# The cement industry: eco-efficiency country comparison using Data Envelopment Analysis

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## Abstract

Cement industry is an high energy intensive industrial sector. Coal combustion and calcination of limestone and magnesium carbonate in kilns, in the clinker sub-process, generate considerable amount of carbon dioxide emissions. In recent years, environmental regulations have been introduced in order to monitor $CO_2$ emissions in the industrial sectors. The European Emission Trading Scheme (EU-ETS) is the widest cap and trade system in the world. Other emission trading schemes have been also applied in other countries. All these programs cover several sectors and cement industry is one of them. In this paper, we analyze the environmental performance of cement industry of 21 worldwide countries within a production framework of both desirable and undesirable outputs. Three DEA models with undesirable outputs and a directional distance function approach are compared in order to capture the different environmental performances of the cement industry operating in these countries. We take as measures the desirable output expansion and the inputs or undesirable outputs reduction. The analysis is carried out for the years 2005-2008, pointing out the changes in efficiency levels within these years and the regulation effects on global performances.

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

## 1 Introduction

Used in building and in civil engineering constructions, cement is at the basis of the economic development of a country. Starting from a level of 594 million tons in 1970, the worldwide production of cement is quadruplicated in twenty-five years, reaching an amount of 2,284 million tons in 2005 (see [23]). In 2009, the worldwide production of cement has been of 3 million tons (see Cembureau [4]). This significant growth can be mainly traced back to developing countries, such as China and India, and to the U.S.A., Japan and Turkey. In Europe, Italy, Germany, Spain, France, UK and Poland are the major cement producers.

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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 40% of the total production costs of 1 ton of cement (see [9]).

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. In all these processes, cement production starts with the extraction of specific raw materials from quarries, continues with their grinding and the intermediate production of clinker and finally concludes with the grinding of clinker with additives. Depending on the type of cement produced, the required proportions of clinker and other materials (especially limestone) change. One ton of cement is typically composed for the 80% of clinker and for the remaining 20% of other materials (see [18])[2]. In recent years, companies operating in countries with a scarce availability of natural sources have introduced the production of Blended cement as a substitute for the most common Portland cement. Blended cement, produced only with rotary kilns, requires a lower portion of limestone that is replaced with other materials. It is currently produced in France, Germany, Japan, India and other countries[3]. From an environmental point of view, cement production releases to air nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$) and carbon dioxide ($CO_2$).

Clinker production is the most energy and ($NO_x$, $SO_2$, $CO_2$) emission intensive among all these sub-phases. This is due to the process applied to its production. The production of 1 ton of clinker requires, on average, 1.52 ton of raw materials (see [9]). In particular, clinker is produced by burning a mixture of mainly limestone, silicon oxides, aluminum oxides and iron oxides in kilns that differs according to the process adopted at a temperature of about 1,450 Celsius degrees. This burning process is responsible for emissions. The chemical reactions needed for transforming this raw material mixture into clinker require a huge quantity of thermal energy. Thermal energy is usually produced by burning the highly emitting coal and pet-coke in the kilns, even though less emitting alternative fuels, like biomass, are now available (see [5] for a complete list). Rotary kilns with 5 or 6 suspension preheaters and precalciners are the most advanced technology available for clinker production. They are usually adopted in the (semi-)dry processes. For the dry process rotary kiln equipped with cyclone preheaters, the thermal energy required amounts to 3,100-4,200 MJ/ton clinker (see [9]). While thermal energy is essential in clinker production, electricity is employed in grinding sub-phases. Raw material and cement grinding mills consume more than 80% of the total electrical energy usage.

The aim of this paper consists in studying the efficiency levels of cement industries operating in different world countries through a Data Envelopment Analysis (DEA) approach. In particular, we intend to measure the environmental performance of cement producers both in terms of $CO_2$ emissions and of utilization of alternative fuels and alternative raw materials. Recently, the new class of DEA models with undesirable outputs has been developed. In literature, many approaches have been proposed to solve this new kind of DEA problems. To the best of our knowledge, few papers treat undesirable outputs of cement sector as a DEA model and in all of them only interstate analyzes have been developed (see [2], [16] and [21]). In this paper, we depart from this assumption

[1] See http://www.cembureau.be/about-cement/cement-industry-main-characteristics
[2] For more details see [9].
[3] See ABS Blended Cement. Presentation available at: http://cementconsultant.org/Abs.ppt

and we introduce a country-based study for the cement industry. In particular, we evaluate the efficiency level of 21 countries in terms of cement production. This quite large set of countries includes the major cement producer European States, Canada, the U.S.A., Australia and developing countries such as China, India and Brazil. Taking $CO_2$ emissions as undesirable outputs, we compare four DEA models providing different efficiency information, but all accounting for identical inputs and outputs. This allows us to identify the cause of the cement production efficiency/inefficiency in the countries considered.

Our analysis shows that efficiency levels is affected by the tendency of the different countries to invest in technologically advanced kilns and to adopt alternative fuels and alternative raw materials in the cement production process. Surprisingly, emerging countries, like India and China that are the largest cement producers in the world, appear efficient. In fact, as we will explain in the following, the recent economic boom of these two countries has forced their cement companies to invest in the most advanced technologies.

The remainder of the paper is organized as follows. Section 2 gives an overview of the environmental regulations applied in Europe and outside of Europe. Section 3 presents the developed models, while Sections 4 and 5 respectively illustrate the dataset used in our simulations and the obtained results. Final remarks are reported in Section 6.

