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Carbon emissions reduction and financial effects of a cap and tax system on an operating supply chain in the cement sector

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ABSTRACT

While the cement industry is perceived as one of the major contributors to climate change, with a 7% share of total CO_2 emissions, direct taxes on emissions of these gases have been little applied to this productive sector. The present study addresses the issue of assessing the effectiveness of carbon taxation methods in encouraging sustainable cement production processes. In particular, the effect of different carbon emission prices on decisions that lead to a reduction of CO_2 emissions in a representative cement supply chain, was studied. A mixed-integer linear formulation is used to describe a non-taxed base case against a case that explicitly includes carbon taxes. Computational experiments conducted on a realistic-sized instance built based on publicly available data from the cement sector, showed that environmental benefits can be attained after implementing a carbon taxation mechanism. The results indicate that with a rate between 15 US$ and 150 US$ by CO_2 emitted ton over a predefined cap, will drive cleaner cement production scenarios with a reduction of emissions up to 24%, respect to a non-taxed scenario used as the base line. The proposed decision-making tool can be effectively used by any cement company that needs to better assess the trade-off between its financial objectives and the sustainability goal of carbon emissions reduction.

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1. Introduction

Although drivers such as energy costs, operational efficiency, and market forces are likely to motivate a firm to reduce its carbon emissions, public policy mechanisms are nowadays widely accepted as an effective method to achieve this goal. Since 1992, William D. Nordhaus, awarded with the Nobel Prize in economics in 2018, suggested that "a modest carbon tax would be an efficient approach to slow global warming, whereas rigid emission standards -or climate stabilisation approaches-would impose significant net economic costs", (Nordhaus, 1992).

Carbon taxes are a frequently used public policy mechanism for encouraging emissions reduction; according to carbon pricing annual report of World Bank and Ecofys (2019), by the year 2019, more than 57 national or sub-national jurisdictions had used some kind of financial mechanism to put a price on carbon emissions. In 2019, approximately 11 GtCO_2e, representing more than 20% of the global greenhouse gas (GHG) emissions were covered by this mechanism, with a total value of approximately 44 US$ billion, (World Bank and Ecofys, 2019).

Whereas it is true that the share of global emissions covered by some carbon pricing mechanism has increased almost fourfold over the past decade (World Bank and Ecofys, 2018), it is also true that the variability among the rates across the world is still high. Table 1 presents the carbon tax rates per ton of CO_2 used by 30 different jurisdictions around the world (i.e., countries, states, provinces, and the like). While almost three-quarters of the covered emissions are priced at less than 20 US$ per ton, the rate in Sweden is equivalent to 126 US$ (World Bank and Ecofys, 2019). The 2018 World Bank Report (World Bank and Ecofys, 2018) shows that among the wide set of jurisdictions employing carbon emission taxes, only Ontario, Switzerland and the Republic of Korea apply direct taxes to the building sector, the target of this work. However, the International Finance Corporation (IFC) has been applying carbon prices to the economic rate of return analysis of investment projects in various sectors, including the cement industry. The entity applied rates of around 30 US$/t$CO_2$e in 2016. These rates are expected to increase to 80 US$/t$CO_2$e by 2050 (International Finance Corporation and

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Table 1
Current carbon prices around the world (2018–2019). The prices marked with (*) represent the highest price at the corresponding jurisdiction. ETS (Emission Trading System); CAT (Cap and Trade); SGER (Specified Gas Emitters Regulation). Source: World Bank Carbon Pricing Dashboard (World Bank and Ecofys, 2018), (World Bank and Ecofys, 2019).

Jurisdiction	Year of introduction	US$ by CO_2 ton	Mechanism
Ontario	2017	14	Tax
Alberta	2017	23	Tax
China upper	2017	9*	ETS
Chile	2017	5	Tax
Colombia	2017	5	Tax
Portugal	2015	7	Tax
Korea	2015	16	ETS
Mexico upper	2014	3*	Tax
France	2014	33	Tax
Chongging	2014	2	Tax
Hubei	2014	4	Tax
Guangodong	2013	2	Tax
Beijing	2013	6	Tax
Shangai	2013	1	Tax
Shenzhen	2013	6	Tax
United Kingdom	2013	22	Tax
Japan	2012	3	Tax
California	2012	13	Cat
Ukraine	2011	1	Tax
Tokyo	2010	38	Cat
Ireland	2010	22	Tax
Iceland	2010	9	Tax
Switzerland	2008	60	Tax
New Zealand	2008	5	ETS
Liechtenstein	2008	84	Tax
Alberta	2007	12	SGER
Estonia	2000	2	Tax
Slovenia	1996	18	Tax
Latvia	1995	4	Tax
Denmark	1992	25	Tax
Sweden	1991	126	Tax
Norway upper	1991	52	Tax
Poland	1990	1	Tax
Finland upper	1990	62	Tax

Carbon Pricing Leadership Coalition, 2019).

The high variability of carbon the tax rates shown in Table 1 is relevant as it implies that determining appropriate carbon tax rates is an issue that needs to be addressed. These rates are fixed by assuming that for a firm to be willing to reduce its carbon emissions because of a taxation scheme, the tax rate must be high enough to motivate the firm to act, but without putting profitability at risk. The cost incurred to modify the supply chain to reduce carbon emissions should be compared by the benefits from avoiding taxes and cost savings due to operational efficiency. Therefore, the cost of reducing carbon emissions, also known as the carbon abatement cost, must be estimated. These costs are highly variable among various industrial sectors as well as within a sector, mainly because a firm's abatement cost depends on factors such as obsolescence of its equipment and the consequent upgrading cost, local energy costs, availability of cleaner fuels, and the design of its supply chain network. The aim of this work is to assess the effect of a carbon taxation mechanism on the cement sector. Our focus on cement industry is motivated by the following reasons:

1. Concrete, composed of between 10 and 20% of cement, is considered the second most consumed substance in the world, only surpassed by water (Juenger et al., 2011).
2. Between 5 and 7% of the total global anthropogenic CO_2 emissions are due to cement production (International Energy Agency and Cement Sustainability Initiative, 2018). According to Di Filippo et al. (2019), 76% of CO_2 emissions of one cubic meter of concrete made with Ordinary Portland Cement, belongs to the production and transportation of cement.
3. Commitments of the cement sector to achieve the two celsius target (2DS) of the Paris agreement, include key indicators such as clinker-to-cement ratio, thermal energy intensity of clinker, electricity intensity of cement, alternative fuel use, carbon capture and storage (CCS) systems, and direct CO_2 intensity of cement (International Energy Agency and Cement Sustainability Initiative, 2018; Schneider, 2019; Scrivener et al., 2016). All of these metrics are tied to strategic supply chain management decisions.
4. As a key building material, cement production is expected to grow more than 10% from now and 2050 (Statista, 2018; Schneider, 2019). Within this frame of production growth, the global emissions reduction continues to be an important challenge.

Having identified the cement supply chain as an important source of GHG emissions worldwide and the carbon taxes as a strategic instrument to address climate change mitigation, in the present study, the effect of different carbon tax rates on the performance of the supply chain of a cement production firm, was addressed from an operations research approach. The following set of works provide us with a wide spectrum of applications of mathematical optimisation models designed to describe the effect of carbon pricing mechanisms on the supply chains of other specific economic sectors.

