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Environmental improvement of operating supply chains: An optimization approach for the cement industry

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Abstract

Companies worldwide face growing pressure to reduce the environmental impact of their activities. However, the strategies to achieve this goal are usually in conflict with financial outcomes. In the context of large and complex supply chains, environmental improvement implies not only technology upgrading decisions aiming at adopting cleaner technologies but also decisions regarding the structure of the supply chain itself. Making these decisions becomes difficult due to the number of variables involved and the nature of the relations among them. This research aims at providing a solution approach for rigorously making these decisions so that both environmental and financial goals are best met.

Keywords
Sustainability, supply chain design, multi-objective optimization

1. Introduction
A supply chain is said to be sustainable if it meets two basic conditions: first, it is expected to be profitable for an extended period of time; and second, its operation is expected to be harmless to the environment and the society [1]. From the environmental point of view, companies nowadays face growing pressure to achieve higher levels of sustainability, not only from the government in the form of tighter laws and regulations, but also from the market as customers have become more environmentally conscious [2]. Due to this pressure, more companies are now concerned with the problem of assessing the environmental impacts of their supply chains so that action can be taken to mitigate them. In particular, the amount of greenhouse gas (GHG) emissions resulting from their operations has emerged as the international standard to assess the environmental impact of a given corporation; and furthermore, the amount of CO_2 emissions or the so-called carbon footprint is now the most commonly used indicator. According to the 2014 annual report or the Intergovernmental Panel on Climate Change [3], global industrial GHG emissions accounted for just over 30% of global GHG emissions in 2010, not including the sectors of power generation and transportation; and CO_2 accounted for approximately 85% of the total GHG emissions in 2010 [3]. According to the United States Environmental Protection Agency (EPA), in 2010 the supply chain of a typical industrial organization was responsible for around two thirds of the total emissions of the company [4].

As several governmental and non-governmental organizations keep track of the global CO_2 emissions on a yearly basis, there is strong evidence of a steady growth in CO_2 global emissions during the past ten years, even though the growth rate has decreased recently [5]. The authors in [3] conclude that the energy intensity of the industrial sector "could be reduced by approximately up to 25% compared to current level through the wide-scale deployment of best available technologies, particularly in countries where these are not in practice and for non-energy intensive industries". All of these reports suggest that there is room for significant environmental improvement of the supply chains currently in operation.

In practice, the decisions around improving the environmental performance of an operating supply chain are usually led by the intuition and experience of the decision makers, mainly because of the lack of engineering tools tailored to support this decision–making process. In addition, a broad consensus among researchers in the environmental field has been achieved regarding the opportunity for reducing the environmental impact of current industrial processes by means of adopting cleaner fuels and more energy efficient technologies. As decision makers are provided with better engineering tools, financial resources could potentially be best assigned and thus, higher environmental returns should be expected. This outcome not only benefits the company using the decision–making tool, but society in general.

We focus our attention on the cement industry given its high demand, large energy use and substantial emissions of CO_2. It is known that concrete is the second most consumed material worldwide, only surpassed by water [6]; and that a typical concrete mix is prepared with around 10% to 15% proportion of cement. This is even more important if we know that the worldwide cement demand is expected to grow around 1.3% per year in the near term [7]. Regarding energy use, this industry was responsible for around 8.5% of the total industrial energy consumed in 2012 [7]. Regarding the emissions of CO_2, it was estimated in 2012 that to produce one metric ton of cement, between 650 and 950 Kg of CO_2 are released to the environment. Of this total emission, approximately half comes from the chemical reaction that takes place when the calcium carbonate ($CaCO_3$) is fed into a kiln to produce clinker, the main component of cement. The actual value of emissions depends mainly on the production technology, the heating and electricity sources, and the mixture of raw materials [8, 9]. In total, this industry accounts for approximately 5% of human-produced CO_2, and 34% of total industry CO_2 emissions [6]. These elements combined show that improving the environmental performance of this industry is an important step towards limiting GHG emissions.

