phi_{pp'} Q^p_{p'hnt} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in F, \forall t \in T$$

Capacity of production units:

$$Q^p_{phnt} \le q^p_{pnt} Y^p_{phnt} \quad \forall p \in P^{SF} \cup P^{PF} \quad \forall h \in H, \forall n \in F, \forall t \in T$$

Logic constraints: if a technology is not selected at a production unit, there is no need for configuration:

$$Y^p_{phnt} \le Y^h_{hnt} \quad \forall p \in P, \forall n \in F, \forall h \in H, \forall t \in T$$

Logic constraints: if the production unit is not operational, there is no need to implement a technology in this facility:

$$Y^h_{hnt} \le Y^f_{nt} \quad \forall n \in F, \forall h \in H, \forall t \in T$$

Inventory of input products (raw material, components):

$$I^{fi}_{pn(t-1)} + \sum_{n'\in S} \sum_{m\in M} F_{pn'nmt} + \sum_{n'\in R} \sum_{m\in M} F_{pn'nmt} = I^{fi}_{pnt} + Q^n_{pnt} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in F, \forall t \in T$$

Initial inventory levels for products:

$$I^{fi}_{pnt_0} = 0 \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in F$$

Inventory capacity constraints (raw material, components): $I^{fi}_{pnt} \le i^{fi}_{pnt} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in F, \forall t \in T$

Inventory of output products:

$$I^{fo}_{pn(t-1)} + \sum_{h\in H} Q^p_{phnt} = I^{fo}_{pnt} + \sum_{n'\in D} \sum_{m\in M} F_{pnn'mt} \quad \forall p \in P^{SF} \cup P^{MP}, \forall n \in F, \forall t \in T$$

Initial inventory levels for products:

$$I^{fo}_{pnt_0} = 0 \quad \forall p \in P^{SF} \cup P^{PF}, \forall n \in F$$

Inventory capacity constraints (components, products): $I_{pnt}^{fo} \leq i_{pnt}^{fo} \forall p \in P^{SF} \cup P^{PF}, \forall n \in F, \forall t \in T$

If a production unit is operational, it will stay for the whole planning horizon: $Y_{nt}^{f} \geq Y_{n(t-1)}^{f} \forall n \in F, \forall t \in T$

If a technology is acquired, it is used for the whole horizon: $Y_{hnt}^{h} \geq Y_{hn(t-1)}^{h} \forall h \in H, \forall n \in F, \forall t \in T$

Distribution centers (DCs)

Inventory constraints at distribution centers:

$$I_{pn(t-1)}^{d} + \sum_{n' \in F} \sum_{m \in M} F_{pn'nmt} = I_{pnt}^{d} + \sum_{n' \in C} \sum_{m \in M} F_{pnn'mt} \quad \forall p \in P^{PF}, \forall n \in D, \forall t \in T$$

Initial inventory levels for final products:

$$I_{pnt_0}^{d} = 0 \quad \forall p \in P^{PF}, \forall n \in D$$

Inventory capacity constraints for final products at DCs:

$$I_{pnt}^{d} \leq i_{pnt}^{d} \quad \forall p \in P^{PF}, \forall n \in D, \forall t \in T$$

Distribution center capacity:

$$\sum_{n' \in F} \sum_{m \in M} F_{pn'nmt} \leq \chi_{pnt} Y_{nt}^{d} \quad \forall p \in P^{PF}, \forall n \in D, \forall t \in T$$

If the production center is selected, it will stay operational for the whole planning horizon:

$$Y_{nt}^{d} \geq Y_{n(t-1)}^{d} \quad \forall n \in D, \forall t \in T$$

Customers

Demand constraint:

$$\sum_{n' \in D} \sum_{m \in M} F_{pn'nmt} = d_{pnt} \forall p \in P^{PF}, \forall n \in C, \forall t \in T$$

Recycling centers

Recovery of used product:

$$\sum_{n' \in R} \sum_{m \in M} F_{pnn'mt} = \delta_{pnt} d_{pnt} \forall p \in P^{PF}, \forall n \in C, \forall t \in T$$

Inventory of used product at recycling centers:

$$I_{pn(t-1)}^{ri} + \sum_{n' \in C} \sum_{m \in M} F_{pnn'mt} = I_{pnt}^{ri} + Q_{pnt}^{a} \quad \forall p \in P^{PF}, \forall n \in R, \forall t \in T$$

Initial inventory of used products at recycling centers:

$$I_{pnt_0}^{ri} = 0 \quad \forall p \in P^{PF}, \forall n \in R$$

Inventory capacity of used products of recycling centers:

$$I_{pnt}^{ri} \leq i_{pnt}^{ri} \quad \forall p \in P^{PF}, \forall n \in R, \forall t \in T$$