In Wang et al. (2008), an optimisation model was proposed to select the operating conditions in a steel production plant, considering its costs and emissions; the model includes the impact of an emissions trading scheme (ETS) on the CO_2 emissions of the system. The work in Ramudhin et al. (2010) also focuses its attention on the steel production sector by addressing the trade-offs between logistics and carbon abatement costs under various operating strategies and environmental regulatory constraints, by means of a multi-objective optimisation approach. The aluminum industry is addressed in Chaabane et al. (2012); in their work, the authors proposed a mixed-integer linear programming formulation to evaluate the trade-offs between economic and environmental objectives under various cost and operating strategies, including the option of using recycled aluminium as a raw material. The work in Jin et al. (2014) considers the retail industry, in this work an optimisation model is proposed aiming at finding a minimum cost supply chain design under different transportation modes, and several environmental constraints. An analytic supply chain planning model that can be used to examine the supply chain performance at the tactical/operational planning level under two different policy schemes is proposed in Zakeri et al. (2015) for a furniture company in Australia, whereas in reference (Fahimnia et al., 2015), a model is proposed to assess the impact of a carbon taxation mechanism on the economic and environmental performance of a manufacturing firm involved in the production and distribution of metal containers also located in Australia. The latter model suggests tactical planning decisions, including production and distribution allocation strategies such that the overall supply chain cost and carbon emissions are both minimised. A two-stage stochastic programming model is proposed in Rezaee et al. (2015) to design the supply chain of an Australian manufacturer of office furniture under a carbon trading environment; the model solves a discrete location problem and determines the optimal material flows and the number of carbon allowances that should be traded. In Santibanez-Gonzalez (2017) a mathematical model is proposed for the cement sector with the aim of determining a tax rate that makes it economically favourable for a company to pay taxes and/or invest in the deployment of a network for capturing, transporting,

and sequestering the CO_2 generated by ten cement factories located in Brazil. The problem of the design of a sustainable coal supply chain for power generation is addressed in Li et al. (2019); a mathematical model is proposed for the problem of minimising the production costs in the coal supply chain. The proposed model was used to evaluate four different emission policies: emission cap, carbon tax, carbon trade and carbon offset. For the case of the mining industry, authors in Valderrama et al. (2020) proposes a multi-echelon, multi-period and multi-product mixed integer linear program to design a supply chain network, with the objective to reduce greenhouse gas emissions under an emission trading scheme. The model considers the location and assignment of facilities along the different echelons of the supply chain, inventory levels, product distribution and reprocessing flows, taking into consideration the ore grade, material quality, and blending and beneficiation processes. A sensibility analysis of price variation shows that total emissions of the supply chain tend to decrease when the carbon credits price is increased.

By describing in detail the supply chains of specific production sectors, these tailor-made models are highly accurate and become an important contribution for improving the strategic decision-making process. The review of previous works show that carbon abatement costs vary widely among different sectors depending on the particular conditions of each supply chain, but they all coincide in that carbon pricing mechanisms are effective in inducing cleaner production scenarios. The second part of the literature revision, is focused on works dealing with carbon abatement cost estimation for the cement sector. In a two-step, bottom-up approach, the authors in Brunke and Blesl (2014) first assessed the effectiveness of the individual measures in terms of CO_2 emission reduction and costs at the cement plant levels, whereas in a second step, they assessed the cost-effectiveness and carbon abatement potential of each technical measures in the German cement sector. In conclusion, they present the CO_2 cost-effective abatement curve for the sector and highlight the possibility of avoiding 3.4% of annual emissions, with savings of 14.5 million Euros (2012). Based on the official statistics for the cement sector, which contains information on nearly 25 % of global cement producers, the authors in Kajaste and Hurme (2016) estimate the abatement cost between 4 US$ and 448 US$ per ton of CO_2 depending on the technology, geographical location, and initial level of CO_2 emissions. Finally, using a bottom-up CO_2 carbon abatement cost model, the authors in Hasanbeigi et al. (2010) present the cost-effective annual CO_2 abatement potential for the Thai cement industry during a 15-year period (2010–2025). The authors estimate that the abatement potential is of 3095 kilotons CO_2/year; the estimated CO_2 abatement cost is between 60 and 240 US$ per CO_2 ton.

The present study builds on these works by recognising that decisions on updating technology should not be tackled independently. Instead of a set of single cost-benefit analyses of each emission reduction strategy, this study proposes a mathematical tool that allows each cement firm to select the global optimal strategy to minimise its impacts on the climate change problem, while consider financial aspects of the planning process. The question about the effect of carbon taxes over the performance of a supply chain was specifically answered for the cement case, considering all the particularities of its production system.

The proposed mathematical formulation is, to the best of our knowledge, the first work in the literature that allows a cement company to completely revise its supply chain, given the effect of CO_2 emission taxes, its planning, operational, and financial implications. The model determines the optimal decisions to be made with regard to technological updating, network design, fuel changes, production capacity allocation, or even process shut down. The simultaneous tree-level decision process: production allocation, technological updating decisions, and supply chain design is crucial for the cement sector because of the very high transportation cost comprising the total costs and its potential benefit from economies of scale. The tool was validated within a Latin-American cement company with satisfactory results.

1.1. Problem description

The basic characteristics of the strategic planning problem in the framework of the emission payment system for the cement supply chain are described below. To that end, the manufacturing process is divided into sub-processes: (1) milling of limestone or other carbonate rocks in the raw mill, (2) calcination of the raw materials in the kiln to produce the clinker, and (3) clinker milling and mixing in the cement mill. Each sub-process has its own CO_2 emission reduction alternatives. The modeling approach implies the selection of one operation project for each process at each facility; a set of operation projects includes possibilities for technical improvement or the do-nothing option (the latter has no improvement cost). Every improvement project simultaneously represents various decisions: (1) production technology and (2) operation capacity range. In the case of the kiln process, other decision variables in the improvement projects formulation are as follows: (3) operating fuel and (4) technical complements for the kiln. Emissions and cost of each improvement project are pre-estimated to create parameters of the model.

The problem solution requires to describing the flow of sub-products between the individual components of the process. The decisions to update technology to increase production capacity are implemented in specific plants. Those improvements may require redesigning of the entire supply chain, which comprises suppliers, manufacturers, and customers. The cement type and mixture are constant, which implies that only one kind of cement is considered in the case study. All these possibilities are the result of recognising the low-energy efficiency of obsolete cement production plants, the importance of fuel supplier selection in terms of emission reduction and operational and logistics costs, the economies of scale (especially in the kiln process), and the very high share of transport cost in a typical cement supply chain.

Financial components of the problem include cost of updating of technology, operating, transportation, fixed, and shut-down costs. Taxed CO_2 emissions include the combustion and calcination process in the kiln, electricity use, and transportation between all the nodes in the supply chain. As a consequence of the multi-period structure of the problem, all involved costs are described as the present value of future cash flows and a demand forecast.

The rest of this paper is organised as follows. Section 2 describes the proposed mathematical formulation for addressing the problem; section 3 describes and analyses the computational results obtained after solving the problem for the three scenarios: a base case scenario with two objectives, cost and emissions; a second scenario with the single objective of minimising the cost under different tax rates; and a third scenario with the single objective of maximising the profits that considers local cement prices and carbon emission tax rates. Section 4 presents the conclusions and finally, section 5 state the limitations of the mathematical model and future work.