The need for simultaneous evaluation of environmental and financial variables has been widely recognized from the point of view of the design of a supply chain. Recently, several literature reviews have been published in the areas of sustainable supply chain management [10-12], green supply chain management [13, 14], and sustainable supply chain network design [15]. The work most related to the problem under study that we are aware of is that of Grossman and Guillen-Gosalbez [16-17]. In [16] the authors addressed the problem of determining the configuration of a three-echelon supply chain with the objectives of maximizing the net present value and minimizing the environmental impact, whereas in [17] the authors expanded the scope by allowing uncertainty associated with the parameters representing the assessment of the different environmental impacts. A detailed analysis of the above mentioned references shows that among operations research techniques, multi-objective optimization is one of the most common solution approaches used to tackle these problems. However, to the best of our knowledge, the crucial subject of technology update decisions in the context of an operating supply chain, and the impact of these decisions on the environmental and financial performance of a firm, has not been addressed before. The aim of this work is to provide a solution approach for the problem of simultaneously selecting a technological upgrade strategy and designing a new network configuration for an operating supply chain, that takes into consideration the current state of the system, and that considers the environmental and financial implications of the recommended solutions.

2. Mathematical Model

2.1 Sets

F	Facilities
$T(i)$	Available technologies for facility $i \in F$
$Q(i, j)$	Available capacities for technology $j \in T(i)$
L	Fuels
C	Customers

2.2 Parameters – business as usual –

h_i	Annualized cost of taking facility $i \in F$ out of operation
q_i^0	Current capacity at facility $i \in F$
f_i^0	Current annual fixed cost at facility $i \in F$
v_i^0	Current variable unit cost at facility $i \in F$

α_i^0	Current unitary thermal energy consumption at facility $i \in F$
β_i^0	Current unitary electrical energy consumption at facility $i \in F$
γ_i^0	Current unitary cost of thermal energy associated with the fuel used at facility $i \in F$
e_i^0	Current unitary emissions of CO_2 due to thermal energy associated with the fuel used at facility $i \in F$

2.3 Parameters – available technologies –

q_{ijk}	The k-th capacity value in $Q(i, j)$
s_{ijk}	Annualized cost of installing technology $j \in T(i)$ at facility $i \in F$ with capacity q_{ijk}
f_{ijk}	Annualized fixed cost associated with technology $j \in T(i)$ with capacity q_{ijk} at facility $i \in F$
v_{ijk}	Variable unit cost associated with technology $j \in T(i)$ with capacity q_{ijk} at facility $i \in F$
α_{ijk}	Unitary thermal energy consumption of technology $j \in T(i)$ with capacity q_{ijk} at facility $i \in F$
β_{ijk}	Unitary electrical energy consumption of technology $j \in T(i)$ with capacity q_{ijk} at facility $i \in F$
γ_r	Unitary cost of the thermal energy when generated with fuel $r \in L$
e_r	Unitary emissions of CO_2 per unit of thermal energy generated with fuel $r \in L$

2.4 Parameters – general –

η	Unitary cost of the electrical energy
θ	Cost of transporting one unit of product for one unit of distance
μ	Emissions of CO_2 per unit of product due to the chemical reaction in the cement production process
ψ	Emissions of CO_2 per unit of electrical energy used
ρ	Emissions of CO_2 due to the transportation of one unit of product for one unit of distance
d_{ic}	Distance from facility $i \in F$ to customer $c \in C$
δ_c	Demand of customer $c \in C$

2.5 Decision Variables

$$z_i = \begin{cases} 1, \text{ if facility } i \in F \text{ remains in operation} \\ 0, \text{ otherwise} \end{cases}$$

$$u_i = \begin{cases} 1, \text{ if it is decided to change the technology and/or the capacity at facility } i \in F \\ 0, \text{ otherwise} \end{cases}$$

$$y_{ijk}^r = \begin{cases} 1, \text{ if technology } j \in T(i) \text{ is installed at facility } i \in F \text{ with capacity } q_{ijk} \text{ and operated with fuel } r \in L \\ 0, \text{ otherwise} \end{cases}$$

x_{ijk}^r	Continuous variables representing the production quantity assigned to facility $i \in F$, produced with technology $j \in T(i)$ with capacity q_{ijk} and operated with fuel $r \in L$
π_i	Continuous variables representing the amount of product that facility $i \in F$ will continue to produce with its current technology and capacity.
w_{ic}	Continuous variables representing the amount of product shipped from facility $i \in F$ to customer $c \in C$