## 2 Environmental regulations

Emissions have become a problem for those cement industries that are subject to some environmental regulations. The European Emission Trading Scheme (EU-ETS) is the widest cap and trade system applied in the world. It has been introduced in Europe by Directive 2003/87/EC at the beginning of 2005 to regulate the $CO_2$ emissions generated from specific installations. The EU-ETS is organized in two phases: a first, already concluded, from 2005 to 2007 and a second that covers the period 2008-2012. It involves energy and refining, iron and steel, pulp and paper and cement sectors. The EU-ETS goal consists in reducing greenhouse gas emissions through the abatement of old technologies and the investment in more efficient ones. This Directive implies the creation of a market of emission allowances where players can buy or sell permits at a certain price defined by the market itself. Emission caps are determined according to National Allocation Plans (NAPs) that vary over countries[4]. The introduction of this environmental regulation has created some economic distortions and additional costs to the involved energy intensive industries. There is a huge literature discussing these problems, but they go beyond the scope of this paper. We just say that the new Directive 2009/29/EC, that will regulate the third EU-ETS phase (2013-2020), tries to mitigate the mistakes of the first EU-ETS Directive and to enlarge the the number of sectors and greenhouse gases subject to regulation.

In the European framework, 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. However, 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 EU-ETS starting from 2008 (see [20]).

Along with the EU-ETS, other emission regulation mechanisms have been applied. For instance,

[4]See http://ec.europa.eu/environment/climat/emission/2nd_phase_ep.htm for the National Allocation Plans of the two phases.

in Switzerland, an emission trading scheme entered in force on January 2008, after the approval of the Swiss Parliament and the Federal Government on 2007. This system is voluntary, even though becomes legally binding once accepted. The participating companies have the advantage to avoid the payment of a carbon tax. However this carbon tax is due if companies are not able to accomplish their annual target. This system 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 the company's potential emission reduction[5].

In Japan a voluntary emission trading scheme has been introduced in 2005 to cover $CO_2$ emissions (see [20]). This is organized as follows: the Japanese Ministry of the Environment allocates allowances to all companies participating to this project on a voluntary base. Moreover, they receive subsidies in case companies decide to invest in new technologies. Each company has to accomplish a specific target by the end of each period (that has a duration of about one year). To this aim, companies trade emission allowances among themselves and if they are not able to reach the target, they have to return received subsidies. Many sectors are involved in this voluntary scheme: industries (steel, chemicals, paper, cement, glass, automobiles and other manufacturing), energy conservation (power generation, oil refining), Business (corporations and banks) and finally transportation (aviation and freight) (see [24]).

After a long legislative process started in 2006, the Canadian government issued a regulatory framework for industrial greenhouse gas emissions[6] that set the basis for an emission trading scheme. 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 will enter in force this year[7]. Differently from the EU-ETS, the Canadian program is not a cap and trade scheme, but uses an emission intensity approach. Emission intensity measures the amount greenhouse gases generated per unit of economic output. The Canadian ETS aims at reducing the carbon intensity of industrial activities using specific intensity-based targets per each sector[8]. 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. We further recall that starting from July 2007, facilities in the Alberta region, whose greenhouse emissions are equivalent or higher than 100,000 tons, are subject to the Alberta's Climate Change and Emission Management Act (see [20]). Again based on emission intensity reduction, this program forces the involved facilities to either improve their performance by reducing their emissions or buy credits from the Climate Change and Emission Management Fund at a price of 15 Canadian dollars per each ton of reduced emission. However, it is not yet clear how the Canadian ETS with this regional system will be combined.

In the U.S.A., there is no a federal legislation that controls greenhouse gas emissions. Some States (including Canadian ones) participate to the Western Climate Initiative[9] and to the Regional Greenhouse Gas Initiative[10] 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 program

[5] See [20] and http://www.bafu.admin.ch/emissionshandel/05538/05540/index.html?lang=en for more details.

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

[7] See [20] and http://www.ec.gc.ca/doc/virage-corner/2008-03/pdf/COM-541_Framework.pdf

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

[9] See http://www.westernclimateinitiative.org/

[10] See http://www.rggi.org/home

will take effect by 2012[11] and covers six in-state greenhouse gases emissions[12] generated by several industrial sector. It aims at reducing by 25% the emission level compared to the business-as-usual by 2020.

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[13]. 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.

## 3 Environmental efficiency measures

Data Envelopment Analysis (DEA) 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 decision-making units (DMUs), such as firms or public sector agencies. In the classic DEA model, there are $n$ DMUs to be evaluated. Each DMU consumes various inputs to produce different outputs. No production function needs to be specified.

In the classic DEA model (see [6]), which has been given in the form of a linear fractional program, the efficiency of the $j^{th}$ DMU is defined by the ratio between the weighted sum of outputs and the weighted sum of inputs. In fact, since multiple inputs are used to produce multiple outputs then the individual inputs quantities and the individual outputs quantities need to be aggregated into a composite input and a composite output. The pioneer model (CCR) measures technical efficiency of a DMU which exhibits Constant Returns to Scale (CRS) everywhere on the production frontier. In an important extension of this approach, Banker, Charnes and Cooper [3] generalized the original DEA approach formulating a model (BCC) for exhibiting Variable Returns to Scale (VRS) at different points on the production frontier.

