Universitat Autònoma de Barcelona

Documents de Treball

EFFICIENCY AND ENVIRONMENTAL REGULATION: A 'COMPLEX SITUATION'

Andrés J. Picazo-Tadeo

Diego Prior

Document de Treball núm. 05/2

Departament d'Economia de l'Empresa

Coordinador / Coordinator *Documents de treball:*

Carles Gispert
http://selene.uab.es/dep-economia-empresa/recerca/Documents.htm
e-mail: carles.gispert@uab.es
Telèfon / Phone: +34 93 5814296
Fax: +34 93 5812555

Edita / Publisher*:*

Departament d'Economia de l'Empresa
http://selene.uab.es/dep-economia-empresa/
Universitat Autònoma de Barcelona
Facultat de Ciències Econòmiques i Empresarials
Edifici B
08193 Bellaterra (Cerdanyola del Vallès), Spain
Tel. 93 5811209
Fax 93 5812555

Abril / April, 2005

EFFICIENCY AND ENVIRONMENTAL REGULATION: A 'COMPLEX SITUATION'

Andrés J. Picazo-Tadeo

Diego Prior

Document de Treball núm. 05/2

Efficiency and environmental regulation: a 'complex situation'

Andrés J. Picazo-Tadeo [(a)]
Diego Prior [(b)]

(a) Universitat de València. Dpto. Economía Aplicada II.
Avda. dels Tarongers, s/n. 46022. Valencia, SPAIN.
Email: Andres.j.picazo@uv.es

(b) Universitat Autònoma de Barcelona. Dpto. Economia de l'Empresa.
08193 Bellaterra, Barcelona, SPAIN.
Email: Diego.prior@uab.es

February 22, 2005

***ABSTRACT**.- Production of desirable outputs is often accompanied by undesirable by-products that have damaging effects on the environment, and whose disposal is frequently regulated by public authorities. In this paper, we compute directional technology distance functions under particular assumptions concerning disposability of bads in order to test for the existence of what we call 'complex situations', where the biggest producer is not the greatest polluter. Furthermore, we show that how in such situations, environmental regulation could achieve an effective reduction in the aggregate level of bad outputs without reducing the production of good outputs. Finally, we illustrate our methodology with an empirical application to a sample of Spanish tile ceramic producers.*

***Key words**: environmental regulation; efficiency; disposability of bads.*
***JEL Classification**: C61; D21; L68.*

1. Introduction

The analysis of firms' environmental performance and the assessment of the costs of abating undesirable *by-products* that frequently come jointly with production of desirable goods, are receiving growing attention by both academics and policy decision-makers. Furthermore, environmental issues are also becoming a major matter of concern for firms' managers.

From the eighties onward, a growing literature has arisen devoted to incorporating environmental issues into traditional production theory, which has, to date, produced a wealth of contributions (see Tyteca, 1996 and Allen, 1999 for a review). On the one hand, some studies have focused on adjusting conventional productivity indexes to allow for *undesirables* into the output vector. Pitman (1983) pioneered this line of research by using econometric techniques to calculate shadow prices for undesirable outputs, which were used to compute an index of productivity change that accounts for environmental effects. Färe *et al.* (1993) calculated firm-specific shadow prices of *undesirables* from the computed parameters of an output distance function. Afterward, this methodological approach has been applied in numerous papers, Coggins and Swinton (1996), Swinton (1998) and Reig-Martínez *et al.* (2001), among others. On the other hand, a second strand of the literature has addressed the issue of extending the traditional efficiency analysis framework (Farrell, 1957) to explicitly account for the presence of undesirable outputs. Färe *et al.* (1989) suggested the computation of hyperbolic productive efficiency measures under both strongly and weakly disposable technologies, to measure the impact on firms' performance of lack of free disposability of wastes, e.g. due to environmental-friendly regulations. Other interesting papers that analyse environmental and economic performance are Ball *et al.* (1994), Brännlund *et al.* (1995), Färe *et al.* (1996), Tyteca (1997), Hernández-Sancho *et al.* (2000) and Zofio and Prieto (2001).