2. Methodology

Three mixed-integer linear programming formulations (MILP) were developed. The first is a bi-objective formulation aimed at minimising both cost and CO_2 emissions. This formulation does not include any carbon taxation scheme, and it is primarily used to identify the carbon abatement costs, and to define a baseline for

comparison purposes. The original multi-objective structure proposed in Cadavid-Giraldo et al. (2016) was used to build the base case, but for this case, a new multi-period formulation was created, so it is possible to model growing demand scenarios or even, growing tax rates.

The second formulation is a single-objective problem that explicitly includes a carbon taxation mechanism that translates CO_2 emissions into cost. A comparison between the set of non-dominated solutions obtained from the first formulation and the optimal solution obtained from the second, leads to a better understanding of the effect of the carbon taxation scheme.

The third formulation aims at maximising the profit instead of minimising the cost. By explicitly including the price of cement, the latter formulation addresses the issue of the financial viability of the carbon taxation scheme. These formulations were tested on a realistic-sized test instance built based on publicly available data from the cement sector that resembles a realistic cement supply chain.

The proposed mathematical structure enables description of the current state of an operating supply chain and selects form the defined sets of technology-updating alternatives that efficiently achieve the defined objectives. The manufacturing process is decomposed into sub-processes. Each sub-process has its own alternatives for improvement.

2.1. Mathematical formulation

Let R be de set of Raw materials mills; K, the set of Kilns; M, the set of Cement mills; U^R, the set of improvement projects for every raw mill r ∈ R; U^K, the set of improvement projects for every kiln k ∈ K; U^M, the se of improvement projects for every cement mill m ∈ M; Y, the set of gypsum suppliers; C, the set of customers; T, the set of planning periods and; F, the set of available fuels

2.1.1. Parameters

Π_{art}, Emissions if project $a \in U^R$ is executed in raw mill $r \in R$ in period $t \in T$
Υ_{bkt}, Emissions if project $b \in U^K$ is executed in kiln $k \in K$ in period $t \in T$
Λ_{cmt}, Emissions if project $c \in U^M$ is executed in mill $m \in M$ in period $t \in T$

E^R_{art}, Cost of implementing project $a \in U^R$in raw material mill $r \in R$ in period $t \in T$
E^K_{bkt}, Cost of implementing project $b \in U^K$in kiln $k \in K$ in period $t \in T$
E^M_{cmt}, Cost of implementing project $c \in U^M$in mill $m \in M$ in period $t \in T$

O^R_{art}, Per – unit operating cost if project $a \in U^R$ is executed in raw mill r∈R in period $t \in T$
O^K_{bkt}, Per – unit operating cost if project $b \in U^K$ is executed in kiln k∈K in period $t \in T$
O^M_{cmt}, Per – unit operating cost if project $c \in U^M$ is executed in mill m ∈M in period $t \in T$

F^R_{art}, Fixed cost if project $a \in U^R$ is executed in raw mill $r \in R$ in period $t \in T$
F^K_{bkt}, Fixed cost if project $b \in U^K$ is executed in kiln $k \in K$ in period $t \in T$
F^M_{cmt}, Fixed cost if project $c \in U^M$ is executed in mill $m \in M$ in period $t \in T$

S^{R}_{rt}, Closing cost for raw mill $r \in R$ in period $t \in T$
S^{K}_{kt}, Closing cost for kiln $k \in K$ in period $t \in T$
S^{M}_{mt}, Closing cost for mill $m \in M$ in period $t \in T$

Q^{R}_{ar}, Production capacity if project $a \in U^{R}$ is executed in raw mill $r \in R$
Q^{K}_{bk}, Production capacity if project $b \in U^{K}$ is executed in kiln $k \in K$
Q^{M}_{cm}, Production capacity if project $c \in U^{M}$ is executed in mill $m \in M$
q^{R}_{ar}, Minimum production required if project $a \in U^{R}$ is executed in raw mill $r \in R$
q^{K}_{bk}, Minimum production required if project $b \in U^{K}$ is executed in kiln $k \in K$
q^{M}_{cm}, Minimum production required if project $c \in U^{M}$ is executed in mill $m \in M$

2.1.2. Binary decision variables

H^{RK}_{rk}, Distance from raw material mill $r \in R$ to kiln $k \in K$
H^{KM}_{km} Distance from kiln $k \in K$ to mill $m \in M$
H^{YM}_{ym}, Distance from gypsum supplier $y \in Y$ to mill $m \in M$
H^{MC}_{cmt}, Distance from mill $m \in M$ to customer $c \in C$

2.1.3. Continuous decision variables

ϕ, Per – unit, per distance transportation emisions
χ, Per – unit, per distance transportation cost
τ^{C}_{bk}, Cost factor of transportation of the fuel used in the project $b \in U^{K}$ to kiln $k \in K$
τ^{E}_{bk}, Emission factor of transportation of the fuel used in the project $b \in U^{K}$ to kiln $k \in K$
ν_{bk}, Specific heat of the fuel used in the project $b \in U^{K}$ of kiln $k \in K$
ϑ, Limestone – clinker proportion
μ, Clinker – cement proportion

R^{R}, R^{K}, R^{M}, Percentual reduction in operation capacity of raw material mills, kilns and Cement mills, during the updating period

$x^R_{art} = 1$, If project $a \in U^R$ is executed in raw material mill $r \in R$, in period $t \in T$
$x^K_{bkt} = 1$, If project $b \in U^K$ is executed in kiln $k \in K$, in period $t \in T$
$x^M_{cmt} = 1$, If project $c \in U^M$ is executed in mill $m \in M$, in period $t \in T$
$a^R_{rt} = 1$, If raw material mill $r \in R$ is operating, in period $t \in T$
$a^K_{kt} = 1$, If kiln $k \in K$ is operating, in period $t \in T$
$a^M_{mt} = 1$, If mill $m \in M$ is operating, in period $t \in T$
$z^R_{art} = 1$, If project $a \in U^R$ is executed by first time in raw material mill $r \in R$, in period $t \in T$
$z^K_{bkt} = 1$, If project $b \in U^K$ is executed by first time in kiln $k \in K$, in the period $t \in T$
$z^M_{cmt} = 1$, If project $c \in U^M$ is executed by first time in mill $m \in M$, in period $t \in T$

A^R_{art}, Production volume with the project $a \in U^R$ in the raw material mill $r \in R$, in period $t \in T$
A^K_{bkt}, Production volume with the project $b \in U^K$ in the kiln $k \in K$, in period $t \in T$
A^M_{cmt}, Production volume with the project $c \in U^M$ in the mill $m \in M$, in period $t \in T$
T^{RK}_{rkt}, Amount of mill limestone shipped from raw material mill $r \in R$ to kiln $k \in K$, in period $t \in T$
T^{KM}_{kmt}, Amount of clinker shipped from kiln $k \in K$ to mill $m \in M$, in period $t \in T$
T^{YM}_{ymt}, Amount of gypsum shipped from gypsum supplier $y \in Y$ to mill $m \in M$, in period $t \in T$
T^{MC}_{cmt}, Amount of bulk cement shipped from mill $m \in M$ to customer $c \in C$, in period $t \in T$