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 DMU, DEA classifies the remaining DMUs from the most efficient to the less one. However, both desirable (good) and undesirable (bad) output and input factors may be present. The undesirable and desirable outputs should be treated differently when we evaluate the production performance: if inefficiency exists in the production, the undesirable pollutants should be reduced to improve efficiency. However, in the standard DEA model, decreases in outputs are not allowed and only inputs are allowed to decrease. When undesirable outputs are taken into consideration, the choice between two alternative disposable technologies (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, e.g., heavy metals, $CO_2$, etc., if the undesirable outputs are freely disposable, **i.e. they do not have limits**. The case of weak disposability refers to situations when a reduction in waste or emissions forces a lower production of desirable outputs, i.e., in order to meet some pollutant

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

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

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

emission limits (regulations), reducing undesirable outputs may not be possible without assuming certain costs (see Zofío and Prieto, [25]). In order to include undesirable outputs in DEA models, different approaches have been introduced. In the next paragraphs, a brief review of existing models is presented. 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<br>$i = 1, \dots, m, \quad j = 1, \dots, n$ |
| $y^g_{rj} \in \mathbb{R}_+$: | $r^{th}$ "good" output quantity produced by the $j^{th}$ decision making unit<br>$r = 1, \dots, q, \quad j = 1, \dots, n$ |
| $y^b_{kj} \in \mathbb{R}_+$: | $k^{th}$ "bad" output quantity produced by the $j^{th}$ decision making unit<br>$k = 1, \dots, t, \quad j = 1, \dots, n$ |

**Variables:**

| | |
|---|---|
| $v_i \in \mathbb{R}_+$: | weight multipliers related to the $i^{th}$ input<br>$j = 1, \dots, n$ |
| $u_r \in \mathbb{R}_+$: | weight multipliers related to the $r^{th}$ "good" output<br>$r = 1, \dots, q$ |
| $w_k \in \mathbb{R}_+$: | weight multipliers related to the $k^{th}$ "bad" output<br>$k = 1, \dots, t$ |
| $u_0 \in \mathbb{R}$: | 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<br>$j = 1, \dots, n$ |

## 3.1 INP model: undesirable factors treated as inputs

A first class of DEA models with undesirable data suggests to include undesirable inputs as desirable outputs, or undesirable outputs as desirable inputs in the production process (see [15]). Its starting point is that efficient DMUs wish to minimize desirable inputs and undesirable outputs, and to maximize desirable outputs and undesirable inputs. If one only wishes to investigate operational efficiency from this point of view, there is no need to distinguish between inputs and outputs, but only minimum and maximum. In our perspective we focus our attention on desirable inputs and outputs and undesirable outputs only. The mathematical formulation of the model, in case of strong output disposability and input oriented DEA, is as follows:

$(P1)$

$$\max_{u,v,w,u_0} \quad \sum_{r=1}^{q} u_r y^g_{rj_0} + u_0 \tag{1}$$

$$s.t. \quad \sum_{i=1}^{m} v_i x_{ij_0} + \sum_{k=1}^{t} w_k y^b_{kj_0} = 1 \tag{2}$$

$$\sum_{r=1}^{q} u_r y^g_{rj} + u_0 - \sum_{i=1}^{m} v_i x_{ij} - \sum_{k=1}^{t} w_k y^b_{kj} \leq 0 \quad j = 1, \ldots, n \tag{3}$$

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

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

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

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

and the corresponding dual formulation is:

$(D1)$

$$\min_{\theta,\lambda} \quad \theta \tag{4}$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y^g_{rj} \geq y^g_{rj_0} \quad r = 1, \ldots, q \tag{5}$$

$$\sum_{j=1}^{n} \lambda_j y^b_{kj} \leq \theta y^b_{kj_0} \quad k = 1, \ldots, t \tag{6}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_0} \quad i = 1, \ldots, m \tag{7}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{8}$$

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

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 constraints (6) hold with equality in the corresponding dual formulation. For an exhaustive discussion on strong and weak disposability in INP models see Liu et al. [14]. The main drawback of this formulation is that if one treats the undesirable outputs as inputs, the resulting DEA model does not reflect the true production process.

### 3.2 TR$\beta$ model: a linear transformation approach

This section presents the approach proposed by of Seiford and Zhu [22]. 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. They introduced a linear transformation approach to treat undesirable factors and then incorporated transformed undesirable factors into standard BCC DEA models. For the purpose of preserving convexity relations, Seiford and Zhu [22] suggested a linear monotone decreasing transformation, $\overline{y}^b_{kj} = -y^b_{kj} + \beta_k > 0$, where $\beta$ is a proper translation vector that makes $\overline{y}^b_{kj} > 0$. Based upon the above linear transformation, the standard BCC DEA model can be modified as the following linear program:

$$
\begin{aligned}
&(P2) && \\
&\max_{u,v,w,u_0} && \sum_{r=1}^{q} u_r y^g_{rj_0} + \sum_{k=1}^{t} w_k \overline{y}^b_{kj_0} + u_0 && (9)\\
&s.t. && \sum_{i=1}^{m} v_i x_{ij_0} = 1 && (10)\\
& && \sum_{r=1}^{q} u_r y^g_{rj} + \sum_{k=1}^{t} w_k \overline{y}^b_{kj} + u_0 - \sum_{i=1}^{m} v_i x_{ij} \le 0 \quad j = 1,\dots,n && (11)\\
& && u_r \ge 0 \quad r = 1,\dots,q \\
& && w_k \ge 0 \quad k = 1,\dots,t \\
& && v_i \ge 0 \quad i = 1,\dots,m \\
& && u_0 \in \mathbb{R}
\end{aligned}
$$

$$
\begin{aligned}
&(D2) && \\
&\min_{\theta,\lambda} && \theta \\
&s.t. && \sum_{j=1}^{n} \lambda_j y^g_{rj} \ge y^g_{rj_0} \quad r = 1,\dots,q && (12)\\
& && \sum_{j=1}^{n} \lambda_j \overline{y}^b_{kj} \ge \overline{y}^b_{kj_0} \quad k = 1,\dots,t && (13)\\
& && \sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{ij_0} \quad i = 1,\dots,m && (14)\\
& && \sum_{j=1}^{n} \lambda_j = 1 \\
& && \lambda_j \ge 0 \quad j = 1,\dots,n
\end{aligned}
$$

Specifically speaking, 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 $P2$ and by assuming that constraints (14) hold with equality in the corresponding dual formulation $D2$.

