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Eco-efficiency of the world cement industry: A Data Envelopment Analysis

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Abstract Chemical reactions and the combustion of dirty fuels, as coal and petcoke, used in cement production process generate a significant amount of CO_2 emissions, as undesirable output. In this paper, we provide an eco-efficiency measure of twenty-one prototypes of cement industries operating in as many worldwide countries by applying both a Data Envelopment Analysis (DEA) and a directional distance function approaches that are particularly suitable for models where several production inputs and desirable and undesirable outputs are taken into account. In order to understand whether eco-efficiency is due to a rational utilization of inputs or to a real carbon dioxide reduction as a consequence of environmental regulation, we analyze the cases where CO_2 emissions can be either considered as an input or as an undesirable output. Empirical results show that countries where cement industries invest in technologically advanced kilns and adopt alternative fuels and raw materials in their production process are eco-efficient. This gives a comparative advantage to those emerging countries, like India and China, that are more incentivised in modernizing their production process.

Key words: Data Envelopment Analysis, undesirable output, environmental regulation.
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JEL - 1999 Class. Syst. C14, C61, D24.

1 Introduction

Cement is essential for the economic development of a country, but its production is highly energy and emission intensive. Among the non-metallic minerals production processes, cement manufacturing is the most expensive in terms of energy consumption. According to the European Cement Association (Cembureau), "*each ton of cement produced requires 60 to 130 kg of fuel oil or its equivalent, depending on the cement variety and the process used, and about 105 KWh of electricity*"[1]. On average, energy costs, in form of fuel and electricity, represent the 40% of the total production costs of one ton of cement (see European Commission [10]). In addition, cement industry is responsible

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[1] See `http://www.cembureau.be/about-cement/cement-industry-main-characteristics`

for about the 5% of the current worldwide CO_2 emissions (see IEA [16]). These data are worrying considering that the worldwide production of cement is more than quadruplicated in the last twenty-five years, reaching an amount of 3 million tons in 2009 (see Cembureau [4]), and it is expected to increase even further because of the exponential growth rates of developing countries, like China and India that are the major cement producers in the world. Clinker production is the main responsible for CO_2 emissions. Clinker is a cement sub-product that is produced by burning a mixture of limestone, silicon oxides, aluminum oxides and iron oxides in kilns that differs according to the process adopted[2] at an average temperature of about 1,450 Celsius degrees. This high temperature, that is usually reached by burning highly emitting fuels, like coal and pet-coke, leads to chemical reactions that transform raw materials in clinker, but also generate CO_2 and other greenhouse gas emissions as undesirable outputs.

CO_2 emissions become a problem for those industries operating in countries where an environmental regulation applies. This the situation that European cement industries are facing since 2005, the year of inception of the European Emission Trading Scheme (EU-ETS). Introduced by Directive 2003/87/EC, the EU-ETS is the widest cap and trade system applied in the world and regulate CO_2 emissions generated from specific installations[3]. The cap and trade system implies the imposition of a CO_2 emission ceiling for all covered installations in the different countries, the National Allocation Plans (NAPs[4]), and the creation of an emission permit market where players can buy or sell CO_2 allowances at a certain price defined by the market itself. The EU-ETS was originally organized in two phases: the first, already concluded, from 2005 to 2007 and the second covering the period 2008-2012[5]. A third phase has been announced for the period 2013-2010. This will be regulated by the new Directive 2009/29/EC that enlarges the number of sectors and greenhouse gases subject to regulation. The European energy intensive industries (and then also cement producers) complain about EU-ETS because it imposes additional costs, deriving from emissions abatement and the purchase of allowances, that put their European plants in a competitive disadvantage with respect to those operating in countries where emissions constraints are more lenient or even absent (see Business Europe [5] and Cefic [7]). In fact in many countries, emission trading scheme are not mandatory, but are organized on a voluntary basis. This is the case of Switzerland, Japan, Canada and the USA (see Appendix A for more details). In Australia, the announced ETS program has not been approved by the government and its application will be postponed (see Appendix A).

However, one can notice a growing awareness about greenhouse gas emissions and, in general, about environment in developing countries. China is the world's largest CO_2 emitter, but has shown a determination to curb its greenhouse gas emissions. The application of the China's national Climate

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[2] Cement can be produced with four different processes: dry, wet, semi-dry and semi-wet. Dry and semi-dry processes are generally more productive and require a lower amount of energy than the other two. Cement production is subdivided in two main steps: first, clinker is produced from raw materials in kilns whose efficiency varies according to the process adopted and then cement results from the mixture of clinker with other additives.

[3] The sectors currently involved are: energy and refining, iron and steel, pulp and paper and cement.

[4] See `http://ec.europa.eu/clima/policies/ets/allocation_2005_en.htm` for the National Allocation Plans of the two phases.

[5] European Commissions lists the countries involved in the EU-ETS and provides information about the two phases at `http://ec.europa.eu/clima/policies/ets/index_en.htm`. A special case is represented by Norway. This EU Member State started in 2005 a domestic emission trading scheme. The organization of the original Norwegian ETS was identical to that of the EU-ETS. Thanks to an agreement signed between the EU and the members of the European Economic Association (Iceland, Liechtenstein and Norway) in October 2007, Norway has officially entered in the EU-ETS starting from 2008 (see Reinaud [25]). The same happened to United Kingdom that after some problems in determinating its NAP was included in the EU-ETS in 2008.

Change Program has been the first step of a modernization process whereby China intends "*to address climate change and promote sustainable development*" through "*policies and measures, such as economic restructuring, energy efficiency improvement, development and utilization of hydropower and other renewable energy*"[6]. This means that China does not impose a cap on CO_2 emissions, but aims at reducing emissions by setting binding energy intensive reduction targets, stringent fuel efficiency standards and investments in more efficient technologies. Several key sectors are involved in this program and cement is one of them. Note that the effectiveness of the targets imposed by the Chinese climate program on the cement sector[7] is confirmed by a study conducted by the International Energy Agency pointing out that cement industries dispose of four tools suitable for reducing their CO_2 emissions, namely thermal and electric efficiency, the utilization of alternative fuels, clinker substitution and the adoption of the carbon capture and storage process that captures CO_2 before being released into the atmosphere (see IEA [16]).

Similar policies are also in force in India, where an Energy Conservation Act[8] has been introduced in 2001, and in Brazil where the National Climate Change Plan has been effective since 2008[9]. Also in Turkey there are some signals in this direction. The candidature to become an European Member State has induced Turkish government to ratify the Kyoto Protocol on May 2009[10] and to introduce eco-innovation policies in order to reduce their emissions (see OECD [22]).

Considering this framework, the aim of this paper consists in studying the eco-efficiency level of cement industries operating in different world countries. Among the several environmental performance indicators (see Tyteca [29] for a complete review), we have chosen that resulting from the application of a Data Envolopment Analysis (DEA) approach. DEA evaluates the efficiency of chosen Decision Making Units (DMUs), that can been plants, firms or even entire sectors, producing an homogeneous good. It has the advantage to simultaneously consider the multiple inputs (with their respective measures) and both the desirable (produced good) and undesirable (waste and pollutants) outputs that characterize a certain production process. This allows DMUs to have an immediate information on their global efficiency (or inefficiency) status and, depending on the DEA approach adopted, on which input or output they have to intervene in order to improve their production.