Reprocessing of good products

$$Q_{pnt}^{r} = \sum_{p' \in P^{PF}} \varphi_{pp'} Q_{p'nt}^{a} \forall p \in P^{MP} \cup P^{SF}, \forall n \in R, \forall t \in T$$

Disposal of non valuable products:

$$Q_{pnt}^{d} = \sum_{p' \in P^{PF}} \theta_{pp'} Q_{p'nt}^{a} \forall p \in P^{PD}, \forall n \in R, \forall t \in T$$

Inventory of output products (raw material, components) from recycling centers:

$$I_{pn(t-1)}^{ro} + Q_{pnt}^{r} = I_{pnt}^{ro} + \sum_{n' \in F} \sum_{m \in M} F_{pnn'mt} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in R, \forall t \in T$$

Initial inventory level of output products (raw material and components) from recycling centers:

$$I_{pnt_0}^{ro} = 0 \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in R$$

Inventory capacity of output products (raw material and components) at recycling centers:

$$I_{pnt}^{ro} \leq i_{pnt}^{ro} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in R, \forall t \in T$$

Recycling process capacity:

$$Q_{pnt}^{r} \leq q_{pnt}^{r} Y_{nt}^{r} \quad \forall p \in P^{MP} \cup P^{SF}, \forall n \in D, \forall t \in T$$

If a node is operational, it is used for the planning horizon:

$$Y_{nt}^{r} \geq Y_{n(t-1)}^{r} \quad \forall n \in D, \forall t \in T$$

Transportation

Transportation capacity:

$$F_{pnn'mt} \leq c_{pnn'mt} Y_{nn'mt}^{t} \quad \forall p \in P, \forall n \in N, \forall n' \in N, \forall m \in M, \forall t \in T$$

Carbon management

The level of greenhouse emissions is limited:

$$\sum_{o \in O} E_{ot} CO_{o}^{out} + \sum_{i \in I} C_{it} CO_{i}^{in} + CC_{t}^{+} - CC_{t}^{-} \leq L_{t}^{CO2éq} \quad \forall t \in T$$

Limit on the number of allowances available for purchase:

$$CC_{t}^{-} \leq A_{t} \qquad \forall t \in T$$

Limit on the number of allowances sold:

$$CC_{t}^{+} \leq V_{t} \qquad \forall t \in T$$

5 EXPERIMENTAL EVALUATION

The mathematical model has been developed, validated and was used in preliminary study of a supply chain from the aluminum industry. In the aluminum industry, there are typically two sources of raw materials, namely, bauxite which is the primary raw material from which aluminum is made, and secondary aluminum which is obtained by recycling aluminum products. Since aluminum is 100% recyclable without any loss of its natural qualities, recovery of the metal via recycling has become an important facet of the industry. In this study, the product under consideration can be made either made from primary or secondary aluminum using either one of two potential technologies which have different operating costs and different GHG emissions. Critical inputs and outputs including liquid, solid, energy and gaseous wastes are considered.

The first aspect analyzed is the impact of carbon price variations on the supply chain configuration under two different scenarios. In scenario 1, carbon prices are stable in time. However, in scenario 2, carbon prices increases over time. The carbon prices (Figure 5) and results for scenario 2 are shown in Figure 6. Here, the carbon credit component is positive and represent 7% of the total cost. This is means that the supply chain needs to buy $1,441,320 worth of carbon credits over its life cycle to be in compliance with the environmental regulation.

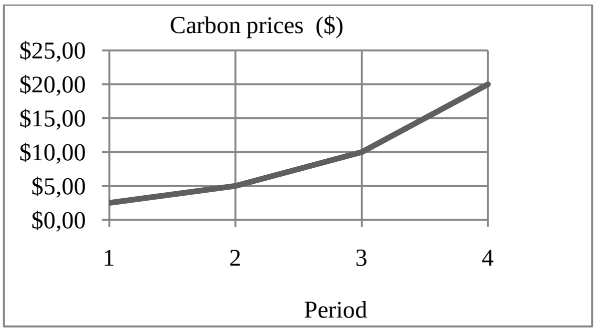

Figure 5: Carbon prices variation for scenario 2

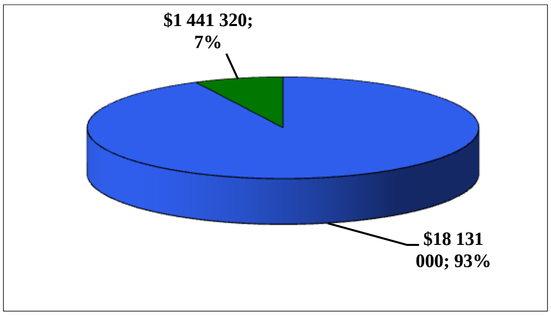

Figure 6: Cost distribution for scenario 2

Table 1 compares the results obtained for the two scenarios. First, we observe that the emission cost for scenario 2 is higher but that the total logistic cost remains the same for both scenarios. This is because the supply chain configuration (combination of sites, technology used, distribution channels, etc.) is the same in both scenarios. Here carbon prices only resulted in an increase in total cost with no consequence on the supply chain configuration because the marginal cost for reducing one unit of GHG emissions is greater than the carbon price from the market. Hence, the best decision is to buy allowances form the carbon market to be in compliance with the regulation limits on carbon emissions.