2.1.4. Objective functions

Equation (1) defines the objective of minimising the emissions of CO_2, which is comprised of the emissions associated with the operation of the facilities (equation (4)) and the transportation of fuels, limestone, clinker, gypsum and cement (equation (5)). The total cost is defined in equation 2, and is comprised of five terms: operating cost (equation (6)), fixed cost (equation (7)), the cost of executing the technological improvement projects (equation (8)), the shut-down costs (equation (9)) and the transportation cost (equation (10)). Financial information is presented as the present value (PV) of future cash flows (CF), obtained using equation (3). Objective functions of the taxed problems are described in Section 3.2.1, equation (48), and Section 3.2.2, equation (49).

$$Minimise Z_1 = Z^{EO} + Z^{ET} \tag{1}$$

$$Minimise\ (PV)Z_2 = (PV)Z^O + (PV)Z^F + (PV)Z^E + (PV)Z^S + (PV)Z^T \tag{2}$$

$$PV = \sum_{t \in T} \frac{CF}{(1+r)^{t-1}} \tag{3}$$

$$Z^{EO} = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} \Pi^R_{ar} \cdot A^R_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} \Upsilon^K_{bk} \cdot A^K_{bkt} + \sum_{c \in U^M} \sum_{m \in M} \sum_{t \in T} \Lambda^M_{cm} \cdot A^M_{cmt} \tag{4}$$

$$Z^{ET} = \sum_{r \in R} \sum_{k \in K} \sum_{t \in T} \phi \cdot H^{RK}_{rk} \cdot T^{RK}_{rkt} + \sum_{k \in K} \sum_{m \in M} \sum_{t \in T} \phi \cdot H^{KM}_{km} \cdot T^{KM}_{kmt} + \sum_{m \in M} \sum_{c \in C} \sum_{t \in T} \phi \cdot H^{MC}_{mc} \cdot T^{MC}_{mct} + \sum_{y \in Y} \sum_{m \in M} \sum_{t \in T} \phi \cdot H^{YM}_{ym} \cdot T^{YM}_{ymt} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} \tau^E_{bk} \cdot \langle A^K_{bkt} \Big/ \nu_{bk} \rangle \tag{5}$$

$$(PV)Z^O = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} O^R_{ar} \cdot A^R_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} O^K_{bk} \cdot A^K_{bkt} + \sum_{c \in U^M} \sum_{m \in M} \sum_{t \in T} O^M_{cm} \cdot A^M_{cmt} \tag{6}$$

$$(PV)Z^F = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} F^R_{ar} \cdot A^R_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} F^K_{bk} \cdot A^K_{bkt} + \sum_{c \in U^M} \sum_{m \in M} \sum_{t \in T} F^M_{cm} \cdot A^M_{cmt} \tag{7}$$

$$(PV)Z^E = \sum_{a \in U^R} \sum_{r \in R} \sum_{t \in T} E^R_{ar} \cdot z^R_{art} + \sum_{b \in U^K} \sum_{k \in K} \sum_{t \in T} E^K_{bk} \cdot z^K_{bkt} + \sum_{c \in U^M} \sum_{m \in M} E^M_{cm} \sum_{t \in T} \cdot z^M_{cmt} \tag{8}$$

$$(PV)Z^S = \sum_{r \in R} \sum_{t \in T} S^R_r \cdot \left(1 - a^R_{rt}\right) + \sum_{k \in K} \sum_{t \in T} S^K_k \cdot \left(1 - a^K_{kt}\right) + \sum_{m \in M} \sum_{t \in T} S^M_m \cdot \left(1 - a^M_{mt}\right) \tag{9}$$

$$(PV)Z^T = \sum_{r\in R}\sum_{k\in K}\sum_{t\in T}\chi_t \cdot H^{RK}_{rk}\cdot T^{RK}_{rkt} + \sum_{k\in K}\sum_{m\in M}\sum_{t\in T}\chi_t \cdot H^{KM}_{km}\cdot T^{KM}_{kmt} + \sum_{m\in M}\sum_{y\in Y}\sum_{t\in T}\chi_t \cdot H^{MY}_{my}\cdot T^{MY}_{myt} + \sum_{m\in M}\sum_{c\in C}\sum_{t\in T}\chi_t \cdot H^{MC}_{mc}\cdot T^{MC}_{mct}$$
$$+ \sum_{b\in U^K}\sum_{k\in K}\sum_{t\in T}\tau^C_{bk}\cdot\langle A^K_{bkt}\Big/\nu_{bk}\rangle \tag{10}$$

2.1.5. Constraints

Constraints 11–13 ensure the selection of one technical project per equipment.

$$\sum_{a\in U^R} x^R_{art} \le 1 \qquad \forall r\in R, \forall t\in T \tag{11}$$

$$\sum_{b\in U^K} x^K_{bkt} \le 1 \qquad \forall k\in K, \forall t\in T \tag{12}$$

$$\sum_{c\in U^M} x^M_{cmt} \le 1 \qquad \forall m\in M, \forall t\in T \tag{13}$$

Constraint 14 enforces demand satisfaction, whereas constraints 15–19 ensure mass balances.

$$\sum_{m\in M} T^{MC}_{cmt} = D_c \forall c\in C, \qquad \forall t\in T \tag{14}$$

$$\sum_{r\in U^R} A^R_{art} = \sum_{k\in K} T^{RK}_{rkt} \forall r\in R, \qquad \forall t\in T \tag{15}$$

$$\sum_{b\in U^K} A^K_{bkt} = \mu\cdot\sum_{r\in R} T^{KM}_{kmt} \forall k\in K, \qquad \forall t\in T \tag{16}$$

$$\sum_{g\in U^M} A^M_{cmt} = \sum_{y\in Y} T^{YM}_{ymt} + \sum_{k\in K} T^{KM}_{kmt} \forall m\in M, \qquad \forall t\in T \tag{17}$$

$$\sum_{g\in U^M} A^M_{cmt}\cdot\vartheta = \sum_{k\in K} T^{KM}_{kmt} \forall m\in M, \qquad \forall t\in T \tag{18}$$

$$\sum_{g\in U^M} A^M_{cmt} = \sum_{c\in C} T^{MC}_{mct} \forall m\in M, \qquad \forall t\in T \tag{19}$$

Constraints 20–22 allow recognising the period in which a new technical project begins its operation.

Table 2
Demand forecast scenario.

Period	Demand (annual tons)
1	8,580,280
2	8,940,816
3	9,147,720
4	9,364,492
5	9,591,621
total	45,624,929

$$x^R_{art} - x^R_{ar(t-1)} \ge z^R_{art} \forall a\in U^R, \qquad \forall r\in R, \qquad \forall t\in T\backslash\{1\} \tag{20}$$

$$x^K_{bkt} - x^K_{bk(t-1)} \ge z^K_{bkt} \forall b\in U^K, \qquad \forall k\in K, \qquad \forall t\in T\backslash\{1\} \tag{21}$$

$$x^M_{cmt} - x^M_{cm(t-1)} \ge z^M_{cmt} \forall c\in U^M, \qquad \forall m\in M, \qquad \forall t\in T\backslash\{1\} \tag{22}$$

Constraints 23–25 ensure that only one change is undertaken in each process during the planing period.

$$\sum_{a\in U^R} z^R_{art} \le 1 \forall r\in R, \qquad \forall t\in T \tag{23}$$

$$\sum_{b\in U^K} z^K_{bkt} \le 1 \forall k\in K, \qquad \forall t\in T \tag{24}$$

$$\sum_{c\in U^M} z^M_{cmt} \le 1 \forall m\in M, \qquad \forall t\in T \tag{25}$$

Constraints 26–28 allow recognising equipment in operation.