Differently from other papers on cement sector already existing in literature (Bandyopadhyay [2], Mandal and Madheswaran [20] and Sadjadi and Atefeh [26]) where the analysis is conducted at interstate level, in our study, DMUs are prototypes of cement plants located in twenty-one world's countries. We measure their eco-efficiency by including CO_2 emissions as an undesirable production factor. According to the DEA literature, undesirable factors can be modeled either as an input or as undesirable output. We apply both these already existing approaches in addition to a directional distance function model to our study. With these models, eco-efficiency of cement DMUs can be measured either as a contraction of CO_2 emissions or as an increased utilization of alternative fuels and raw materials. Our analysis shows that units' efficiency level is affected by the tendency of

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[6] Directly taken from `http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File188.pdf`

[7] At point (4) of the China's national Climate Change Program, one can read that "*new dry process kiln with pre-calcinator technology should be developed; promote energy efficient grinding equipment and power generating technology by using waste heat recovered from cement kiln; improve the performance of existing large-and medium-size rotary kiln, mills and drying machines for the purpose of energy conservation; gradually phase out mechanized vertical kiln, wet process kiln and long dry process kiln and other backward cement production technologies*". Directly taken from `http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File188.pdf`

[8] See `http://www.powermin.nic.in/acts_notification/pdf/ecact2001.pdf`

[9] See `http://www.eoearth.org/article/Greenhouse_Gas_Control_Policies_in_Brazil'`

[10] See`http://en.wikipedia.org/wiki/List_of_Kyoto_Protocol_signatories#cite_note-13`

the different DMUs to invest in technologically advanced kilns and to adopt alternative fuels and raw materials in their cement production processes. Surprisingly, emerging countries, like India and China that are the largest cement producers in the world, appear efficient. As we will explain in Section 4, their recent economic boom and the energy efficiency targets imposed by their authorities have forced their cement companies to invest in the most advanced technologies.

The remainder of the paper is organized as follows. Section 2 presents the model that we apply in our analysis, while Sections 3 and 4 respectively illustrate the dataset used in our simulations and the obtained results. Final remarks are reported in Section 5.

2 Modeling Eco-efficiency

The notion of eco-efficiency is worldwide used with different meanings and definitions. We define *eco-efficiency*, in an operational way, as the ability of producing goods or services by saving energy and resources and/or reducing waste and emissions. Different instruments for measuring eco-efficiency are introduced in the literature (see Tyteca [29]), but most of them are simple indicators[11] that approach eco-efficiency from a very limited perspective since they consider only few factors of a production process. One should aggregate all these indicators in order to a synthetic information on the overall impact of certain production process on environment. Moreover, measuring eco-efficiency at a worldwide base, as we do in this paper, encounters the problem of information availability since environmental policies are not uniformly applied around the world.

Some of these difficulties can be overcome by using DEA to determine eco-efficiency. Data Envelopment Analysis has been first proposed in the pioneering paper by Charnes, Cooper and Rhodes (CCR) [6]. It is a nonparametric method for estimating the efficiency of n DMUs. Each DMU consumes various inputs to produce different outputs. No production function needs to be specified.

The classic DEA model (see [6]) is a linear fractional problem that measures the efficiency of the j^{th} DMU through a ratio between the weighted sum of outputs and the weighted sum of inputs that aggregated into a composite input and a composite output all inputs and all outputs. The CCR pioneer model estimates the technical efficiency of a DMU with Constant Returns to Scale (CRS) on the entire production frontier. The extension proposed by Banker, Charnes and Cooper [3] generalized this assumption formulating the so-called BCC model which exhibits Variable Returns to Scale (VRS) at different points of the production frontier.

In general, DEA evaluates the efficiency of each DMU through the better system of weights (or shadow prices) for the considered DMU, identifying the best one. Stating the benchmark, DEA classifies the remaining DMUs from the most efficient to the less one. Efficiency is evaluated taking into account both desirable (good) and undesirable (bad) output and input factors. Note that undesirable and desirable outputs should be treated in a different way: if production is inefficient, the undesirable pollutants should be reduced. However, standard DEA models do not allow decreases in outputs; only inputs can be reduced.

When undesirable outputs are taken into consideration, the choice between improved technologies or reference technologies has an important impact on DMUs efficiencies. Technology disposability can be also read in terms of strong and weak disposability of undesirable outputs. A production process is said to exhibit strong disposability of undesirable outputs, if the undesirable outputs are

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[11] For instance, economic output per unit of waste ratios

freely disposable, i.e. they do not have limits. The case of weak disposability refers to situations where a reduction of the undesirable output forces a lower production of desirable outputs. This means that the reduction of undesirable outputs imposed by an external regulation may not be possible without assuming certain costs (see Zofío and Prieto, [33]).

Different variants of DEA models can be used for the estimation of eco-efficiency. In the following, we present a brief review of the existing models. For the sake of convenience, the list of common variables and parameters used in the different models is provided below.

Parameters:

$x_{ij} \in \mathbb{R}_+$: i^{th} input quantity used by the j^{th} decision making unit
$i = 1, \ldots, m, \quad j = 1, \ldots, n$

$y^g_{rj} \in \mathbb{R}_+$: r^{th} "good" output quantity produced by the j^{th} decision making unit
$r = 1, \ldots, q, \quad j = 1, \ldots, n$

$y^b_{kj} \in \mathbb{R}_+$: k^{th} "bad" output quantity produced by the j^{th} decision making unit
$k = 1, \ldots, t, \quad j = 1, \ldots, n$

Variables:

$v_i \in \mathbb{R}_+$: weight multipliers related to the i^{th} input
$j = 1, \ldots, n$

$u_r \in \mathbb{R}_+$: weight multipliers related to the r^{th} "good" output
$r = 1, \ldots, q$

$w_k \in \mathbb{R}_+$: weight multipliers related to the k^{th} "bad" output
$k = 1, \ldots, t$

$u_0 \in \mathbb{R}$: scale factor variable

$\theta \in \mathbb{R}_+$: dual variable related to the first constraint

$\lambda_j \in \mathbb{R}_+$: dual variables related to the second set of constraints
$j = 1, \ldots, n$

According to the literature, two different approaches can be used to model undesirable factors: a first group of DEA models threats them as inputs, while a second one considers them as undesirable outputs. In the light of this distinction, we now present the four alternative DEA models that we use to measure eco-efficiency.

2.1 Pollutant as inputs

2.1.1 Eco-efficiency measure as input and pollutant contraction

A first approach to treat both desirable and undesirable factors following the standard linear BCC model, suggests to include undesirable outputs as desirable inputs in the production process (see

[18]). Efficient DMUs wish to minimize desirable inputs and undesirable outputs. The mathematical formulation of the model, in case of strong output disposability and input oriented DEA, is as follows:

$$
\begin{aligned}
&(P1)\\
&\max_{u,v,w,u_0} && \sum_{r=1}^{q} u_r y^g_{rjo} + u_0 && (1)\\
&s.t. && \sum_{i=1}^{m} v_i x_{ijo} + \sum_{k=1}^{t} w_k y^b_{kjo} = 1 && (2)\\
& && \sum_{r=1}^{q} u_r y^g_{rj} + u_0 - \sum_{i=1}^{m} v_i x_{ij} - \sum_{k=1}^{t} w_k y^b_{kj} \leq 0 \quad j = 1,\dots,n && (3)\\
& && u_r \geq 0 \quad r = 1,\dots,q\\
& && w_k \geq 0 \quad k = 1,\dots,t\\
& && v_i \geq 0 \quad i = 1,\dots,m\\
& && u_0 \in \mathbb{R}
\end{aligned}
$$

and the corresponding dual formulation is:

$$
\begin{aligned}
&(D1)\\
& && \min_{\theta,\lambda} \; \theta && (4)\\
&s.t. && \sum_{j=1}^{n} \lambda_j y^g_{rj} \geq y^g_{rjo} \quad r = 1,\dots,q && (5)\\
& && \sum_{j=1}^{n} \lambda_j y^b_{kj} \leq \theta y^b_{kjo} \quad k = 1,\dots,t && (6)\\
& && \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ijo} \quad i = 1,\dots,m && (7)\\
& && \sum_{j=1}^{n} \lambda_j = 1 && (8)\\
& && \lambda_j \geq 0 \quad j = 1,\dots,n
\end{aligned}
$$

The primal formulation corresponds to a standard input-oriented primal BCC-model where undesirable outputs behave like inputs. The objective function of the primal formulation maximizes the weighted sum of desirable outputs, under the condition that the weighted sum of inputs and undesirable outputs for the considered DMU is equal to one (as it results in constraint (2)). From a dual point of view, this means that a DMU can simultaneously reduce all inputs and undesirable outputs by the same proportion θ in order to increase its eco-efficiency. An efficient DMU will have as optimal solution $\theta^* = 1$ implying that no equiproportional reduction in inputs and undesirable outputs is possible. According to this model formulation, eco-efficiency in the cement sector can be interpreted as the ability to reduce undesirable outputs by introducing more efficient technologies and to reduce inputs by substituting them with alternative raw materials while maintaining the same outputs levels.