In recent years, it has emerged a renewed interest in measuring environmental performance together with pollution abatement costs arising from public regulations aimed at achieving determined standards of environmental quality. A number of papers, including that by Chung *et al.* (1997) and Ball *et al.* (2001), have proposed the use of directional distance functions (Färe and Grosskopf, 2000; see also Färe and Grosskopf, 2004) as an useful tool in modelling production theory in presence of *undesirables* and, particularly, in assessing environmental performance. Some other studies have used directional distance functions to explicitly calculate the costs of abating contamination. Färe *et al.* (2003) interpret pollution abatement costs as the foregone production of good outputs that results from the reallocation of *productive* inputs to pollution reduction activities, i.e. resources that otherwise could be addressed to good output production. Furthermore, Picazo-Tadeo *et al.* (2005) utilise directional technology distance functions to calculate productive-oriented efficiency measures under both strongly and weakly disposable technologies, which are used to compute firm-specific reduced production of *goods* resulting from regulations that prevent free disposal of residuals. This paper differs from Färe *et al.* (2003) by scaling both *goods* and inputs, instead of scaling only good outputs.

In this paper, we propose to consider in more detail the use of directional distance functions in assessing firms environmental performance and the opportunity cost of pollution abatement. Particularly, we show that computing directional distance functions under certain assumptions concerning disposability of *undesirables*, allows to identify what we call *complex situations*, where the biggest producer is not the greatest polluter. In such situations, firms can increase their production of *goods* reducing *bads*, and regulating authorities could achieve an effective environmental regulation without affecting firms' desirable production.

The remainder of the paper is organised as follows. Section two deals with methodological issues. Section three describes the data and discuses the empirical application. Finally, section four concludes.

2. Methodology

Introducing some notation, let us consider that production technology is defined by the set of feasible input, $\mathbf{x}=\left(x_1,...,x_i,...,x_I\right)\in\mathbf{R}_+^I$, and output, $\mathbf{y}=\left(y_1,...,y_j,...,y_J\right)\in\mathbf{R}_+^J$, vectors:

$$S=\left\{\left(\mathbf{x},\mathbf{y}\right)\mid \mathbf{x}\text{ can produce }\mathbf{y}\right\} \qquad (1)$$

Traditional production theory assumes that the properties of the production technology are the following (Shephard, 1970; see also Grosskopf, 1986):

a) <u>*Inactivity*</u>.

a.1) *Possibility of inaction:* $\left(\mathbf{0},\mathbf{0}\right)\in S$ (2)

It is technological possible not to produce.

a.2) *No free lunch:* $(\mathbf{0},\mathbf{y})\notin S;\ \mathbf{y}>\mathbf{0}$ (3)

Positive quantities of inputs are required to produce positive amounts of outputs.

b) <u>*Strong disposability of inputs (SDI)*</u>.

$$\forall\mathbf{x}\in\mathbf{R}_+^I,\ \ if\ \left(\mathbf{x},\mathbf{y}\right)\in S\ \Rightarrow\ \left(\mathbf{x'},\mathbf{y}\right)\in S,\ \mathbf{x'}\geq\mathbf{x} \qquad (4)$$

It is feasible to produce the same amount of output using a bigger quantity of any input, i.e., the inputs excess can be disposed at no cost.

c) <u>*Strong disposability of outputs (SDO)*</u>.

$$\forall\mathbf{y}\in\mathbf{R}_+^J,\ \ if\ \left(\mathbf{x},\mathbf{y}\right)\in S\ \Rightarrow\ \left(\mathbf{x},\mathbf{y'}\right)\in S,\ \mathbf{y'}\leq\mathbf{y} \qquad (5)$$

Any feasible output can be freely disposed.

d) <u>*Convexity*</u>.

$$\forall \mathbf{x},\mathbf{x'} \in \mathbf{R}_+^I,\ \forall \mathbf{y},\mathbf{y'} \in \mathbf{R}_+^J,\ if\ (\mathbf{x},\mathbf{y}),(\mathbf{x'},\mathbf{y'}) \in S \\ \Rightarrow\ \alpha(\mathbf{x},\mathbf{y}) + (1-\alpha)(\mathbf{x'},\mathbf{y'}) \in S,\ \alpha \in [0,1] \tag{6}$$

The linear combinations of feasible production plans are also feasible.