### 3.3 Korhonen-Luptacik DEA model

A third possibility to incorporate undesirable outputs in DEA models is the one proposed by Korhonen and Luptacik in [13]. In this paper, several DEA models are introduced according to the efficiency measure they want to compute. To the aim of our work, we consider the eco-efficiency measure as the ratio between the weighted sum of the desirable outputs minus that of the inputs and the weighted sum of the undesirable outputs. The Primal-Dual LP-model pair is as follows:

$$
\begin{aligned}
&(P3) && \\
&\max_{u,v,w,u_0} && \sum_{r=1}^{q} u_r y^g_{rj_0} - \sum_{i=1}^{m} v_i x_{ij_0} + u_0 && (15)\\
&s.t. && \sum_{k=1}^{t} w_k y^b_{kj_0} = 1 && (16)\\
& && \sum_{r=1}^{q} u_r y^g_{rj} - \sum_{i=1}^{m} v_i x_{ij} + u_0 - \sum_{k=1}^{t} w_k y^b_{kj} \leq 0 \quad j = 1,\dots,n && (17)\\
& && u_r \geq 0 \quad r = 1,\dots,q \\
& && w_k \geq 0 \quad k = 1,\dots,t \\
& && v_i \geq 0 \quad i = 1,\dots,m \\
& && u_0 \in \mathbb{R}
\end{aligned}
$$

$$
\begin{aligned}
&(D3) && \\
&\min_{\theta,\lambda} && \theta \\
&s.t. && \sum_{j=1}^{n} \lambda_j y^g_{rj} \geq y^g_{rj_0} \quad r = 1,\dots,q && (18)\\
& && \sum_{j=1}^{n} \lambda_j y^b_{kj} \leq \theta y^b_{kj_0} \quad k = 1,\dots,t && (19)\\
& && \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{ij_0} \quad i = 1,\dots,m && (20)\\
& && \sum_{j=1}^{n} \lambda_j = 1 \\
& && \lambda_j \geq 0 \quad j = 1,\dots,n
\end{aligned}
$$

In this formulation (Model C in the paper of Korhonen and Luptacik [13]), DMUs proportionally reduce just the undesirable outputs in order to increase their eco-efficiency.

### 3.4 A directional distance function approach

A directional output distance function, in its original formulations by Färe et al. [12], expands (contracts) good (bad) outputs along a path that varies according to the direction vector adopted. Extensions of this methodology (see for all [10, 11, 17]) obtain a measure of technical efficiency from the potential for increasing outputs while reducing inputs and undesirable outputs simultaneously. 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:

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

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:

$$
\begin{aligned}
&(P4)\\
&\max_{\delta,\lambda} \quad \delta\\
&s.t. \quad \sum_{j=1}^{n} \lambda_j y_{rj}^g - \delta d_{rj_0}^g \geq y_{rj_0}^g \quad r = 1, \ldots, q && (24)\\
&\qquad \sum_{j=1}^{n} \lambda_j y_{kj}^b + \delta d_{kj_0}^b \leq y_{kj_0}^b \quad k = 1, \ldots, t && (25)\\
&\qquad \sum_{j=1}^{n} \lambda_j x_{ij} + \delta d_{ij_0}^x \leq x_{ij_0} \quad i = 1, \ldots, m && (26)\\
&\qquad \sum_{j=1}^{n} \lambda_j = 1\\
&\qquad \lambda_j \geq 0 \quad j = 1, \ldots, n
\end{aligned}
$$

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 [16] 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.

# 4 Database description

A database concerning 21 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 collected in the database (Austria, Belgium, Czech Republic, Denmark, Estonia, France, Germany, Italy, Norway, Poland, Spain, Switzerland and UK) produce more than the 80% of the total EU cement production. In order to compare the productive and ecological performance of these EU countries with non-EU ones, data concerning eight major non-EU countries (Australia, Brazil, Canada, China, India, Japan, U.S.A. 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. Specifically speaking, for all 21 countries (DMUs in DEA) the collected data are: clinker and cement production, considering also clinker and cement import/export, the consumption of raw materials, electricity and thermal energy, the number of employees (labour) and $CO_2$ emissions. 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 A), OECD (especially for labour data), Eurostat and ComTrade (for clinker and cement 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 A).

Missing data on emission factors and fuel consumption have been estimated taking into account different technology plants (vertical or rotary kilns), different fuel mix (according to the natural resources of each country under consideration) and setting the emission factors as estimated by the World Business Council for Sustainable Development (WBCSD) for each country member.

In Table 1, we report mean and standard deviation of input and output parameters used in the models for the considered 2005-2008 period. Notice 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.