Note that models $P1$ and $D1$ can be used with the assumption of weak disposability by respectively considering variables w_k as unconstrained in sign in the primal formulation and by assuming that constraint (6) holds with equality in the corresponding dual formulation. For an exhaustive discussion on strong and weak disposability in this class of models see Liu et al. [17]. Note that considering the undesirable outputs as inputs, the resulting DEA model does not reflect the true production process. This is the main drawback of this formulation.

2.1.2 Eco-efficiency measure as pollutant contraction

The class of DEA models we present in this subsection permits to measure eco-efficiency as the ability to reduce pollutants while maintaining the same inputs and desirable outputs levels. The eco-efficiency measure, as formally defined by Korhonen and Luptacik in [15], is then the ratio between the weighted sum of the desirable outputs minus the weighted sum of the inputs and the weighted sum of the undesirable outputs. The Primal-Dual linearized version of this class of DEA models is as follows:

$$(P2)$$

$$\max_{u,v,w,u_0} \quad \sum_{r=1}^{q} u_r y^g_{rjo} - \sum_{i=1}^{m} v_i x_{ijo} + u_0 \tag{9}$$

$$s.t. \quad \sum_{k=1}^{t} w_k y^b_{kjo} = 1 \tag{10}$$

$$\sum_{r=1}^{q} u_r y^g_{rj} - \sum_{i=1}^{m} v_i x_{ij} + u_0 - \sum_{k=1}^{t} w_k y^b_{kj} \leq 0 \quad j = 1, \ldots, n \tag{11}$$

$$u_r \geq 0 \quad r = 1, \ldots, q$$

$$w_k \geq 0 \quad k = 1, \ldots, t$$

$$v_i \geq 0 \quad i = 1, \ldots, m$$

$$u_0 \in \mathbb{R}$$

$$
\begin{aligned}
&(D2) && \\
&\min_{\theta,\lambda} \quad \theta && \\
&s.t. \quad \sum_{j=1}^{n} \lambda_j y_{rj}^{g} \geq y_{rjo}^{g} \quad r = 1, \ldots, q && (12)\\
&\qquad \sum_{j=1}^{n} \lambda_j y_{kj}^{b} \leq \theta y_{kjo}^{b} \quad k = 1, \ldots, t && (13)\\
&\qquad \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{ijo} \quad i = 1, \ldots, m && (14)\\
&\qquad \sum_{j=1}^{n} \lambda_j = 1 && \\
&\qquad \lambda_j \geq 0 \quad j = 1, \ldots, n &&
\end{aligned}
$$

The objective function in the dual formulation gives information on the pollutants contraction to the largest extent possible. If $\theta^* < 1$, that is DMU is inefficient, the firm can still reduce undesirable outputs without increasing the corresponding inputs level or reducing desirable outputs. Model $P2$-$D2$ under the hypothesis of weak disposability can be obtained considering variable w_k as uncostrained in sign in the primal formulation and assuming that constraints (13) hold with equality in dual formulation. Notice that, in the case of a single undesiderable factor, weak and strong eco-efficiency scores coincide.

2.2 Pollutant as undesirable outputs

2.2.1 Eco-efficiency as input contraction

The analysis on eco-efficiency can be deepened on by considering a third efficiency measure which concentrates on the efficiency improvement by reducing inputs while maintaining the same fixed outputs levels both for undesirable and desirable ones. In this light, we present the approach proposed by Seiford and Zhu [27]. Under the context of the BCC model (Banker et al., [3]), Seiford and Zhu developed an alternative method to deal with desirable and undesirable factors in DEA. In order to increase the desirable outputs and to decrease the undesirable outputs, they transform the values of the undesirable outputs by a monotone decreasing function. The transformed data can then be included as desirable outputs in the problem and maximized. In fact, after the decreasing transformation, maximizing these values means minimizing the original undesirable outputs. In particular, for the purpose of preserving linearity and convexity relations, Seiford and Zhu [27] suggested a linear monotone decreasing transformation, $\overline{y}_{kj}^{b} = -y_{kj}^{b} + \beta_k > 0$, where β is a proper translation vector that makes $\overline{y}_{kj}^{b} > 0$. Based upon the above linear transformation, the standard BCC DEA model can be modified as the following pair of linear programs:

$(P3)$

$$\max_{u,v,w,u_0} \quad \sum_{r=1}^{q} u_r y^g_{rj_0} + \sum_{k=1}^{t} w_k \overline{y}^b_{kj_0} + u_0 \tag{15}$$

$$s.t. \quad \sum_{i=1}^{m} v_i x_{ij_0} = 1 \tag{16}$$

$$\sum_{r=1}^{q} u_r y^g_{rj} + \sum_{k=1}^{t} w_k \overline{y}^b_{kj} + u_0 - \sum_{i=1}^{m} v_i x_{ij} \leq 0 \quad j = 1, \ldots, n \tag{17}$$

$$u_r \geq 0 \quad r = 1, \ldots, q$$

$$w_k \geq 0 \quad k = 1, \ldots, t$$

$$v_i \geq 0 \quad i = 1, \ldots, m$$

$$u_0 \in \mathbb{R}$$

$(D3)$

$$\min_{\theta,\lambda} \quad \theta$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y^g_{rj} \geq y^g_{rj_0} \quad r = 1, \ldots, q \tag{18}$$

$$\sum_{j=1}^{n} \lambda_j \overline{y}^b_{kj} \geq \overline{y}^b_{kj_0} \quad k = 1, \ldots, t \tag{19}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_0} \quad i = 1, \ldots, m \tag{20}$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0 \quad j = 1, \ldots, n$$

In model $D3$, like the classical BCC models, the efficiency is measured taking into account the possible input reductions while the outputs are kept at their current levels. According to this model a DMU j_0 can improve the eco-efficiency by reduce the inputs, while the values of the desirable and undesirable outputs of the DMU j_0 are taken as lower bounds for a linear combination of the other desirable and undesirable outputs.

From a theoretical point of view, notice that, by assuming Variable Return to Scale (VRS), the model is invariant with respect to the linear translation. It has been proved by Ali and Seiford in [1] that affine translation of data values does not alter the efficient frontier. Thus the classification of DMUs as efficient or inefficient is translation invariant. We recall that the same models can be used with the assumption of weak disposability by respectively considering variables w_k as unconstrained in sign in the primal formulation $P3$ and by assuming that constraints (20) hold with equality in the corresponding dual formulation $D3$.

2.2.2 Eco-efficiency as undesirable output contraction and desirable output expansion

The directional output distance function, in its original formulations by Färe et al. [13], is an alternative approach to evaluate eco-efficiency. This approach expands desirable outputs and contracts undesirable outputs along a path that varies according to the direction vector adopted, in order to increase eco-efficiency. Extensions of this methodology (see for all [11, 12, 23]) obtain a measure of eco-efficiency from the potential for increasing outputs while reducing inputs and undesirable outputs simultaneously.

In order to describe this approach, let us define the following sets. Let T be the technology set, such that:

$$T = \Big[(x, y^g, y^b) : x \text{ can produce } (y^g, y^b)\Big] \tag{21}$$

In presence of undesirable outputs, the output set $\mathscr{P}(x)$ represents all the feasible output vectors (y^g, y^b) for a given input vector x, that is:

$$\mathscr{P}(x) = \Big[(y^g, y^b) : (x, y^g, y^b) \in T\Big] \tag{22}$$

The directional technology distance function generalizes both input and output Shephard's distance functions, providing a complete representation of the production technology.