Furthermore, let us assume that production of *desirable* outputs comes jointly with undesirable *by-products*, and that the output vector can be partitioned into a sub-vector of desirable or *good* outputs, $\mathbf{y}^g = \left(y_1^g,...,y_g^g,...,y_G^g\right) \in \mathbf{R}_+^G$, and a sub-vector of undesirable or *bad* outputs, $\mathbf{y}^b = \left(y_1^b,...,y_b^b,...,y_B^b\right) \in \mathbf{R}_+^B$, so that $\mathbf{y} = \left(\mathbf{y}^g,\mathbf{y}^b\right) \in \mathbf{R}_+^J$.

In order to introduce joint production of good and bad outputs into the characterisation of the technology, two additional axioms are usually assumed, null-joint production (Shephard and Färe, 1974) and weak disposability of outputs, both desirable and undesirable (Färe and Primont, 1995). Formally, these axioms are formulated as:

e) <u>*Null-jointness*</u>.

$$\forall \mathbf{y}^g \in \mathbf{R}_+^G,\ \forall \mathbf{y}^b \in \mathbf{R}_+^B,\ \mathbf{y}^b = 0 \Rightarrow \mathbf{y}^g = 0 \tag{7}$$

If some *good* outputs are produced, then some *bads* will also be produced.

f) <u>*Weak disposability of outputs (WDO)*</u>.

$$\forall \mathbf{y}^g \in \mathbf{R}_+^G,\ \forall \mathbf{y}^b \in \mathbf{R}_+^B,\ \left(\mathbf{x},\mathbf{y}^g,\mathbf{y}^b\right) \in S \Rightarrow \left(\mathbf{x},\alpha\mathbf{y}^g,\alpha\mathbf{y}^b\right) \in S,\ \ \alpha \le 1 \tag{8}$$

Proportional reduction of good and bad outputs is feasible, but the isolated disposal of bad outputs may not be.

The axiom of *WDO* constitutes a reasonable way of recognising that reducing *undesirables* may not be a free activity, as traditional production theory assumes. Conversely, when firms face environmental-friendly regulations, disposing undesirable outputs involves a cost that could be measured in terms of *opportunity* as a shrinkage of the maximum attainable production of *goods* from a given endowment of resources (Färe *et al.*, 1989). In other words, inputs that otherwise could have a productive use, i.e. production of desirable outputs, have to be diverted to reduce or eliminate undesirable outputs in compliance with the environmental regulations.

Our next theoretical building block is the *directional distance function* (*DDF*). This function generalises both input and output Shephard's distance functions, providing a complete representation of the production technology (Färe *et al.*, 2000 summarise the theory and main applications of these functions). In presence of undesirable outputs, the *DDF* is defined as:

$$\vec{D}\left(\mathbf{x},\mathbf{y}^g,\mathbf{y}^b;-g_x,g_{y^g},-g_{y^b}\right)=\text{Sup}\left[\beta\ \middle|\left(\mathbf{x}-\beta g_x,\ \mathbf{y}^g+\beta g_{y^g},\ \mathbf{y}^b-\beta g_{y^b}\right)\in S\right] \qquad (9)$$

$\mathbf{g}=\left(-g_x,g_{y^g},-g_{y^b}\right)$ being the *direction vector*.

Directional distance functions model joint production of desirable and undesirable outputs, allowing for increasing *goods* while simultaneously reducing *bads*, along a path previously determined through a particular direction vector. Accordingly, the *DDF* of expression (9) inflates the vector of good outputs in the g_{y^g} direction and contracts the vectors of inputs and bad outputs in the $-g_x$ and $-g_{y^b}$ directions, respectively, while staying within the set of technologically feasible productive plans *S*. Furthermore, it can be proved that[1]:

$$\vec{D}\left(\mathbf{x},\mathbf{y}^g,\mathbf{y}^b;-g_x,g_{y^g},-g_{y^b}\right)\geq 0 \Leftrightarrow \left(\mathbf{x},\mathbf{y}^g,\mathbf{y}^b\right)\in S \qquad (10)$$

The computed *DDF* for a particular decision making unit measures its level of technical efficiency[2]. If the *DDF* equals to zero, the productive unit under evaluation is efficient in the *Farrell-Debreu* notion[3]. In other words, no other peer has been found that yields greater vector of good outputs with little consumption of inputs and smaller level of bad outputs.