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. Not specified in the table, it results that this growth can be ascribed to non-OECD countries and Turkey that are developing their economy without any environmental limits and compensates the progressive reduction of the volume of cement produced by EU-countries. Notice also that the clinker to cement ratio shows a progressive reduction thanks to the use of alternative raw material in the cement production process and the increasing production of blended cement which requires a lower proportion of clinker. A similar behavior can be found in energy consumption with the use of alternative fuels like waste or biomass.

| Variable | 2005 | | 2006 | | 2007 | | 2008 | |
|---|---|---|---|---|---|---|---|---|
| | **Mean** | **Std Dev** | **Mean** | **Std Dev** | **Mean** | **Std Dev** | **Mean** | **Std Dev** |
| Cement (Ml t) | 79.93 | 222.12 | 89.91 | 260.04 | 96.54 | 285.40 | 98.70 | 294.39 |
| Clinker (Ml t) | 63.61 | 176.79 | 70.76 | 204.17 | 74.67 | 217.90 | 71.21 | 205.11 |
| Materials (Ml t) | 114.48 | 324.52 | 129.06 | 379.95 | 138.68 | 417.01 | 143.03 | 430.04 |
| 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 |
| $CO_2$ (Ml t) | 68.33 | 205.70 | 76.32 | 237.12 | 81.89 | 260.26 | 83.96 | 268.39 |

Table 1: Mean-Std Dev (21 countries)

## 5 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 aspects of environmental and production efficiency in the cement industry. To avoid imbalances caused by different magnitudes, input and output parameters are normalized with respect to their mean (see Table 1). We recall that the study of efficiency using an INP model gives information on the global environmental efficiency taking into account both input and $CO_2$ reductions; the analysis is then deepened on by considering the TR$\beta$ and KL formulations which focus their attention respectively on input reduction (via the use of alternative raw materials) and bad output reduction (via the use of alternative fuels or most efficient production technologies). Finally, in order to point out the impact of environmental regulations, a directional distance approach is also tested under strong and weak disposability assumptions. We implement these four models under different assumptions on inputs and outputs. The results of these tests are reported in Tables 2, 3, 4 and 5.

The first test considers four inputs (namely clinker, raw materials, labour, energy), one desirable output (cement production) and one undesirable output ($CO_2$). The results of this test with INP, TR$\beta$, KL models in case of strong output disposability are reported in Table 2. For each year, the three models have common efficient units. The ranking of the inefficient units is different depending on the considered model. For the entire period 2005-2008, eight countries are efficient: Belgium, Estonia, Spain, Switzerland, China, India, Japan and the U.S.A.

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. In Spain, cement industry 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. In the Annual Belgian Cement Association Report 2008, the IEE and IGES indexes show a progressive effort in reducing $CO_2$ emission and in improving energy efficiency since 2005[14]. Estonia cement plants began using alternative fuels in 2000. In 2007, more than 36,000 tons of liquid waste fuels was burned in rotary kilns, providing about 10% of energy requirements. The use of alternative raw materials both in the production of clinker and as additives in the cement grinding process makes the Estonian cement industry efficient

[14] IEE stands for *indice damèlioration de lefficience ènergètique*) and IGES stands for *indice de rèduction des èmissions de $CO_2$ ènergètique (combustibles).* See Report Febelcem 2009 at page 20, available at http://www.febelcem.be/index.php?id=rapports-annuels

in the period under consideration.

As mentioned in Section 2, Japanese Cement Industry is involved in the Voluntary Emissions Trading Scheme, in particular in 2008 the cement industry outperforms the $CO_2$ emission target imposed by the regulation. 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 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 U.S.A. cement industry participates in several voluntary national and international environmental protection projects (such as Asia-Pacific Partnership on Clean Development and Climate Partners with Indian, Chinese and Japanese cement industries; Energy Star Cement Manufacturing Focus[15], Climate VISION) with the aim of improving its environmental performance. 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.

The time varying analysis shows that Canada, Norway and Denmark improve their performance among the different years. Norway has implemented a voluntary emission protocol since 2005 and successively entered in the EU-ETS in 2008. The participation to this environmental system has induced Norwegian cement companies to reduce by 40% the $CO_2$ emission and to substitute traditional energy sources with alternative ones for more than 50%.

In Canada the development of cement industry can be assimilated to the one of the U.S.A. cement industry. Regional regulations (like Alberta's Climate Change and Emission Management Act)and voluntary compliance to international environmental programs have forced cement industry to increase their level of efficiency.

The case of Danish cement industry can be evaluated by taking into account the evolution of the EU-ETS normative. Parallel to the other cement industries operating in the European countries, Danish cement sector became efficient in 2008 when the second phase of the EU-ETS imposed a more stringent constraint on $CO_2$ emissions.

Among inefficient countries, the ranking of efficiency is different with respect to the model we consider. In particular INP model gives information about a global efficiency measure obtained by reducing inputs and $CO_2$ (bad) output, while TR$\beta$ and KL focus respectively on input reduction (in the sense of use of alternative raw material and alternative fuels) and on $CO_2$ reduction (technology enhancing and alternative fuels utilization). Czech Republic represents the case of an efficient country that degrades to inefficiency. By comparing the results of TR$\beta$ and KL in the different years, the inefficiency can be ascribed to $CO_2$ emission, even though, in 2008, fossil fuel consumption reduces in favour of alternative fuels improving the overall performance. In terms of $CO_2$ emission factors, the most inefficient countries are Turkey, Poland, Austria, Denmark, United Kingdom and Australia.