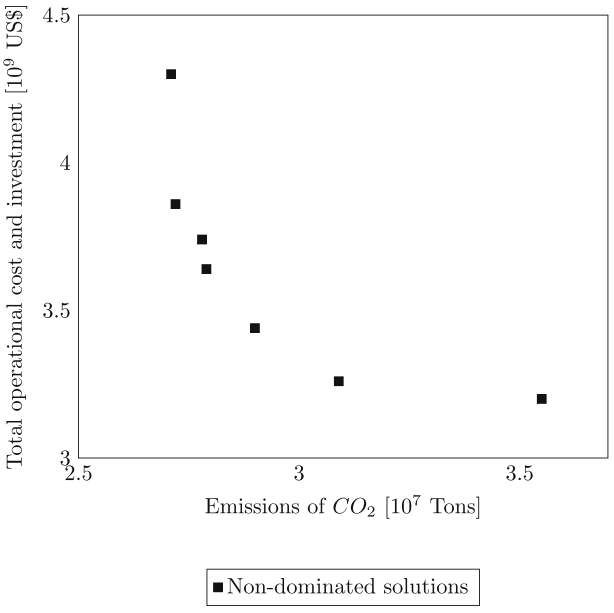


Fig. 1. Pareto solutions for the base case. Total Costs vs. Emissions of CO_2

$$\sum_{a\in U^R} x^R_{art} = a^R_k \forall r\in R, \qquad \forall t\in T \tag{26}$$

$$\sum_{b\in U^K} x^K_{bkt} = a^K_m \forall k\in K, \qquad \forall t\in T \tag{27}$$

$$\sum_{c\in U^M} x^M_{cmt} = a^M_c \forall m\in M, \qquad \forall t\in T \tag{28}$$

Constraints 29–31 ensure that a closed plant cannot operate again.

$$a^R_{art} \le a^R_{ar(t-1)} \forall a \in U^R, \qquad \forall r \in R, \qquad \forall t\in T\backslash\{1\} \tag{29}$$

$$a^K_{bkt} \le a^K_{bk(t-1)} \forall b \in U^K, \qquad \forall k \in K, \qquad \forall t\in T\backslash\{1\} \tag{30}$$

$$a^M_{cmt} \le a^R_{cm(t-1)} \forall c \in U^M, \qquad \forall m \in M, \qquad \forall t\in T\backslash\{1\} \tag{31}$$

Constraints 32–34 activate closing costs.

$$out^R = a^R_{ar(t-1)} - a^R_{art} \forall a \in U^R, \qquad \forall r \in R, \qquad \forall t\in T\backslash\{1\} \tag{32}$$

$$out^K = a^K_{bk(t-1)} - a^K_{bkt} \forall b \in U^K, \qquad \forall k \in K, \qquad \forall t\in T\backslash\{1\} \tag{33}$$

$$out^M = a^R_{cm(t-1)} - a^M_{cmt} \forall c \in U^M, \qquad \forall m \in M, \qquad \forall t\in T\backslash\{1\} \tag{34}$$

Constraints 35–37 guarantee that if a technical project is executed on a given equipment, then that particular equipment needs to be in operation.

$$x^R_{art} \ge z^R_{ar(t-1)} \ge z^R_{art} \forall a \in U^R, \qquad \forall r \in R, \qquad \forall t\in T\backslash\{1\} \tag{35}$$

$$x^K_{bkt} \ge z^K_{bk(t-1)} \ge z^K_{bkt} \forall a \in U^R, \qquad \forall k \in K, \qquad \forall t\in T\backslash\{1\} \tag{36}$$

$$x^M_{cmt} \ge z^M_{cm(t-1)} \ge z^M_{cmt} \forall a \in U^R, \qquad \forall m \in M, \qquad \forall t\in T\backslash\{1\} \tag{37}$$

Constraints 38–43 ensure that the production capacity of each equipment lies between the minimum and maximum capacity of the selected project (it is only within this range, that the parameters of the executed technical project are valid); in the period when a technological change is happening, variables z^R_{art}, z^K_{bkt} and z^M_{cmt} acquire the value of 1 and activate a reduction in the minimal production capacity, representing the non productive time during the updating process. This time is higher in the case of kilns because of their more complex updating process.

$$q^R_{ar} \cdot x^R_{art} - z^R_{art} \cdot q^R_{ar} \cdot R^R \le A^R_{art} \qquad \forall a\in U^R, \forall r\in R, \forall t\in T \tag{38}$$

$$Q^R_{ar} \cdot x^R_{art} - z^R_{art} \cdot Q^R_{ar} \cdot R^R \ge A^R_{art} \qquad \forall a\in U^R, \forall r\in R, \forall t\in T \tag{39}$$

$$q^K_{bk} \cdot x^K_{bkt} - z^K_{bkt} \cdot q^K_{bk} \cdot R^K \le A^K_{bkt} \qquad \forall b\in U^K, \forall k\in K, \forall t\in T \tag{40}$$

$$Q^K_{bk} \cdot x^K_{bkt} - z^K_{art} \cdot Q^K_{bk} \cdot R^K \ge A^K_{bkt} \qquad \forall b\in U^K, \forall k\in K, \forall t\in T \tag{41}$$

$$q^M_{cm} \cdot x^M_{cmt} - z^M_{cmt} \cdot q^M_{cm} \cdot R^M \le A^M_{cmt} \qquad \forall c\in U^M, \forall m\in M, \forall t\in T \tag{42}$$

$$Q^M_{cm} \cdot x^M_{cmt} - z^M_{art} \cdot Q^M_{cm} \cdot R^M \ge A^M_{cmt} \qquad \forall c\in U^M, \forall m\in M, \forall t\in T \tag{43}$$

Taking into account that during updating periods, production capacity of the kilns is less than 100% of its potential, the Θ parameter defines the percentage reduction in the operational capacity of the kiln during this period. Constraint 44 describes the operational capacity during this period.

$$A^K_{bkt} \le Q^K_{bk} \cdot x^K_{bkt} - Q^K_{bk} \cdot z^K_{bkt} \cdot \Theta \qquad \forall b\in U^K, \forall k\in K, \forall t\in T \tag{44}$$

Constraint 45 ensures that an updated kiln can not be closed in the following periods. This constraint is necessary in order to obtain more realistic solutions for those experiments when the main objective is minimise emissions and financial constraints are weak.

$$\sum_{b\in U^K}\sum_{t\in T} z^K_{bkt} + \sum_{t\in T} out^H_{bt} \le 1 \qquad \forall r\in R, \tag{45}$$

3. Experimental results and discussion

In order to assess the effect of carbon emissions taxes over the cement supply chain, a base case without considering taxes, is

Table 3
Abatement cost calculation for each efficient solution of the base case.