Let $d = (-d^x, d^g, -d^b)$, the function is formally defined as:

$$\vec{D}_T(x, y^g, y^b; d) = \sup \Big[\delta : (y^g + \delta d^g, y^b - \delta d^b) \in \mathscr{P}(x - \delta d^x)\Big] \tag{23}$$

Expression (23) seeks for the maximum attainable expansion of desirable outputs in the d^g direction and the largest feasible contraction of undesirable outputs and inputs in d^b and d^x directions. Under the assumptions made on the technology of reference, the directional technology distance function of expression (23) can be computed for firm j_0 by solving the following programming problem:

$$(P4)$$

$$\max_{\delta,\lambda} \quad \delta$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y^g_{rj} - \delta d^g_{rj_0} \geq y^g_{rj_0} \quad r = 1, \dots, q \tag{24}$$

$$\sum_{j=1}^{n} \lambda_j y^b_{kj} + \delta d^b_{kj_0} \leq y^b_{kj_0} \quad k = 1, \dots, t \tag{25}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} + \delta d^x_{ij_0} \leq x_{ij_0} \quad i = 1, \dots, m \tag{26}$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0 \quad j = 1, \dots, n$$

The choice of a direction vector $d = (-x, y^g, -y^b)$ permits to evaluate a global technology and ecological efficiency by reducing inputs and undesirable outputs and simultaneously expanding desirable outputs. A different direction vector can be used in order to restrict the analysis on output factors, by considering, for instance, a direction vector $d = (0, y^g, -y^b)$. In this case Mandal and Madheswaran [20] focus their attention on expansion of desirable factors and contraction of undesirable ones without increasing the inputs.

Notice that in the directional distance function model, efficiency is reached when $\delta = 0$, corresponding to the case of $\theta = 1$ in the standard DEA formulations.

Let us recall that this model can be also considered under the assumption of weak disposability by assuming that constraints (25) hold with equality.

2.3 Construction of the production frontier

In the DEA literature, three types of frontiers have been proposed to evaluate efficiency in a panel-data framework. The first one is the standard Contemporaneous Frontier, where the frontier in each year is constructed with the observations of the year under consideration only. The second type of frontier is the Intertemporal Frontier and it is based on observations from all the considered periods at a time. The third one is the Sequential Frontier, where each observation for a given year is compared to all other observations in the same year and to observations in the previous years (see Tulkens and Eeckaut [31] for a detailed discussion about different DEA frontiers). This last methodology is based on the assumption that the production possibility set can expand each year and no technological regress is admitted. For the aim of this work, the Sequential Frontier seems to be the most suitable for the analysis of the world cement sector in the years 2005-2008. In these years, in facts, the world cement industry has faced a rapid expansion and technological improvement (especially in developing countries).

3 Database description

A database concerning twenty-one regulated and non-regulated cement producer countries has been collected. The dataset can be ideally divided into European (EU) and non-European (non-EU) countries according to the geographic and regulation emission aspects. The thirteen European countries included in the database (Austria, Belgium, Czech Republic, Denmark, Estonia, France, Germany, Italy, Norway, Poland, Spain, Switzerland and United Kingdom) produce more than the 80% of the total EU cement production. In order to compare the eco-efficiency of these EU countries with non-EU ones, data concerning eight major non-EU countries (Australia, Brazil, Canada, China, India, Japan, USA and Turkey) have been added.

For the purpose of our analysis, the choice of input and output factors of DEA models has been done taking into account the cement and clinker production processes. Four input data have been considered: installed capacity, energy, labour and materials. Desirable output is represented by cement production while CO_2 emissions are the undesirable by-product.

As to the inputs, for all twenty-one countries (DMUs in DEA), we consider capital in the form of installed capacity (a similar approach can be found in Fare et al. [14], Tyteca [30]), energy as the sum of electricity and thermal energy, labour as the number of employees and materials as raw materials (slug, limestone, etc) in addition to clinker imports and production. Notice that, alternative fuels and raw materials are not included in the input factors because we assume that we the use of alternative fuels and alternative raw materials is costly free and contributes to reduce emission factors. As a consequence, countries which decide to use alternative fuels and materials can improve their eco-efficiency.

Desirable output is Portland cement production. The undesirable by-product is measured by the value of carbon dioxide emissions (CO_2) mainly resulting from the clinker production process without considering those related to raw material, fuels and clinker transportation. CO_2 can be interpreted as input or undesirable output according to the different DEA approaches.

Data sources for EU countries are the European association of cement industries (Cembureau), the national cement association of the different countries (see Cembureau website for the link to members' national associations and Appendix B), OECD (especially for labour data), Eurostat and ComTrade (for clinker import/export data), European Pollutant Emission Registry (EPER for CO_2 emission data). National cement associations also provided data for non-EU countries (see the detailed list of the references in Appendix B).

Missing data on emission factors have been estimated according to Intergovernmental Panel on Climate Change (IPCC)[12]. Carbon dioxide is released during the production of clinker in which calcium carbonate ($CaCO_3$) is heated in a rotary kiln to induce a series of complex chemical reactions. Specifically, CO_2 is released as a by-product during calcination, which occurs in the upper, cooler end of the kiln, or a precalciner, at temperatures of 600-900C, and results in the conversion of carbonates to oxides. The simplified stoichiometric relationship is as follows:

$$CaCO_3 + heat \rightarrow CaO + CO_2 \tag{27}$$

At higher temperatures in the lower end of the kiln, the lime (CaO) reacts with silica, aluminum and iron containing materials to produce minerals in the clinker. The clinker is then removed from the kiln to cool, ground to a fine powder, and mixed with a small fraction (about five percent) of gypsum to create the most common form of cement known as Portland cement.

The formula to calculate CO_2 emission has been defined according to the following steps:

1. Data on clinker production (in tonnes) have been collected. In case of missing data the clinker production has been estimated as a fixed proportion on cement production (estimated coefficient varying between 75% and 95% according to the cement blending).

2. Ton of Raw Material (T) per Ton of Clinker (*RM/clinker ratio*) have been estimated in the case of data missing with a fixed coefficient of 1.54 according to IPCC guidelines.

3. The $CaCO_3$ Equivalent to Raw Material Ratio (%) is fixed to a 78.5%.
4. The CO_2 to $CaCO_3$ Stoichiometric Ratio is fixed equal to 0.44.

The total CO_2 emissions expressed in tonnes (T) can be estimated as follows:

$$CO_2 = clinker(T) \cdot (RM/clinker\ ratio) \cdot CaCO_3\% \cdot 0.44 \tag{28}$$

In Table 1, we report means and standard deviations of the input and output parameters used in the models for the considered 2005-2008 period. Note that the high standard deviation values depend on the inclusion of China in the dataset. Cement industry in China, in facts, accounts for more than 40% of world cement production.

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[12] see http://www.ghgprotocol.org/calculation-tools/cement-sector for the clinker based tool suitable when the amount of clinker consumed is known. We also recall that only direct emissions have been considered in this work.

	2005		2006		2007		2008	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Capacity (Ml t)	139.74	320.05	170.75	437.79	169.94	430.95	169.52	424.16
Energy (TWh)	89.17	273.83	98.96	312.62	99.33	310.03	95.30	294.43
Labour (x1000)	77.64	297.01	89.10	347.41	97.02	381.06	99.73	392.24
Materials (Ml t)	178.24	502.92	200.58	586.21	214.34	637.25	213.71	636.01
Clinker	63.42	176.74	70.67	204.15	74.67	217.90	71.21	205.11
Import clinker	0.70	1.71	1.03	2.12	0.98	2.34	0.62	1.21
Raw materials	114.12	324.43	128.88	379.91	138.68	417.01	141.88	429.68
Cement (Ml t)	79.68	222.05	89.91	260.04	96.54	285.40	97.92	294.14
CO2 (Ml t)	68.13	205.65	76.32	237.12	79.88	251.35	80.23	254.60
Ratio	**Ratio**		**Ratio**		**Ratio**		**Ratio**	
Clinker/Cement	0.7959		0.7859		0.7735		0.7272	
Energy/Cement	1.1191		1.1006		1.0289		0.9733	
CO2/Cement	0.8550		0.8488		0.8275		0.8194	

Table 1: Cross Sectional Mean and Standard Deviation of the variables and relevant ratios.