[15]See www.energystar.gov/index.cfm?c=in_focus.bus_cement_manuf_focus

Recall that Australia and Turkey are not subject to any environmental regulation. Regarding inputs reduction, the ranking of efficiency significantly changes. For example countries like Denmark and Czech Republic are closed to efficiency. Finally, all models highlight a loss of efficiency in 2007 when the world cement demand reached the highest value of the last decade.

| **FVal** | **2005** | | | **2006** | | | **2007** | | | **2008** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** |
| **Austria** | 0.9881 | 0.98705 | 0.85798 | 0.68446 | 0.66923 | 0.20509 | 0.72493 | 0.72493 | 0.20396 | 0.74728 | 0.74728 | 0.18928 |
| **Belgium** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Czech Republic** | 1 | 1 | 1 | 0.86368 | 0.8471 | 0.30032 | 0.91014 | 0.91014 | 0.36464 | 0.96297 | 0.96297 | 0.59844 |
| **Denmark** | 0.8551 | 0.8551 | 0.28721 | 0.83835 | 0.83835 | 0.29251 | 0.95331 | 0.95331 | 0.55509 | 1 | 1 | 1 |
| **Estonia** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **France** | 0.79067 | 0.77998 | 0.74467 | 0.76418 | 0.75214 | 0.72195 | 0.74267 | 0.73917 | 0.6742 | 0.83523 | 0.83442 | 0.7628 |
| **Germany** | 0.85586 | 0.80481 | 0.85586 | 0.85693 | 0.80401 | 0.85693 | 0.75934 | 0.74309 | 0.75934 | 0.91315 | 0.86174 | 0.91315 |
| **Italy** | 0.88444 | 0.88444 | 0.82967 | 0.85655 | 0.85655 | 0.80156 | 0.82567 | 0.82567 | 0.74487 | 0.89913 | 0.89913 | 0.83237 |
| **Norway** | 0.98661 | 0.98549 | 0.82641 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Poland** | 0.86512 | 0.86192 | 0.64572 | 0.70368 | 0.70368 | 0.51069 | 0.6968 | 0.6968 | 0.52074 | 0.89693 | 0.89693 | 0.74575 |
| **Spain** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Switzerland** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **United Kingdom** | 0.84816 | 0.84816 | 0.59603 | 0.80531 | 0.80531 | 0.56944 | 0.83428 | 0.83428 | 0.56761 | 0.79218 | 0.79218 | 0.48071 |
| **Australia** | 0.8318 | 0.82499 | 0.53599 | 0.77621 | 0.77534 | 0.50611 | 0.80742 | 0.80723 | 0.51395 | 0.91197 | 0.91197 | 0.5866 |
| **Brazil** | 0.92439 | 0.92439 | 0.8639 | 0.85326 | 0.85326 | 0.79956 | 0.83095 | 0.83095 | 0.75417 | 0.98312 | 0.96183 | 0.98312 |
| **Canada** | 0.98501 | 0.98501 | 0.707 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **China** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **India** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Japan** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Turkey** | 0.74258 | 0.74258 | 0.67974 | 0.73715 | 0.73715 | 0.67512 | 0.7068 | 0.69485 | 0.7068 | 0.91143 | 0.8423 | 0.90643 |
| **U.S.A.** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Table 2: Cement 2005-2008 comparison: INP, TR$\beta$, KL models (EU + other countries)

In Tables 3 and 4 an Eco-Efficiency measure is computed following the lines of Mandal and Madheswaran [16]. The results in Tables 3 and 4 are based on the same input and output factors used in Table 2 except for clinker production input that also includes clinker imports. The inclusion of clinker import allows one to understand if the efficiency improvement can be ascribed to a better use of resources or to investments in advanced technologies or to the choice of relocate clinker production. Under this alternative assumption, results change. For instance, the comparison of Tables 2 and 3 shows that Danish cement industry reduces its efficiency level.

In Table 3, 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. 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. Our simulations show that there is no a significant difference between good output expansion with or without regulation except for the case of Czech Republic and United Kingdom which reduce their good output capacity expansion of respectively 1.4% and 3.6% (see Table 3). A different efficiency measure is proposed in Table 4. While in Table 3 the cost of environmental regulation seems to be irrelevant, in Table 4 environmental efficiency is affected by the weak or strong disposability assumption. The TR$\beta$ model evaluates both the reduction of input factors and the expansion of good outputs. In this case, results in Table 4 show that ecological efficiency varies significantly with or without regulation. For producing the same amount of output on average 8.5% of inputs can be saved under strong disposability assumption, while only 4.7% under weak disposability assumption. This means that a greater input reduction can be reached only by increasing bad output quantities.

Finally, in Table 5 the analysis concerns clinker production process and the results are related to the efficiency measurement of countries under the EU-ETS normative. The three considered inputs of DEA models are raw materials, energy and labour specifically assigned to clinker production, the good output is the total amount of clinker produced, the bad output is $CO_2$ emissions. The results tend to state efficiency in clinker production that is the most energy intensive phase of the cement process and the responsible of the direct $CO_2$ emissions. This analysis substantially confirms the results of the previous instances and strengthens the hypothesis on Denmark efficiency behaviour ascribed to the increase in clinker import. The discriminatory power of this test is lower than in the instances of Tables 2 , 3 and 4 since we only consider thirteen European countries. However, it respects the lower bounds on DMUs numbers imposed by DEA models.