-	Sol 1	Sol 2	Sol 3	Sol 4	Sol 5	Sol 6	Sol 7
Average operational emissions (CO_2 ton/ton)	0.59	0.60	0.60	0.61	0.63	0.68	0.78
Average operational savings (US$/ton)	5.63	15.25	8.16	15.47	17.46	16.63	10.17
Total investment by unit (US$/ton)	0.35	20.13	20.22	15.71	13.24	8.41	0.73
Revenue (US$/ton)	−14.71	−4.88	−12.06	−0.24	4.22	8.22	does not apply
Emission reduction (CO_2 ton/ton)	0.17	0.16	0.16	0.15	0.13	0.08	−0.02
Abatement costs (US$/$CO_2$ ton)	−88.67	−29.95	−73.69	−1.61	33.71	99.37	does not apply
Total avoided emissions millions of CO_2 ton	7.57	7.44	7.4 7	6.73	5.71	3.77	−0.805

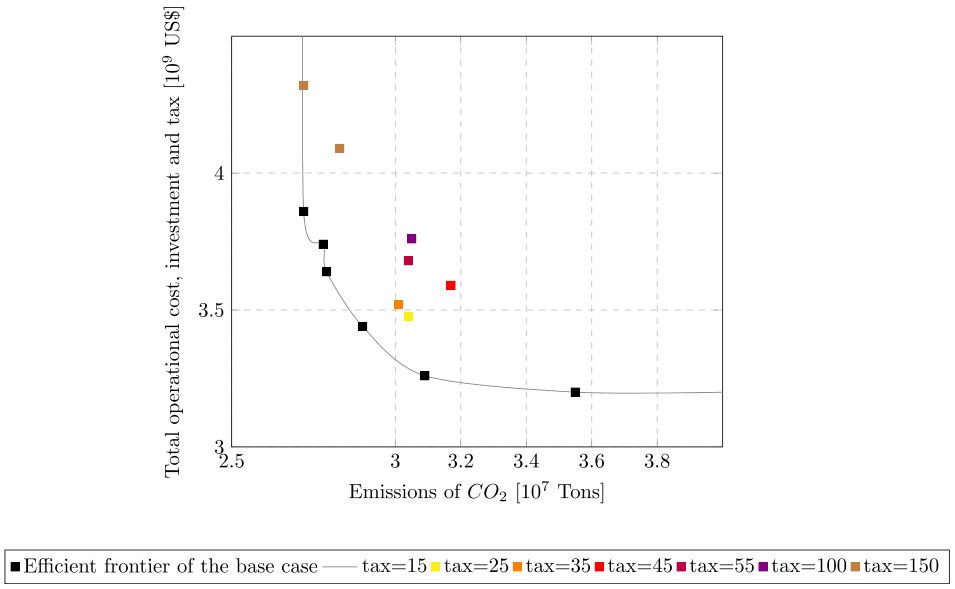


Fig. 2. Comparison cost and emissions between taxed and non-taxed solutions.

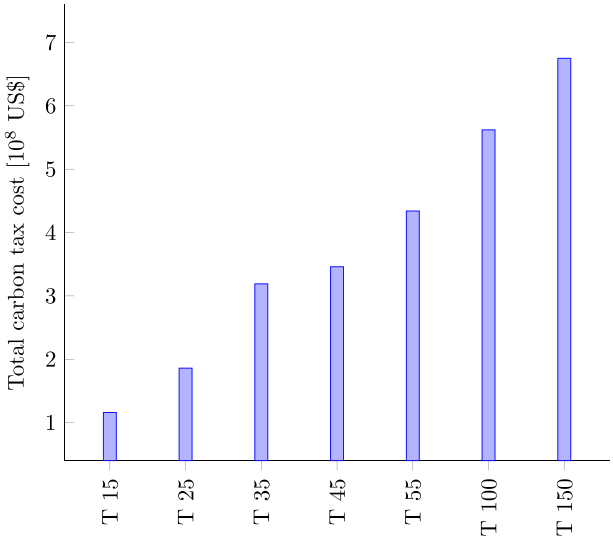


Fig. 3. Total carbon tax cost, for different tax prices scenarios.

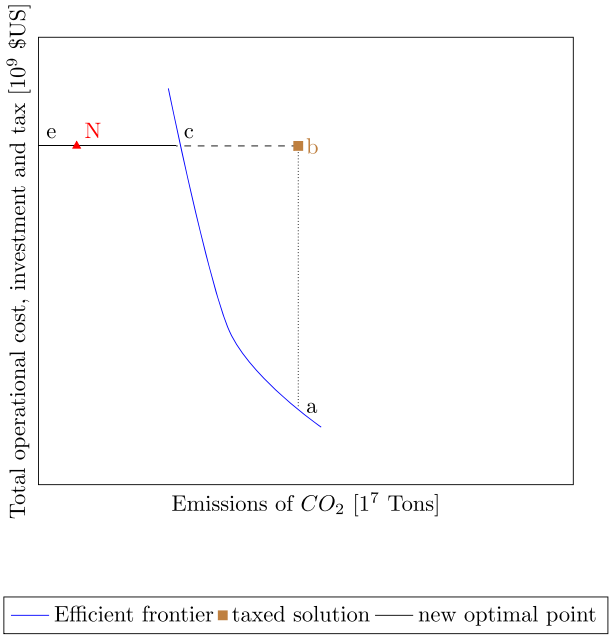


Fig. 4. Efficient frontier displacement due to the carbon tax payment and hypothetical transfer.

described. The supply chain counts with 11 production plants, 33 clients, 4 available fuels and 3 gypsum suppliers; it needs to be redesigned to attend to a growing demand, while minimising costs and emissions. Supply chain redesign implies that each process at each facility can conserve its current operating conditions, be updated or closed, modify fuel or raw materials suppliers, or shut down a sub-process while maintaining the others. For example, a kiln in a production plant could be closed while maintaining the cement mill. A variable number between 8 and 16 updating projects for raw materials and cement mills, and 78–116 kiln updating projects were considered. Technical road maps published by the cement sector have allowed the construction of the parameters for the following computational experiments. A complete description of the cement production process and its environmental improvements and updating opportunities is summarised in Cadavid-Giraldo et al. (2016) and based on (Hoenig and Twigg, 2009; Humphreys and Mahasenan, 2002; Schorcht et al., 2013; Galitsky et al., 2008; Hasanbeigi et al., 2010; Hasanbeigi, 2012; Brunke and Blesl, 2014).

Owing to the multi-period character of the model, all the financial parameters were initially available as present values. Rates to convert them to future values are based on the hypothetical growth rate in the cost of fuels, energy, or capital: annual growth rates for the investment costs were estimated to be 1%; for operating costs including fuel and energy, 3 %; for transporting costs, 2%; and for fixed costs, 2 %. Then, future cash flows were expressed as present values using the same rate, equivalent to a hypothetical annual inflation forecast. In this case, investment cost is presented as its total value, not as its annuity. A planning horizon of 5 years was considered; each year correspond to a planing period. An

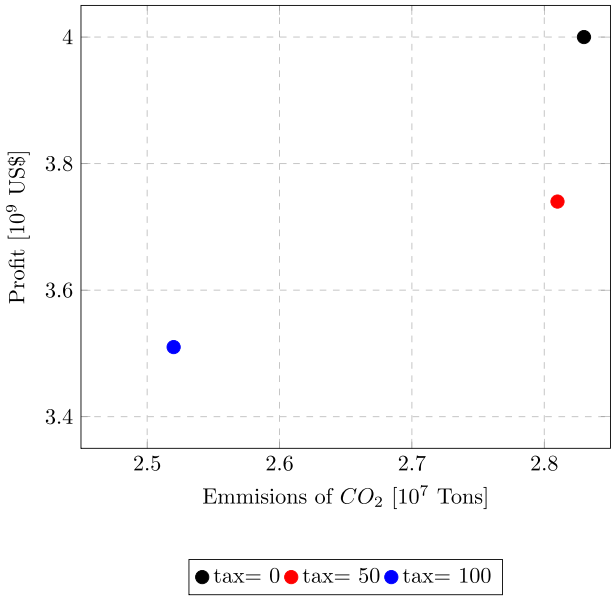


Fig. 5. Profit vs. Emissions of CO_2 on solutions of the maximun profit problem.