2.6 Cost Expressions

Setup:
$$\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L} s_{ijk}\cdot y_{ijk}^r \tag{1}$$

Fixed:
$$\sum_{i\in F} f_i^0\cdot(z_i-u_i)+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L} f_{ijk}\cdot y_{ijk}^r \tag{2}$$

Closing:
$$\sum_{i\in F} h_i\cdot(1-z_i) \tag{3}$$

Production:
$$\sum_{i\in F} v_i^0\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L} v_{ijk}\cdot x_{ijk}^r \tag{4}$$

Thermal energy:
$$\sum_{i\in F}\gamma_i^0\cdot\alpha_i^0\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}\gamma_r\cdot\alpha_{ijk}\cdot x_{ijk}^r \tag{5}$$

Electrical energy: $$\sum_{i\in F}\eta\cdot\beta_i^0\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}\eta\cdot\beta_{ijk}\cdot x_{ijk}^r \qquad (6)$$

Transportation: $$\sum_{i\in F}\sum_{c\in C}\theta\cdot d_{ic}\cdot w_{ic} \qquad (7)$$

2.7 Emissions of CO_2 Expressions

Production: $$\sum_{i\in F}\mu\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}\mu\cdot x_{ijk}^r \qquad (8)$$

Thermal energy: $$\sum_{i\in F}e_i^0\cdot\alpha_i^0\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}e_r\cdot\alpha_{ijk}\cdot x_{ijk}^r \qquad (9)$$

Electrical energy: $$\sum_{i\in F}\psi\cdot\beta_i^0\cdot\pi_i+\sum_{i\in F}\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}\psi\cdot\beta_{ijk}\cdot x_{ijk}^r \qquad (10)$$

Transportation: $$\sum_{i\in F}\sum_{c\in C}\rho\cdot d_{ic}\cdot w_{ic} \qquad (11)$$

2.8 A Mixed Integer Liner Programming (MILP) Formulation

Let *TC* be the total cost, computed as the sum of expressions (1) to (7); and let *TE* be the total emissions of CO_2, computed as the sum of expressions (8) to (11). A MILP formulation to the problem under study follows.

Minimize $$\{TC, TE\} \qquad (12)$$

Subject to:

$$\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}y_{ijk}^r=u_i \qquad \forall\ i\in F \qquad (13)$$

$$u_i\le z_i \qquad \forall\ i\in F \qquad (14)$$

$$x_{ijk}^r\le q_{ijk}\cdot y_{ijk}^r \qquad \forall\ i\in F, j\in T(i), k\in Q(i,j)|k=1, r\in L \qquad (15)$$

$$q_{ijk-1}\cdot y_{ijk}^r\le x_{ijk}^r\le q_{ijk}\cdot y_{ijk}^r \qquad \forall\ i\in F, j\in T(i), k\in Q(i,j)\backslash\{1\}, r\in L \qquad (16)$$

$$\pi_i\le q_i^0\cdot(z_i-u_i) \qquad \forall\ i\in F \qquad (17)$$

$$\sum_{c\in C}w_{ic}=\sum_{j\in T(i)}\sum_{k\in Q(i,j)}\sum_{r\in L}x_{ijk}^r+\pi_i \qquad \forall\ i\in F \qquad (18)$$

$$\sum_{i\in F}w_{ic}=\delta_c \qquad \forall\ c\in C \qquad (19)$$

The objective (12) is to minimize the total cost and the total emissions of CO_2. Constraints in (13) ensure that if it is decided to change the current technology at a given facility, one single option should be chosen. Constraints in (14) ensure that a technology upgrade can only be undertaken in a facility if the facility is kept in operation. Expressions (15) and (16) correspond to the capacity constraints in the case of a change in the current technology at a given facility. Constraints in (15) and (16) ensure that the production quantity assigned to a facility lies within the corresponding capacity interval in the case when it is decided to change the technology at a given facility. Similarly, expression (17) corresponds to capacity constraints for the case when it is decided not to change the technology at a given facility. Constraints in (18) and (19) are required to enforce flow balance, whereas the constraints that define the domains of the decision variables can be deduced from their definition.