| FVal | 2005 | | 2006 | | 2007 | | 2008 | | Eco-Efficiency | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **DirDist Strong** | **DirDist Weak** | **DirDist Strong** | **DirDist Weak** | **DirDist Strong** | **DirDist Weak** | **DirDist Strong** | **DirDist Weak** | **Mean Strong** | **Mean Weak** | **Eco Eff** |
| **Austria** | 0.006802 | 0.006802 | 0.37606 | 0.37606 | 0.3592 | 0.3592 | 0.30944 | 0.30944 | 0.26288 | 0.26288 | 0 |
| **Belgium** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Czech Republic** | 0 | 0 | 0.12611 | 0.12611 | 0.043723 | 0 | 0.013552 | 2.25E-11 | 0.04585 | 0.03153 | 0.01432 |
| **Denmark** | 0.37205 | 0.37205 | 0.37127 | 0.37127 | 0.35944 | 0.35944 | 0.26557 | 0.26557 | 0.34208 | 0.34208 | 0 |
| **Estonia** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **France** | 0.13607 | 0.13607 | 0.15124 | 0.15124 | 0.18329 | 0.18329 | 0.12513 | 0.12513 | 0.14893 | 0.14893 | 0 |
| **Germany** | 0.073755 | 0.073755 | 0.073601 | 0.073601 | 0.12269 | 0.12269 | 0.043239 | 0.043239 | 0.07832 | 0.07832 | 0 |
| **Italy** | 0.088867 | 0.088867 | 0.10687 | 0.10687 | 0.14219 | 0.14219 | 0.068808 | 0.068808 | 0.10168 | 0.10168 | 0 |
| **Norway** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Poland** | 0.14653 | 0.14653 | 0.23318 | 0.23318 | 0.22644 | 0.22644 | 0.11502 | 0.11502 | 0.18029 | 0.18029 | 0 |
| **Spain** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Switzerland** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **United Kingdom** | 0.065176 | 0.04215 | 0.10515 | 0.062595 | 0.082825 | 0.033944 | 0.17936 | 0.14189 | 0.10813 | 0.07014 | 0.03798 |
| **Australia** | 0.24928 | 0.24928 | 0.27852 | 0.27852 | 0.27722 | 0.27722 | 0.19067 | 0.19067 | 0.24892 | 0.24892 | 0 |
| **Brazil** | 0.07009 | 0.07009 | 0.10757 | 0.10757 | 0.13616 | 0.13616 | 0.0067705 | 0.0067705 | 0.08015 | 0.08015 | 0 |
| **Canada** | 0.015119 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00378 | 0.00000 | 0.00378 |
| **China** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **India** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Japan** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Turkey** | 0.18276 | 0.18276 | 0.1754 | 0.1754 | 0.15278 | 0.15278 | 0.036282 | 0.036282 | 0.13681 | 0.13681 | 0 |
| **U.S.A.** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Mean** | 0.066976 | 0.065160 | 0.100237 | 0.098210 | 0.099331 | 0.094922 | 0.064469 | 0.062039 | 0.082753 | 0.080083 | 0.002671 |

Table 3: Cement+imp 2005-2008 Directional Distance comparison (EU + other countries)

| **FVal** | **2005** | | **2006** | | **2007** | | **2008** | | **Eco-Efficiency** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **TR$\beta$ Strong** | **TR$\beta$ Weak** | **TR$\beta$ Strong** | **TR$\beta$ Weak** | **TR$\beta$ Strong** | **TR$\beta$ Weak** | **TR$\beta$ Strong** | **TR$\beta$ Weak** | **Mean Strong** | **Mean Weak** | **Eco Eff** |
| **Austria** | 0.99296 | 0.99295 | 0.70368 | 0.80771 | 0.73661 | 0.82807 | 0.74728 | 0.88759 | 0.7951325 | 0.87908 | 0.0839475 |
| **Belgium** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Czech Republic** | 1 | 1 | 0.88599 | 0.91591 | 0.96044 | 1 | 0.9875 | 1 | 0.9584825 | 0.9789775 | 0.020495 |
| **Denmark** | 0.7475 | 0.91345 | 0.73778 | 0.94846 | 0.75508 | 0.95368 | 0.8019 | 0.94939 | 0.760565 | 0.941245 | 0.18068 |
| **Estonia** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **France** | 0.83394 | 0.87505 | 0.82076 | 0.88226 | 0.81445 | 0.88755 | 0.86557 | 0.92105 | 0.83368 | 0.8914775 | 0.0577975 |
| **Germany** | 0.90695 | 0.92353 | 0.877 | 0.90341 | 0.89099 | 0.93354 | 0.92073 | 0.93955 | 0.8989175 | 0.9250075 | 0.02609 |
| **Italy** | 0.8643 | 0.96409 | 0.82827 | 0.96586 | 0.80871 | 0.96765 | 0.88282 | 0.95081 | 0.846025 | 0.9621025 | 0.1160775 |
| **Norway** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Poland** | 0.86288 | 0.89799 | 0.80655 | 0.94786 | 0.81799 | 0.94639 | 0.87011 | 0.88588 | 0.8393825 | 0.91953 | 0.0801475 |
| **Spain** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Switzerland** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **United Kingdom** | 0.93939 | 0.97552 | 0.906 | 0.97838 | 0.92522 | 0.98294 | 0.84932 | 1 | 0.9049825 | 0.98421 | 0.0792275 |
| **Australia** | 0.77369 | 0.82055 | 0.74555 | 0.8456 | 0.75126 | 0.84114 | 0.83523 | 0.88272 | 0.7764325 | 0.8475025 | 0.07107 |
| **Brazil** | 0.83584 | 0.86656 | 0.79922 | 0.86483 | 0.80613 | 0.89059 | 0.88687 | 0.88687 | 0.832015 | 0.8772125 | 0.0451975 |
| **Canada** | 0.98501 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.9962525 | 1 | 0.0037475 |
| **China** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **India** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Japan** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Turkey** | 0.82542 | 0.91315 | 0.78132 | 0.91086 | 0.79744 | 0.85845 | 0.89487 | 0.91899 | 0.8247625 | 0.9003625 | 0.0756 |
| **U.S.A.** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| **Mean** | 0.93180 | 0.95918 | 0.89962 | 0.95101 | 0.90782 | 0.95667 | 0.93058 | 0.96299 | 0.91746 | 0.95746 | 0.04000 |