The time-varying analysis of mean values in Table 1 shows that the worldwide cement production has grown since 2005 with a peak value in 2007 and a stable situation in 2008. This growth can be mainly ascribed to Turkey and non-OECD countries that are developing their economies with relatively lenient environmental limits. Moreover, looking at the cement and the clinker mean values over years, one can see a progressive reduction of the average clinker to cement ratio that from 0.79 in 2005 drops to 0.72 in 2008. This is due to major use of alternative raw materials in the clinker production process and to the increasing production of blended cement, especially in developing countries, which requires a lower proportion of clinker. A similar behavior can be found in energy consumption where the increasing use of alternative fuels, like waste or biomass justifies the corresponding decreasing of the energy/cement ratio. The combination of these two effects leads to a reduction of CO_2 emission over time.

Since the aim of this work is evaluate the eco-efficiency of different countries, all input and output are divided by the total number of plants for each country in order to evaluate the eco-efficiency of a representative plant within each country (a similar approach can be found in Mandal [19], Mandal and Madheswaran [20], Mukherjee [21]).

4 Empirical Results

The three DEA models and the directional distance function described in Section 3 have been implemented in MatLab 2010a in order to capture the various measures of eco-efficiency in the cement industry. To avoid imbalances caused by different magnitudes, input and output parameters are normalized with respect to their mean value (see Table 1). We recall that the study of eco-efficiency using Model $P1$-$D1$ gives information on eco-efficiency measured by both input and CO_2 contraction; the analysis is then deepened on by separately measuring the impact of pollutant contraction (as resulting from Model $P2$-$D2$) and the impact of good inputs contraction, namely capacity, energy, labour and materials (Model $P3$-$D3$). The directional distance approach (Model $P4$) is also tested in order to verify the possibility of expanding desirable output while reducing the undesirable one.

Finally, in order to point out the impact of the regulation, all the models have been tested under both strong and weak disposability assumption. Notice that, as pointed out in Section 2.1.2, Model $P2$-$D2$, under both strong and weak disposability assumption, gives the same optimal efficiency scores when a single undesirable factor is used.

The methodology used to evaluate these eco-efficiency measures is based on a sequential frontier approach. This way we avoid the possibility of "technical regress", since sequential frontier assumes all current and past observations as feasible. Starting then with a reference sample of 21 observations for the year 2005, we successively accumulate the observations of one more year to create the frontier of each subsequent period.

The results of our tests are reported in Tables 2, 3, 4 and 5.

4.1 Eco-efficiency measure as input and pollutant contraction

Table 2 presents the results of model P1-D1 measuring eco-efficiency in the sense of input and pollutant reduction. We consider both weak and strong disposability assumptions. Strong disposability assumption corresponds to a situation where undesirable outputs are freely disposable and a reduction in emission factors do not produce a corresponding contraction in good outputs. Under weak disposability assumption, undesirable factors reduction can not be possible without assuming a certain loss in terms of good output production (for instance a regulation that could imply an emission control).

The mean value of the world eco-efficiency in the cement sector under the hypothesis of strong and weak disposability are 0.91358 and 0.93458 respectively. This means that inputs utilization and emission factor can still be reduced by a proportion of 8.6% in the case of strong disposability assumption and of 9.3% in the case of weak disposability one. It is well known, in fact, that the efficiency levels under the weak disposability assumption are higher than the ones obtained using the strong disposability hypothesis. The difference in eco-efficiency between the strong and weak models is equal to 2%. This means that without regulation an additional contraction of 2% of input factors (good input and pollutant) can be reached without reducing the corresponding good output. A Wilcoxon signed rank test has been used to compare the eco-efficiency mean results under these two hypothesis. This methodology is a non parametric test that is used to verify the hypothesis of no difference between the eco-efficiency scored obtained under the strong disposability assumption and the eco-efficiency scored obtained under the weak disposability one. The test is carried out with R software. The value of Wilcoxon statistic is 3.52 with a two tailed p-value equal to 0.00015. The hypothesis of no difference among efficiency scores under strong and weak disposability assumption can be rejected at 1% confidence level, namely the assumption of weak or strong disposability significantly influences the efficiency measure.

Looking at the annual means, a progressive decrease in eco-efficiency is measured n the case of strong disposability. Countries without strong or mandatory environmental regulation (like USA, Turkey, Brazil, Canada) are the worst performing during the considered period with a negative trend except China and India which will be analyzed more in detail in the followings. European countries under the EU-ETS regulation, maintain an average efficiency level almost constant during the four years. The best performing countries are China, Denmark, India, Japan and Switzerland and other five countries have an eco-efficiency value greater than 96% (Austria, Belgium, Canada, Italy, Spain).

Considering the European countries, Switzerland efficiency can be addicted to a massive use of alternative fuels that, on average, amounts to 45% of total fuel consumption and of alternative raw material. The combination of these policies leads to a lower emission factor per ton of cement produced. Denmark makes significant investments in environmental improvements and energy optimization in the period 2005-2008, which lead to a progressive decrease of the CO_2 emission factor and energy utilization (see Aalborg Portland Environmental Report 2009).

Japanese Cement Industry is involved in the Voluntary Emissions Trading Scheme since 2005 (see Appendix A for details on countries environmental regulation). The technology used is dry in the 90% of plants since 2000 and a progressive substitution of traditional fuels with alternative ones is operated as reported by the Japan Cement Association. In addition, the proportion of alternative raw materials in the cement production has constantly increased.

Among the remaining efficient countries, India performs well because of the progressive abandon of wet technologies in favour of less energy expensive dry processes based on five and six stages preheating and pre-calcination kilns. Note also that main Indian companies agree with the Cement Sustainability Initiative (CSI) launched by the World Business Council for Sustainable Development (WBCSD).

The case of China cement industry is more controversial. On one hand, the recent fast development of Chinese economy, has led to huge investments in new plants with the best available technologies and on the opposite to focus industry production on low quality cement which requires a lower amount of clinker than portland cement and reduces energy consumption. For these reasons, the emission factor that is ratio between CO_2 emission and cement production is one of the best performing among the considered countries. On the other hand, the analysis of Chinese cement sector suffers for the difficulties of data finding. Only 5% of Chinese Cement companies agrees with the CSI of WBCSD and data available on National Cement Association only refer to the larger operating companies. It is very difficult to have the exact outlook of the sector, so our results may be affected by data uncertainty.

Table 2: Eco-efficiency measure as input and pollutant contraction

Country	**2005**		**2006**		**2007**		**2008**		**Mean**	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
Australia	1	1	0.82478	0.82554	0.83482	0.83482	0.84703	0.84703	0.87666	0.87685
Austria	1	1	0.93766	0.95959	0.96267	0.99578	0.97907	1	0.96985	0.98884
Belgium	1	1	1	1	0.96747	0.98484	0.97881	0.97881	0.98657	0.99091
Brazil	0.88562	0.88562	0.83374	0.83374	0.82356	0.82356	0.82694	0.82694	0.84247	0.84247
Canada	0.99654	1	1	1	0.98914	0.9915	0.93381	0.93501	0.97987	0.98163
China	1	1	1	1	1	1	1	1	1	1
Czech Republic	1	1	0.84239	0.84239	0.86684	0.90213	0.87742	0.88935	0.89666	0.90847
Denmark	1	1	1	1	1	1	0.97882	0.98152	0.99471	0.99538
Estonia	0.82765	1	0.85362	1	0.7624	1	0.65617	1	0.77496	1
France	0.918	0.918	0.8896	0.8896	0.88939	0.88939	0.88509	0.88509	0.89552	0.89552
Germany	0.8887	0.8887	0.88121	0.88121	0.8606	0.86077	0.86754	0.86754	0.87451	0.87456
India	1	1	1	1	1	1	0.98695	1	0.99674	1
Italy	1	1	1	1	0.9923	0.99669	0.95976	0.96175	0.98802	0.98961
Japan	1	1	0.99611	0.99645	1	1	0.97442	0.97725	0.99263	0.99343
Norway	0.85751	0.87328	0.81787	0.83404	0.85053	0.86664	0.86139	0.87147	0.84683	0.86136
Poland	0.85297	0.85297	0.74777	0.80857	0.7489	0.82494	0.81705	0.81871	0.79167	0.82630
Spain	1	1	1	1	1	1	0.94827	0.94827	0.98707	0.98707
Switzerland	1	1	1	1	0.99965	0.99965	1	1	0.99991	0.99991
Turkey	0.80229	0.84793	0.78781	0.82635	0.7701	0.7701	0.75885	0.75885	0.77976	0.80081
U.S.A	0.9169	1	0.88714	0.96493	0.88856	0.96407	0.85515	0.90059	0.88694	0.95740
United Kingdom	0.86022	0.87471	0.82553	0.84497	0.8322	0.8475	0.77723	0.85536	0.82380	0.85564
Mean	0.94316	0.95911	0.91073	0.92892	0.90663	0.93107	0.89380	0.91922	0.91358	0.93458
Improvement	0.01594		0.01820		0.02444		0.02542		0.0210	