Table 4
Results for maximun profit problem, investments constraint I ≤ 1E+009 US.$

-	Tax = 0	Tax = 50	Tax = 100
Total cement production 1E+007	4.55	4.54	4.46
Total tax payment (US$) 1E+008	0	2.77	2.94
CO2 Emissions (ton) 1E+007	2.83	2.81	2.52
Total investment (US$) 1E+008	9.03	9.02	9.59E
Profit 1E+009 (US$)	4.00	3.74	3.51

expected demand forecast scenario is described in Table 2.

3.1. Base case

For this case, a multi-objective optimisation structure was used to build an efficient frontier among the minimal costs and minimal CO_2 emission scenarios. Using the classical epsilon constraint method proposed by Haimes et al. (1971) (Haimes et al., 1971), other five intermediate solutions were obtained. The method consists on set alternately one objective function, and use the other ones as constraints, finding a set of efficient solutions.

The bi-objective MILP proposed in Section 3 was solved using Gurobi 5.6.9. The experiments were run on APOLO, the scientific computing centre of EAFIT University. In particular, the machines used have 16 GB of memory and eight Dell Power Edge 1950 GIII processors running at 2.33 GHz under Linux Rocks 6.1 at 64 bits. For these cases, computing times were between 117 and 13535 s, with gaps not larger than 1.5%. The test instance was built using the parameters described in supplementary material.

Each non-dominated point in the Fig. 1, represents one of the optimal obtained solutions; behind each solution, there is a complete set of technological and logistics decisions that drives to a emission and total cost (operational costs plus investments) scenario. The found efficient solutions, reveal a clear trade-off between financial and environmental results.

Differences among the strategies associated with each solution mainly depends on the decisions tackled over the kiln process. All of the raw mills and cement mills are updated in both cleaner and cheaper scenarios. Along the planning horizon, obsolescent technologies are replaced by new kilns with pre-heater and pre-calciner systems, higher energy efficiency and larger production capacity. Owing to the growing nature of the demand forecast, investments are not only driven by minimisation of emissions but also by higher production requirements. In spite of this growth in global production capacity, most of the solutions suggest shutting down one or more production facilities, as a consequence of updating and economies of scale.

Differences in the operating costs in the set of efficient solutions are highly dependent on the energy efficiency of the installed technology as well as the fuel used. Cleaner solutions privilege the use of natural gas, whereas the cheaper solutions commonly use mixtures of coal and tires or biomass. At this point, the value of biofuels a successful alternative for thermal energy generation for the cement industry is highlighted, especially in geographical areas where agro-industrial activities provide useful residues or by-products as fuel. Authors in Maroušek et al. (2019) (Maroušek et al., 2017), or (Hašková, 2017), widely illustrates the significative potential of bio-fuels as an important component of the set of strategies against climate change.

A complete description of decisions that corresponds to each point in Fig. 1, is provided in supplementary material, which contains model parameters and a detailed copy of the seven obtained solutions that built the Pareto efficient frontier. All values of noncero variables are copied in those supplementary materials, as well as resulting cost and emissions.

3.1.1. Carbon abatement costs

For the base case, carbon abatement costs (CAC) of each solution on the base case, were computed using the formula proposed in (Hasanbeigi et al., 2010) as described in Eq. (46). In such an expression, the abatement cost A, depends on the complete cost of implementing abatement option (CCO), the emissions of abatement option (E^{sol}), the base line cost (BLC), and the base line emissions (BLE). The CCO is computed as in Eq. (47), and it depends on the total investment of the solution (PVC^E), the total production (P), and operational revenues, defined as the difference between the unitary operational costs of the abatement option (UC^{sol}), and the unitary cost of the base line state (UC^{BL}). As the parameters depend on the baseline of each supply chain, and on the particular improvement cost for each obtained solution, they vary widely for each case study.

$$A = \frac{(CCO - BLC)}{\left(BLE - E^{sol}\right)} \tag{46}$$

$$CCO = \frac{PVC^E}{P} + \left(UC^{sol} - UC^{BL}\right) \tag{47}$$

For the case study, base line unitary costs (BLC) are equal to 79,68 ($US/ton); base line unitary emissions (BLE) are equal to 0,76 (CO_2ton/ton) and total production during the planning period (P) corresponds to 45,624,929 (ton). Other components of the equation are particular for each solution and described in Table 3.

The very wide range of abatement costs is explained by the differences in marginal abatement cost of each managerial strategy. As these strategies vary for each solution, abatement costs also are different. While solution 1 avoids the emission of 7.57 million of CO_2 ton, with a cost of 88.67 US$ by CO_2 avoided ton, solution 6 avoids the emission of 3.77 million of CO_2 ton, with a saving of 99.37 US$ by CO_2 ton, while solution 7 does not imply any emission reduction and, hence, abatement cost does not apply for this case. Remember that the case study was based on a five-year planning horizon; an extended horizon would imply lower abatement costs per cement ton produced.

3.2. Tax to carbon emissions

Among the set of efficient solutions that represent the trade-off between costs and emissions, the question of which solution to select depends on the firm's management decisions and on the public policies that create external mechanisms to encourage the reduction of pollutant emissions. A tax on carbon emissions allows transforming CO_2 emissions into a cost, and therefore, a single-objective function that includes investment, operational and transporting costs along with the carbon tax was developed. Among the most frequently used carbon payment systems, this is, carbon tax, emission trade, and cap and tax, the third option is selected because it allows recognition of the minimal possible emissions for the cement sector: emissions below this cap are allowed and those over this cap are subject to taxation. The following results correspond to cap and tax study. For this single-objective function, two experiments were conducted: one consisting of cost minimisation and the other of profit maximisation.

3.2.1. Cost minimisation

The cost of CO_2 emissions is represented in Equation (48); where Z_t^{EO} and Z_t^{ET} represent the operational and transportation emissions of period $t \in T$, respectively; cap_t is equivalent to the maximum amount of CO_2 that can be emitted without incurring a tax, and C_t represents the payment applied to each ton of CO_2 emitted over the cap. Being indexed in the time, it is possible to consider different tax values C_t along the planning period

$$Z^C = C_t \cdot \left(Z_t^{EO} + Z_t^{ET} - cap_t\right) \qquad \forall t \in T \tag{48}$$

For this experiment, carbon cap is defined as the minimum emission possible with the best available technologies for the cement industry under an optimal network design for this case study: 500 kg of CO_2 per cement ton, hence, it is not technically possible to fulfil the estimated demand and have emissions below this cap. This approach guarantees that the emission cost value Z^C will never be negative. In a similar case, authors in Ramudhin et al. (2010) suggest that negative values would be equivalent to emission allowances that could be sold if the operation achieves emissions below the established cap.

Solutions described in Fig. 2 were obtained using a carbon cap located a the minimal emission level of 500 Kg of CO_2 by cement ton, and payment values of 15 US$, 25 US$, 35 US$, 45 US$, 55 US$, 100 US$ and 150 US$ applied to each CO_2 ton emitted over this cap. Brown, purple, red, orange and yellow points respectively correspond to solutions obtained using the mentioned tax rates. Black points corresponds to efficient solutions of the base case, and are graphed again for comparative proposes. Computational times are between 480 and 670 s. As in the base case, detailed decisions that belongs to each solution, are described in supplementary materials.