Table 4: Cement+imp 2005-2008 TR$\beta$ comparison (EU + other countries)

| **FVal** | **2005** | | | **2006** | | | **2007** | | | **2008** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** | **INP** | **TR$\beta$** | **KL** |
| **Austria** | 0.97052 | 0.97052 | 0.2123 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Belgium** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Czech Republic** | 1 | 1 | 1 | 0.90528 | 0.90323 | 0.228 | 0.9614 | 0.9614 | 0.27222 | 0.96882 | 0.96882 | 0.28877 |
| **Denmark** | 0.71349 | 0.71349 | 0.23258 | 0.71795 | 0.71795 | 0.2381 | 0.714 | 0.714 | 0.28512 | 0.7531 | 0.7531 | 0.40436 |
| **Estonia** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **France** | 0.94416 | 0.91625 | 0.91048 | 0.93988 | 0.90642 | 0.90831 | 0.93005 | 0.90367 | 0.8834 | 0.93536 | 0.91811 | 0.86901 |
| **Germany** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Italy** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Norway** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Poland** | 0.93155 | 0.8972 | 0.79515 | 0.97273 | 0.97273 | 0.82889 | 0.95354 | 0.95354 | 0.77904 | 0.94639 | 0.923 | 0.82365 |
| **Spain** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Switzerland** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **United Kingdom** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.89315 | 0.89315 | 0.63317 |

Table 5: Clinker 2005-2008 comparison: INP, TR$\beta$, KL models (only EU countries)

# 6 Conclusions

Cement manufacturing is a long process that starts with the extraction of specific raw materials from quarries, continues with the intermediate production of clinker and concludes with the final mining of the clinker with additives needed by for the production of different kinds of cements. Among all these phases, the production of clinker is the most energy and $CO_2$ intensive. Clinker is produced by burning a mixture of mainly limestone, silicon oxides, aluminium oxides and iron oxides in kilns that differ according to the process adopted. Cement can be produced with four different processes: dry, wet, semi-dry and semi-wet. Dry and semi-dry technologies are more recent and more efficient in terms of energy consumption than the other two. Emissions have become a problem for those cement industries that are subject to some environmental regulations. For these reasons, cement industry since early 2000s has been included in most of environmental protection programs. European cement producers are involved in EU-ETS directive concerning $CO_2$ emission regulation; among non-EU countries voluntary emission trading schemes have been also introduced (see for instance Japan, Switzerland, Canada).

In this paper a cross-country comparison of cement industry efficiency using several Data Envelopment Analysis (DEA) models has been presented, referred to a four-year period since 2005 to 2008. This work differs from literature since it compares 21 countries covering the 90% of the world cement production. Traditional industrialized countries are compared with emerging producers like India and China. The different impact of regulation and economy crisis can be also derived by the four years tendency. Both environmental efficiency and production efficiency measure have been analyzed and compared by implementing four different models. An overall perspective of cement industry has been then obtained. The study of efficiency using an input oriented (INP) DEA model has given information on the global environmental efficiency taking into account both input reduction and $CO_2$ emission reduction; the two alternative formulations TR$\beta$ and KL focused their attention respectively on input reduction (via the use of alternative raw materials) and bad output reduction (via the use of alternative fuels or most efficient production technologies). Finally, in order to point out the impact of environmental regulations, a directional distance approach has been also tested under strong and weak disposability assumptions. 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 aspects of environmental and production efficiency in the cement industry. Different instances have been formulated in order to understand efficiency or inefficiency reasons. A first instance considers cement and $CO_2$ emissions as outputs, energy, labour, raw materials and clinker as inputs of the process. This analysis is able to evaluate the efficiency of the whole cement production process. A second instance modifies the clinker production input by adding clinker import in order to test delocalization choices of sub products production which causes $CO_2$ emissions. A third analysis on the sub process of clinker production has also been developed both considering the full dataset and the restricted EU countries dataset. In this case, the results give information on leading technology plants and energy efficiency consumption.

The analysis has shown that the efficiency level mainly depend 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. Among countries without environmental regulation, in particular emerging countries increasing their cement production in recent years, like China and India, show high efficiency levels. This feature can be addicted to two different factors: plants with more efficient technologies (progressive substitution of small wet process plants with bigger and dry technology ones), investments on the production of low quality cements which require less proportion of clinker, the main responsible for $CO_2$ emissions. The case of China cement industry, however, requires careful attention taking into account lack or fragmentary data. Further developments are in the direction of enlarging the actual dataset by including more cement producing countries useful 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.

## Appendix A: 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.

### 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://appsso.eurostat.ec.europa.eu/nui/setupModifyTableLayout.do

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