4.2 Eco-efficiency measure as pollutant contraction

In the previous section, cement industries can improve their efficiency by either moderating the use of traditional inputs (fuel and raw materials) or minimizing their CO_2 emission level. With model P2-D2, eco-efficiency is measured in terms of pollutant contraction only and results are collected in Table 3. In this case the means of eco-efficiency taken by year are lower and vary between 0.69 (in 2005) and 0.60 (in 2008). This implies that focusing on emission only there are large possibilities to improve the current status of cement technologies in the different countries.

Considering eco-efficiency mean values by country, Table 3 shows that China, India, Japan, Denmark and Switzerland remain the most efficient countries, followed by Spain, Italy and Belgium with an efficiency rate greater than 90%. This confirms the results of the previous eco-efficiency analysis. In particular, the Italian and Spanish cement industries show a similar behavior. In the period 2005-2007 that coincides with the first phase of the EU-ETS, their efficiency levels are equal or slightly lower than one, but these fall in 2008 with the inception of the second and more stringent EU-ETS phase. Belgium apart from 2007, is efficient. This is the results of its effort in progressively reducing CO_2 emission and in improving energy efficiency since 2005.[13]

Table 3: Eco-efficiency measure as pollutant contraction

Country	**2005**	**2006**	**2007**	**2008**	**Mean**
Australia	1	0.33302	0.40802	0.46142	0.55062
Austria	1	0.56387	0.61639	0.72356	0.72596
Belgium	1	1	0.8761	0.92221	0.94958
Brazil	0.31298	0.3277	0.38556	0.53459	0.39021
Canada	0.72471	1	0.86006	0.57942	0.79105
China	1	1	1	1	1.00000
Czech Republic	1	0.26051	0.29932	0.33776	0.47440
Denmark	1	1	1	0.95593	0.98898
Estonia	0.15611	0.28768	0.30787	0.14854	0.22505
France	0.45618	0.26915	0.26384	0.28034	0.31738
Germany	0.23397	0.37931	0.38406	0.41761	0.35374
India	1	1	1	0.90682	0.97671
Italy	1	1	0.96277	0.8378	0.95014
Japan	1	0.99344	1	0.96423	0.98942
Norway	0.20207	0.1936	0.31251	0.28671	0.24872
Poland	0.59322	0.44637	0.55098	0.80581	0.59910
Spain	1	1	1	0.67496	0.91874
Switzerland	1	1	0.98755	1	0.99689
Turkey	0.37663	0.46219	0.5165	0.55245	0.47694
USA	0.24495	0.19857	0.1713	0.19025	0.20127
United Kingdom	0.20817	0.2036	0.23474	0.19657	0.21077
Mean	0.69090	0.61519	0.62560	0.60843	0.63503

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[13] See the IEE (*indice d'amélioration de l'efficience énergétique*) and IGES (*indice de rèduction des èmissions de* CO_2 *ènergètique (combustibles)*) indices in the Report Febelcem 2009 at page 20, available at `http://www.febelcem.be/index.php?id=rapports-annuels`.

4.3 Eco-efficiency as input contraction

In the P3-D3 DEA approach introduced in Section 2.2.1, we measure eco-efficiency as the ability of cement industries to reduce input factors (traditional raw materials and fuels) without increase of CO_2 emissions or cement production curtailment. Traditional raw material can be reduced by substituting them with alternative materials in the cement production process. This implies a reduction of the clinker to cement ratio. Results of this model are reported in Table 4. The mean eco-efficiency levels are equal to 0.91342 in the case of strong disposability assumption and 0.95240 in the case of weak disposability assumption. When emission factors are freely disposable, a 3.8% additional input contraction can be obtained without reducing the corresponding outputs. The eco-efficiency mean values significantly differ by comparing the results under these two assumptions. The value of Wilcoxon statistic, in facts, is equal to 3.92 with a two tailed p-value equal to 0.000096. The hypothesis of no difference among efficiency scores under strong and weak disposability assumption can, then, be rejected at a confidence level of 1%.

In the case of strong disposability assumption, eco-efficiency mean levels are in line with those of Table 2. China, India, Japan, Denmark and Switzerland remain the top five in terms of efficiency and Austria, Belgium, Canada, Italy and Spain reach an efficiency level greater than 98%. By comparing the results of Tables 2, 3 and 4, we can argue that Austria and Canada's efficiency levels reported in Table 2 are mainly related to the utilization of alternative raw materials since the eco-efficiency levels based on emission contraction only (Table 3) are significantly lower. As concerning Spanish cement industry, it has doubled the utilization of alternative fuels and raw materials in the last decades. In 2008, in facts, alternative fuels accounted for the 15% of the total, while alternative raw materials were the 10% of total use. This environmental policy has reflection on both eco-efficiency measures provided in Tables 3 and 4. A similar reasoning can be applied to Belgium and Italy, as pointed out in the previous model discussion.

Table 4: Eco-efficiency as input contraction

Country	**2005**		**2006**		**2007**		**2008**		**Mean**	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
Australia	1	1	0.82478	0.82829	0.83463	0.83546	0.84389	0.98398	0.87583	0.91193
Austria	1	1	0.96449	0.96449	1	1	0.97907	1	0.98589	0.99112
Belgium	1	1	1	1	0.96747	0.96803	0.97095	1	0.984605	0.992008
Brazil	0.87641	0.89829	0.82956	0.83939	0.82303	0.82303	0.826	0.94549	0.83875	0.87655
Canada	0.99654	1	1	1	0.99617	0.99617	0.93381	1	0.98163	0.99904
China	1	1	1	1	1	1	1	1	1	1
Czech Republic	1	1	0.84111	0.84111	0.86705	0.86705	0.87742	0.98347	0.89639	0.92291
Denmark	1	1	1	1	1	1	0.97882	1	0.99471	1
Estonia	0.82765	1	0.85362	0.97389	0.7624	1	0.65617	1	0.77496	0.99347
France	0.91359	0.92332	0.89679	0.89679	0.9048	0.9048	0.88217	0.99852	0.89934	0.93086
Germany	0.88137	0.89653	0.87763	0.87763	0.8645	0.8645	0.86288	0.95544	0.87159	0.89853
India	1	1	1	1	1	1	0.98695	1	0.99674	1
Italy	1	1	1	1	1	1	0.95976	1	0.98994	1
Japan	1	1	1	1	1	1	0.97442	1	0.99361	1
Norway	0.85751	0.9113	0.81787	0.83015	0.85053	0.85188	0.86139	0.98102	0.84683	0.89359
Poland	0.84992	0.9139	0.74777	0.84933	0.7489	0.83451	0.81705	0.96038	0.79091	0.88953
Spain	1	1	1	1	1	1	0.94795	1	0.98699	1
Switzerland	1	1	1	1	1	1	0.9304	0.93147	0.9826	0.98287
Turkey	0.80229	0.92308	0.78781	0.84155	0.7701	0.78395	0.75867	0.91883	0.77972	0.86685
U.S.A	0.9169	1	0.88714	0.92442	0.88856	0.89547	0.85515	1	0.88694	0.95497
United Kingdom	0.86022	0.90948	0.82553	0.84786	0.83227	0.83227	0.77723	0.99537	0.82381	0.89624
Mean	0.94202	0.97029	0.9121	0.92928	0.91002	0.92653	0.88953.	0.98352	0.91342	0.95240
Improvement	0.02826		0.01718		0.01651		0.09399		0.03899	

4.4 Eco-efficiency as undesirable output contraction and desirable output expansion

The results of models P1-D1 and P2-D2 respectively presented in Section 4.1 and 4.2 are based on the assumption that undesirable factors (CO_2 emissions) are threated as an input of the production process and the eco-efficiency measures evaluate the reduction of CO_2 emissions without changing the desirable output levels (cement production). The Directional distance function approach (model P4) whose results are presented in Table 5 of this section provides an alternative eco-efficiency measure. It allows to measure the potential reduction of the undesirable emission output and the potential expansion of the desirable output. We consider both weak and strong disposability assumptions. Strong disposability corresponds to a situation where good outputs can be arbitrary expanded, while the weak disposability assumption limits their expansion according to a certain regulation (that could imply an emission control). The difference between efficiency levels under weak and strong disposability in the directional distance approach can be interpreted as the cost of regulation with respect to the emission factors (see [20]) that we denote as "Normative Price" in Table 5.