	Scenario 1	Scenario 2
	Stable	Increase
Total Logistics Cost	$18 131 000	$18 131 000
Cost of Carbon credit	$1 216 320	$1 441 320
Total Cost	$19 347 300	$19 572 300

Table 1: Comparison of the two scenarios

The second aspect analyzed is the impact of recycling strategies on supply chain planning decisions. Here we assume that legislation forces the company to accept all recycled products first. The supply chain is solved for different return rates (δ) of aluminum products. For the first scenario, we consider that only 80% of products available in the market are recycled (δ=80%). In the second scenario, secondary aluminum may come from other sources including the direct customers and hence a return rate of 120% (δ =120%). Table 2 summarizes the results obtained in this case. It shows that an increase in recycling of the products increases the total cost by 8.2% which translates into a 5.9% increase in logistics cost and a 41.1% increase in carbon credit cost. In this case, the legislation on recycling has a negative impact on carbon costs as it forces the supply chain to use technologies that have higher GHG emissions.

	Scenario 1 (δ = 80%)	Scenario 2 (δ = 120%)
Total Cost	$19 347 300	$20 929 800
Total Logistics Cost	$18 131 000	$19 214 100
Carbon credit	$1 216 320	$1 715 700

Table 2: Cost for the different scenarios (Return rate variation)

The final aspect studied is the impact of limit on emissions (LCO_2). We analyse two scenarios where regulations in terms of carbon emissions becomes more stringent (LCO_2 = 5 000 tCO_2e; LCO_2 = 25 000 tCO_2e). In this case, we suppose that carbon prices will increase (Figure 5). Figure 7 shows that the quantity of recycled product increases as the limit of emissions is more stringent because carbon emissions are reduced. When recycling is cheaper and with less GHG emissions, product recycling mostly increases and the cost is minimized.

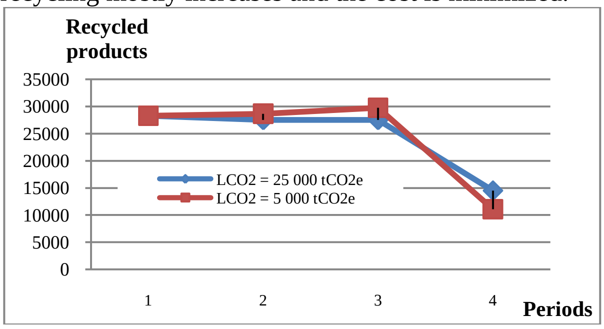

Figure 7: Recycled product under policy stringency

However, in the last period the quantity of recycled product decreases because the strategy of carbon management that consists of buying carbon credits when carbon prices are not expensive helps the company in reducing the cost of compliance to the regulation.

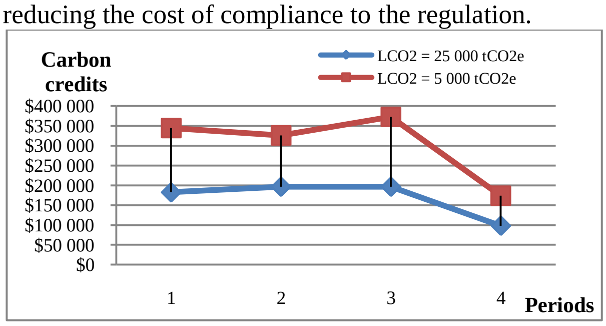

Figure 8: Carbon management under policy stringency

6 CONCLUSION

In this article, we present a generic mathematical model to assist decision makers in designing sustainable supply chain over its entire life cycle under the emission trading scheme. The model shows that the various environmental legislations must be strengthened and harmonized at a global level in order to drive a meaningful long-term environmental strategy. The explicit consideration of environmental costs within supply chain design is critical under the emergence of emission trading schemes. The integration of Life Cycle Analysis principles at the supply chain design phase maximizes the long term sustainability. The methodology presented here is general enough and may be applied to other supply chain studies to design sustainable supply chain and evaluate their performance in term of cost and carbon emissions. Although, only the economic and environmental dimensions of sustainability are considered in the mathematical model, the methodology can integrate the social dimension as soon as measures of sustainability are well defined.

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