3. Computational Experiment

To approximate the set of non-dominated solutions, the formulation presented in Section 2 was solved as a single-objective mixed integer linear program by linearly combining the two objectives into a single one as per equation

(20). This solution approach, commonly known as the weighted sum approach, allows scaling of each objective by pre-multiplying it by a user-supplied weight [18]. If it is possible to find an optimal solution for a single weighted-sum objective model, this solution is an efficient point of the Pareto frontier. Hence, systematic changes in the weight values can construct the efficient frontier of a multi-objective optimization problem [19].

$$Minimize\ \lambda \cdot TC + (1 - \lambda) \cdot TE \quad (20)$$

The model was implemented using the FICO® Xpress Optimization Suite. The model was solved on a desktop computer running the 64-bit version of Windows 7 Professional, with an Intel Core i7 8-core processor running at 2.93 GHz with 16 GB of RAM memory. A problem instance was built using public data regarding the available technologies, capacities and fuels for the cement industry; and a hypothetical, yet realistic, supply chain network of a cement company. The test instance built includes 30 customers, 10 facilities, 6 available technologies with 3 capacity levels per technology, and considers 4 types of fuels. The complete data set is available upon request to the corresponding author. The value of λ was varied from 0 to 1 in increments of 0.01, for a total of 100 values. The solver was able to find the optimal solution for the proposed MILP formulation for every value of λ. The computer was able to find the 100 solutions in 10.2 seconds, of which 27 are non-dominated solutions, as depicted in Figure 1. As expected, it can be observed there is a clear trade-off between the environmental and financial goals.

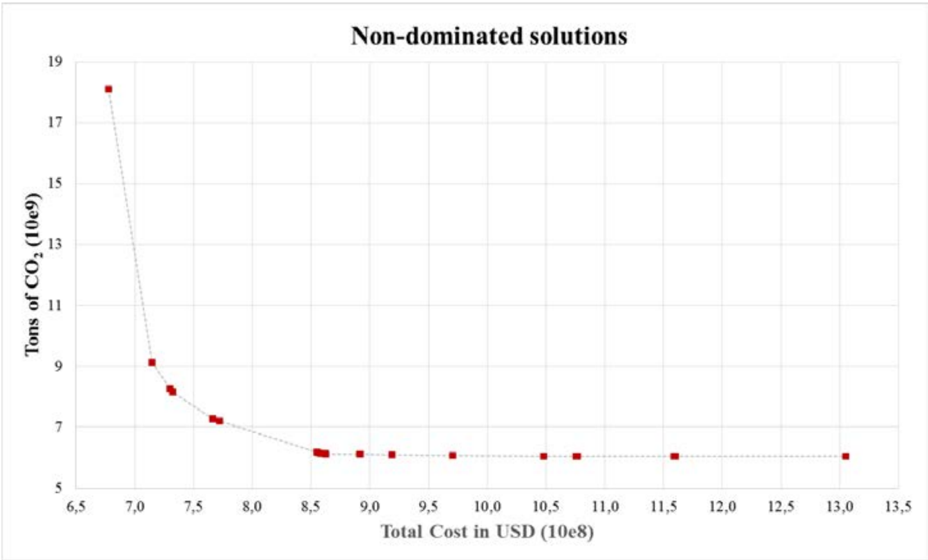

Figure 1: Set of non-dominated solutions

4. Conclusions

In this paper we addressed the problem of improving the current environmental performance of an operating supply chain at the lowest possible cost. In particular, we focused our attention in the cement industry as it is one of the most contaminating industries worldwide. A mixed integer linear programming formulation was proposed, with two objectives: the total cost and the total emissions of CO_2. In the model, the environmental improvement is achieved mainly by adopting cleaner technologies and fuels, and by consolidating production at larger facilities, as unitary emissions of CO_2 decrease with the production amount. A commercial solver was used to minimize a convex combination of the two objectives in order to approximate the set of non-dominated solutions. A test instance was built based on public information about available technologies, capacities and fuels for the cement industry. A hypothetical, yet realistic, supply chain network was also defined to complete the test instance. The proposed approach showed to be effective in finding a set of non-dominated solutions within a short amount of computational time, and thus enabling a decision maker to better assess the trade-off between the financial and environmental metrics when facing the problem of improving the environmental performance of an operating supply chain.

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