In Table 5, the mean eco-efficiency under the hypothesis of strong disposability is equal 0.09983 that is to say that desirable output could be still increased by an amount of about 10%.. In the case of weak disposability assumption, this percentage amounts to 9%. This means that in presence of normative constraints cement industries have a more limited production expansion capability. Both in the cases of weak and strong disposability assumptions, eco-efficiency slightly decreases over time. Considering the mean eco-efficiency levels in 2008, the values of strong and weak disposability approaches are really close values, while in 2005-2007 their discrepancy is more evident. This results can be justified as follows. In 2008, only in India there is a significant difference between strong and weak disposability eco-efficiencies, while in the other countries the two directional distance function approaches give identical results. This can explained by the fact that the cement market (apart from developing countries, especially India whose consumption level increased of 7.5% in 2008 with respect to the previous year) was suffering from a decrease of cement consumption due to the global financial crisis. However, globally considered, the differences in eco-efficiency measures under the hypothesis of weak and strong disposability assumptions are not statistically significant according to this model formulation (Wilcoxon test statistics equal to 1.83). The not so obvious difference between weak and strong disposability assumptions in the Direction Distance formulation, which may be starring as cost of regulation was almost nil. This can be attributed to the effects of existing environmental regulations during the period 2005-2008, adopted in order to reduce greenhouse gas emissions through the abatement of old technologies and investment in more efficiency ones. As concerning the most efficient countries, Belgium reaches eco-efficiency levels comparable to the top five countries which in all models results to be the most efficient ones, namely China, Denmark, India, Japan and Switzerland. Apart from these countries that confirm their global efficiency in all four considered models, Austria, in Model P4, loses the efficiency presented in Models P1-D1 and P3-D3. A deeper analysis of the cement industries operating in this country reveals that CO_2 emissions rate (CO_2/cement) is higher with respect to national average in 2006 and 2007. This is strictly related to the increase of the clinker to cement ratio in the same years (see the references for Austria in Appendix B). Spanish, Italian and Canadian cement industries confirm the results of the previous models.

Table 5: Eco-efficiency as undesirable output contraction and desirable output expansion

Country	**2005**		**2006**		**2007**		**2008**		**Mean**	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
Australia	0	0	0.20043	0.20043	0.18364	0.18364	0.16194	0.16194	0.13650	0.13650
Austria	0	0	0.21615	0.21615	0.14425	0.14425	0.10284	0.10284	0.11581	0.11581
Belgium	0	0	0	0	0.02746	0.02741	0.00857	0.00857	0.00901	0.00900
Brazil	0.12000	0.12000	0.17361	0.17361	0.18885	0.18885	0.18107	0.18107	0.16588	0.16588
Canada	0.00471	0	0	0	0.01145	0.01145	0.08243	0.08243	0.02465	0.02347
China	0	0	0	0	0	0	0	0	0	0
Czech Republic	0	0	0.16462	0.16462	0.15227	0.15227	0.13286	0.13286	0.11244	0.11244
Denmark	0	0	0	0	0	0	0.01315	0.01315	0.00329	0.00329
Estonia	0.21799	0	0.18071	0	0.21929	0	0.39763	0.39763	0.25391	0.09941
France	0.11212	0.11212	0.16398	0.16398	0.17336	0.17336	0.16619	0.16619	0.15391	0.15391
Germany	0.11468	0.11468	0.12500	0.12500	0.15117	0.15117	0.13200	0.13200	0.13071	0.13071
India	0	0	0	0	0	0	0.01560	0	0.00390	0
Italy	0	0	0	0	0.00861	0.00828	0.04127	0.04169	0.01247	0.01249
Japan	0	0	0.00241	0.00241	0	0	0.01344	0.01344	0.00396	0.00396
Norway	0.15773	0.15773	0.23148	0.23148	0.21332	0.21332	0.18372	0.18372	0.19656	0.19656
Poland	0.14250	0.14250	0.24280	0.24280	0.19207	0.19207	0.06618	0.06618	0.16089	0.16089
Spain	0	0	0	0	0	0	0.05349	0.05349	0.01337	0.01337
Switzerland	0	0	0	0	0.00051	0.00051	0	0	0.00013	0.00013
Turkey	0.23533	0.23533	0.22851	0.22851	0.20310	0.20310	0.18780	0.18780	0.21369	0.21369
USA	0.12461	0	0.18233	0.14516	0.18405	0.14510	0.24317	0.24317	0.18354	0.13336
United Kingdom	0.15262	0.15262	0.19205	0.19205	0.18757	0.18757	0.27518	0.27518	0.20186	0.20186
Mean	0.06582	0.04928	0.10972	0.09934	0.10671	0.09440	0.11707	0.11635	0.09983	0.08984
Normative Price	0.01654		0.01038		0.01232		0.00072		0.00999	

5 Conclusions

In this paper, we present a cross-country comparison of the *eco-efficiency* level of the worldwide cement industry. By adopting a Data Envelopment Analysis (DEA) approach, this paper makes an attempt to evaluate the impact of environmental regulations on cement industry efficiency by considering a joint production framework of both desirable and undesirable output. This work differs from literature since it compares twenty-one countries covering the 90% of the world cement production. Traditional industrialized countries are compared with emerging producers like India and China.

With *eco-efficiency*, we indicate the possibility of producing goods (or services) by reducing the quantity of energy and resources employed and/or the amount of waste and emissions generated. More specifically, four measures of eco-efficiency have been estimated. The first two measures consider pollutants (CO_2 emissions in our case) as an input of the production process. In the first DEA model (Model $P1$-$D1$) eco-efficiency is measured as the ability to reduce at the same time CO_2 emissions and inputs. According to this model formulation, the cement DMUs eco-efficiency can be interpreted as the capability to reduce undesirable outputs by introducing more efficient technologies and to reduce inputs by substituting them with alternative raw materials while maintaining the same outputs levels. The second eco-efficiency measure (as estimated in Model $P2$-$D2$) focus the attention on just good input contraction maintaining the same CO_2 emission levels and good output volumes.

In the third and fourth eco-efficiency measures, provided in this paper, carbon dioxide emissions are treated as undesirable output. Model $P3$-$D3$ measures eco-efficiency as the ability to reduce pollutants while keeping the same inputs and desirable outputs levels. The eco-efficiency measures provided by models $P1$-$D1$, $P2$-$D2$ and $P3$-$D3$ permit to deeply analyze the ability of the world cement to increase its efficiency by substituting traditional raw materials and traditional fuels with alternative ones in order to reduce CO_2 emissions without reducing the cement production. Moreover, a directional distance function approach (Model $P4$) has been estimated in order to evaluate the ability of a country to simultaneously expand the desirable output and contract the CO_2 emissions by the same proportion without increasing the inputs.

Finally, in order to point out the impact of environmental regulations, Models $P1$-$D1$, $P3$-$D3$ and $P4$ have been tested under strong and weak disposability assumptions.