The results obtained reveal three remarkable facts:

- With respect to the highest emission base scenario (i.e. the point to the right of the efficient frontier in Fig. 2), taxed scenarios represent emission reductions between 11% and 24% .
- Despite this widespread emission reduction effect, the relation between carbon taxes values and emission reductions is not linear.
- Carbon tax costs represents 3% to 16% of the total cost of each solution. Fig. 3 describes the total cost of carbon taxes for obtained optimal solution for each tested carbon price. It is also visible that higher carbon emission price necessarily lead to higher carbon tax share of the total costs. (comparative total cost of each taxed scenario can be visualized on Fig. 2)

Results shows that the solutions with equal emissions show higher costs in the scenarios of carbon taxes implementation; coloured points in Fig. 2 are non optimal solutions. The payment systems can be explained based on Fig. 4; in this figure, assume that point *b* represents a solution under a carbon tax system. The extra cost, represented by the line segment *ab* ($\Delta cost$) should be transferred to another organisation or entity that is capable of investing this amount in a strategy that leads to larger reduction in CO_2 emissions than that represented by the line segment *bc* ($\Delta emissions$). In other words, if production emissions minus prevented emissions are located along the segment *ec*, -as for example, in the *N* point-, the carbon tax system is relevant. This figure represents the value of such mechanism: carbon taxes allow to move the efficient frontier of the original multi-objective problem to the left, towards point *N*, where lower global emission can be attained at the same cost as in point *b*.

3.2.2. Profit maximisation

Carbon emission taxes have an impact on the cost, however, what are the maximum values that the cement sector could endure? The third computational experiment was designed to evaluate the impact of taxes on the profit of the firm, given the cement market prices in Latin-American and Caribbean markets (between 130 US$ and 180 US$ per cement ton). Taxes of 50 US$ and 100US$ were used to answer that question; results in Fig. 5 and Table 4, show total emission and profit of tree different scenarios: tax = 0 US$, tax = 50 US$ and tax = 100 US$. Those results demonstrate that taxes are effective in reducing emissions; a tax of 100 US$ reduces emissions in 11% respect the non taxed solution and profit in 12%; the effect of 50 US$ represents a less attractive emission reduction of 1% and a profit reduction on 7% -It is important to remember that this problem does not imply demand satisfaction. Finally, the work of (Rootzén and Johnsson, 2017) is remarked; authors found that "even if carbon pricing doubled the cost of cement, the cost of a residential building will only increase by one percent".

From a profit perspective, there is no need to fulfil all the demand as the model should be capable of choosing not to fulfil a given demand due to the emissions or the cost of doing so. In this case, decision variables V_{ct} in Equation (49) denote the amount of cement sold to customer $c \in C$ in period $t \in T$; and the parameter P_{ct} defines the price of cement for each customer. CO_t, CT_t and CF_t represent the operational, transportation and fixed costs of the period, respectively. The total investment on updating technology is used as a constraint.

$$Pf = \sum_{c \in C} \sum_{t \in T} V_{ct} \cdot P_{ct} - \sum_{t \in T} (CO_t + CT_t + CF_t) \tag{49}$$

Fig. 5 represents a profit maximisation problem with investment constraints. Detailed description of the solution obtained is presented in supplementary materials.

The results obtained are compatible with the literature reviewed as they demonstrate the impact of the emission charge on the reduction thereof. In the reviewed literature, sensitivity analyses are very common, through numerical experiments where the effect of different prices on emissions is modelled. Our results show that the relationship between carbon emission price and emission reduction is not linear; similar conclusion is explicitly declare by previous works of Zakeri et al. (2015) and Rezaee et al. (2015), while the others authors on previous works do not express it directly, but their results clearly behave accordingly.

Large differences between figures of previous studied the case studies, determined not only by the technical and logistical particularities of each sector studied, but also by the different ways of

applying a carbon price prevent concluding on an appropriate range for taxes; by this way, not only is explained the wide variety of prices currently applied throughout the world, as described in section 1, but also the importance of carrying out many studies such as the one we present, to accumulate a broad information base that refine current emission payment policies. It is clear that numerous sectorial and regional studies will be needed to adjust a pricing policy able to induce emission reductions within a viable financial framework.

4. Conclusions

In this paper the effect of a carbon taxation mechanism as a driver for the reduction of the CO_2 emissions in a cement supply chain, was studied. To study such effect, three mixed integer linear formulations were proposed and solved for a realistic sized instance built using publicly available data from the cement sector. The results of the computational experiments conducted for this study indicate that a tax rate between US$15 and US$150 applied to emissions that exceed the predefined cap of 500kg of CO_2 per cement ton, will drive cleaner cement production scenarios with a reduction of emissions up to 24% with respect to a non-taxed scenario used as the base line; higher emission taxes does not have a linear effect over emission reduction.

The value of the proposed mathematical model lies in being sufficiently detailed to specifically describe the conditions of a cement supply chain and flexible enough to be used by any company in the sector. The tool responds to the strategic planning needs of any company that wants to face the challenges that the urgent restrictions on the emission of CO_2 currently entail.

The literature review demonstrates the frequent use of similar mathematical tools to describe the effect of carbon taxes on specific productive sectors. The wide-set of similar works make more visible the importance of such tools to model, understand and project effective responses to these new taxes. To this set of tools, a specific one for the cement sector, was developed; their major value is in the contribution to the reduction of carbon emissions while protecting the financial sustainability of firms. Systematic application of these bottom-up models will facilitate gathering enough information to frame an assertive carbon pricing system.

Obtained figures demonstrates the advantage of a financial mechanism, such as carbon emission tax, over an emission limit or standard, is the recognition of significant differences between abatement costs for each firm or a product sector. In cases of high CAC, a wise investment of taxes founds could achieve higher avoided CO_2 emissions, than the own firms improvement investments.

5. Future work

After energy efficiency, technological updating, use of alternative fuels and clean electricity sources, next steps in CO_2 emission reductions of the cement sector are: (i) reduce the clinker content in the cement composition, and (ii) capture and storage the emitted CO_2. In the fist case, clinker can be replaced by lower emission -or even carbon negative-alternative cementious materials. The percentage of alternative materials constitute a new decision variable of the problem that will be tackled in future work. The CCS system design within carbon pricing policies was addressed by authors in Santibanez-Gonzalez (2017). This work constitute an important initial reference to add this strategy in the supply chain description that was presented here.

The proposed mathematical model allows to find a global optimum in cement production. Understanding that cement is one more input in the concrete supply chain and this in turn, one more element in the set of construction materials that could be selected in any civil work, the scope of this work ends in supplying cement to the next echelon in the concrete chain. Other improvement opportunities in the cement use during the building activities, as mixing optimisation in regard to final strength requirements of concrete, could be approached more efficiently with another decision tool, which includes the minimum emissions cement resulting from the planning of the cement chain, and other inputs for the production of concrete, where logistical parameters have an even more dominant value.

CRediT authorship contribution statement

Nora Cadavid-Giraldo: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Funding acquisition. **Mario C. Velez-Gallego:** Supervision, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - review & editing, Visualization. **Alexandre Restrepo-Boland:** Validation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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