Countries without strong or mandatory environmental regulation (like USA, Turkey, Brazil, Canada) are the worst performing during the considered period with a negative trend except for China and India. European countries under the EU-ETS regulation, maintain an efficiency level almost constant during the four years. The analysis has shown that the efficiency level mainly depends on decisions to invest in alternative raw materials and alternative fuels both in the case of regulated countries and in the case of voluntary emission trading schemes.

Emerging countries that are increasing their cement production in recent years, like China and India, show high efficiency levels. This feature can be addicted to two different factors: investments in more efficient technologies (progressive substitution of small wet process plants with bigger and dry technology ones) and the production of low quality cements which require less proportion of clinker, the main responsible for CO_2 emissions.

In particular India performs well because of the progressive abandon of wet technologies in favour of less energy expensive dry processes based on five and six stages pre-heatering and pre-calcination kilns. Note also that main Indian companies agree with the Cement Sustainability Initiative (CSI) launched by the World Business Council for Sustainable Development (WBCSD).

The case of China cement industry, however, should be read with particular attention: the partial availability of data (mainly concerning big plants with efficient technology processes) may have affected the analysis. In addition, the construction of CO_2 emissions indirectly may not be a true representation of actual CO_2 emission.

The comparison among the twenty-one world cement producing countries with different choices in terms of environmental regulations in addition to the use of several DEA models and a directional distance function approach provide a comprehensive outlook on the world cement industry efficiency. This study highlights, both at world level and at country one, the possibility of reducing CO_2 emissions and to expand cement production. The use of alternative raw materials, alternative fuels and the possibility of producing blended cements which require less energy consumption and reduce pollutants emissions seems to be the right way. In this light, environmental regulations can provide incentives in terms of tax exemption benefits or more restrictive pollutant limits.

Further developments are in the direction of enlarging the actual dataset by raising the number of DMUs considered in order to increase the discrimination power of the DEA models and to modify the input and output data of the instances. In this light, a further analysis will consider more than one undesirable factor. In recent years, in facts, environmental regulations have been extended to a wider class of greenhouse gases, like NO_x, SO_2 emissions.

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A Voluntary Emission Trading Schemes and other emission regulations

Voluntary emission regulation systems apply in some of the countries included in our study. In Europe, a voluntary emission trading scheme is applied in Switzerland. This system entered in force in January 2008 after the approval of the Swiss Parliament and the Federal Government on 2007. It is voluntary, but becomes legally binding once accepted. As the current EU-ETS program, the Swiss ETS covers the CO_2 emissions generated by heating process and energy intensive industries such as cement, paper and pulp, glass and ceramics sectors during the 2008-2012 period. Allowance are freely allocated taking into account emission reduction potential of each company[14].

In Japan, a voluntary emission trading scheme has been introduced in 2005 to cover CO_2 emissions (see [25]). This is organized as follows: the Japanese Ministry of the Environment distributes allowances to all companies participating to this project and concede subsidies for investments in new technologies. On the other side, each company has to accomplish a specific target by the end of each period (that has a duration of about one year). The sectors involved in the Japanese ETS are: industries (steel, chemicals, paper, cement, glass, automobiles and other manufacturing), energy conservation (power generation, oil refining), business (corporations and banks) and transportation (aviation and freight) (see [32]).

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[14] See [25] and `http://www.bafu.admin.ch/emissionshandel/05538/05540/index.html?lang=en` for more details.

In the USA, some States (including Canadian ones) participate to the Western Climate Initiative[15] and to the Regional Greenhouse Gas Initiative[16] on a voluntary base and only California regulates emissions thanks to the "Global Warning Solution Act" (or AB 32), signed into law on September 27, 2006. This prográm will take effect by 2012[17] and covers six in-state greenhouse gases emissions[18] generated by several industrial sector. It aims at reducing by 25% the emission level compared to the business-as-usual by 2020.

Another example of emission regulation is the the Alberta's Climate Change and Emission Management Act applied in Canada. Starting from July 2007, the Canadian facilities in the Alberta region, whose greenhouse emissions are equivalent or higher than 100,000 tons, are subject to this regulation (see [25]). Differently from the EU-ETS, the Alberta's Act uses an emission intensity approach[19]. This system forces the involved facilities to improve their performance either by reducing their greenhouse gases emissions or by buying credits from the Climate Change and Emission Management Fund at a price of 15 Canadian dollars per each ton of reduced emission. Parallel to this system, in 2006, the Canadian government issued a regulatory framework for industrial greenhouse gas emissions that sets the basis for an emission trading scheme[20]. This scheme covers several sectors (power generation, oil and gas, pulp and paper, iron and steel, smelting and refining of metals, cement, lime, potash, and chemicals and fertilizers) and should have been entered in force this year[21]. As the Alberta's Act, the Canadian ETS aims at reducing the carbon intensity of industrial activities using specific intensity-based targets per each sector[22]. This should globally induce to an absolute emission reduction of 20% compared to 2006 levels by 2020. This emission cut should reach the 50%-60% by 2050.

Finally, not all announced programs have a positive outcome. This is the case of the Australian ETS program. Even though Australia is one of the highest CO_2 emitters among the developed countries, the proposal for an emission trading scheme advanced by the Prime Minister Kevin Rudd has been blocked in Senate[23]. It has been shelved at least until 2013 since the government prefers waiting for the expiration of the Kyoto Protocol, before imposing an emission regulatory program. The proposed ETS had the intent to reduce CO_2 emission by 25% with respect to 2000 levels by 2020.

B Sources of Database

In this appendix, the main web sources for our database construction are collected. These are provided by country and general information on the cement industry are also indicated.

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[15] See `http://www.westernclimateinitiative.org/`

[16] See `http://www.rggi.org/home`

[17] `http://arb.ca.gov/cc/ab32/ab32.htm`

[18] Those that are also covered by the Kyoto Protocol.

[19] The emission intensity measures the amount greenhouse gases generated per unit of economic output.

[20] Available at`http://www.ec.gc.ca/doc/virage-corner/2008-03/pdf/COM-541_Framework.pdf`

[21] Both in [25] and `http://www.ec.gc.ca/doc/virage-corner/2008-03/pdf/COM-541_Framework.pdf`, 2010 has been indicated as the year of inception of this system, but we have not found any document announcing the its launch.

[22] See `http://www.aph.gov.au/library/pubs/climatechange/governance/foreign/canadian.htm`

[23] See `http://news.bbc.co.uk/2/hi/asia-pacific/8645767.stm` and `http://www.rsc.org/chemistryworld/News/2010/April/29041002.asp`

Cement Industry

The European Cement Association (CEMBUREAU) `http://www.cembureau.be/`

World Business Council for Sustainable Development (WBCSD). *Cement Sustainability Initiative (CSI)* `http://www.wbcsdcement.org/`

United Nations Commodity Trade Statistics Database (UN Comtrade).
`http://comtrade.un.org/db/default.aspx`

Eurostat Database.
`http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home`

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`http://www.oecd.org/document/34/0,3343,en 2649 39023495 40917154 1 1 1 1,00.html`

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Czech Republic

Data and several publications are available at `http://www.svcement.cz/`

Denmark

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Japan

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Norway

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Anno: **1989**

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Anno: **1991**

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Anno: **1992**

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Elenco dei report pubblicati

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Anno: **1993**

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Anno: **1994**

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Anno: **1996**

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Elenco dei report pubblicati

☐**n. 110** Luciano Fanti - Piero Manfredi, Un modello "classico" di ciclo con crescita ed offerta di lavoro endogena.
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Anno: **1997**

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Anno: **1998**

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Anno: **1999**

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Anno: **2000**

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Anno: **2001**

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Elenco dei report pubblicati

☐n. 215 Michele Longo - Vincenzo Valori, Existence end stability of equilibria in OLG models under adaptive expectations.
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☐n. 219 Laura Lecchini - Odo Barsotti, Les disparités territoriales au Maroc au travers d'une optique de genre.

Anno: **2002**

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Anno: **2003**

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Anno: **2004**

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Elenco dei report pubblicati

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principali definizionl, proprietà
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Anno: **20100**

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