Under the set of assumptions made concerning the technology, and imposing variable returns to scale[4], for a productive unit *O*, the *DDF* of expression (9) can be computed solving the following linear programming problem (see Färe *et al.*, 2003):

[1] Other relevant properties of *DDF* are summarised in Chambers *et al.* (1998).

[2] Computed scores of technical efficiency must be considered here as measures of *productive-oriented* efficiency, rather than output- or input-oriented efficiencies, given that the directional distance function expands *goods* simultaneously reducing inputs.

[3] Here, we follow the well-known *Farrell-Debreu* notion of efficiency. There exist, however, another more exigent concept of efficiency: the *Pareto-Koopmans* efficiency (see Färe *et al.*, 1994 for details).

[4] Other properties concerning the nature of the scale properties of the technology could also be assumed (see Banker *et al.*, 1984).

$$\vec{D}_O^{WDB}\left(\mathbf{x}_o,\mathbf{y}_o^g,\mathbf{y}_o^b;-g_x,g_{y^g},-g_{y^b}\right)=Max\,\beta$$

subject to:

$$\begin{aligned}
&\left(\mathbf{x}_o-\beta g_x\right)\geq \mathbf{z}\,\mathbf{J} && (i)\\
&\left(\mathbf{y}_o^g+\beta g_{y^g}\right)\leq \delta\mathbf{z}\,\mathbf{G} && (ii)\\
&\left(\mathbf{y}_o^b-\beta g_{y^b}\right)= \delta\mathbf{z}\,\mathbf{B} && (iii)\\
&\mathbf{ez}=1 && (iv)\\
&\mathbf{z}\geq 0 && (v)\\
&0\leq\delta\leq 1 && (vi)
\end{aligned} \qquad (11)$$

where:

- $\mathbf{x}_o$, $\mathbf{y}_o^g$ and $\mathbf{y}_o^b$ are, respectively, the vectors of inputs, good outputs and bad outputs corresponding to the productive unit under evaluation, i.e., firm *O*.
- $\vec{D}_O^{WDB}$ is the computed *DDF* when *bads* are assumed weakly disposable (*WDB*),
- **z** is an activity vector denoting the intensity at which observed productive units are conducted in constructing the technological frontier,
- **J, G** and **B** are three matrices containing the observed vectors of inputs, good outputs and bad outputs, respectively,
- **e** is a vector of ones, and, finally,
- δ is a parameter restricted to be within zero and one.

The strict equality in (11)-(*iii*) and the parameter δ on the right hand side of restrictions (11)-(*ii*) and (11)-(*iii*), assure the accomplishment of the axioms of null-jointness and *WDB* when variable returns to scale are imposed. Likewise, good outputs are freely disposable, according to inequality (11)-(*ii*).

Färe *et al.* (2003) refer to program (11) as *regulated*, provided that bad outputs can not be freely disposed. Conversely, when firms face no environmental rules, instead of weak disposal, the axiom of strong disposability of undesirable outputs constitutes a convenient characterisation of the technology since it allows to model the idea that firms can freely dispose of *undesirables*. In other words, strong disposability can be interpreted here as the plausible assumption that in absence of regulation firms will not bear the cost of disposing in a socially acceptable way of its undesirable output. Thus, the *unregulated* version of program (11) is:

$$
\begin{aligned}
&\vec{D}_O^{SDB}\left(\mathbf{x}_o,\mathbf{y}_o^g,\mathbf{y}_o^b;-g_x,g_{y^g},-g_{y^b}\right)=Max\,\beta \\
&\text{subject to:} \\
&\left(\mathbf{x}_o-\beta g_x\right)\geq \mathbf{z}\,\mathbf{J} && (i) \\
&\left(\mathbf{y}_o^g+\beta g_{y^g}\right)\leq \mathbf{z}\,\mathbf{G} && (ii) \\
&\left(\mathbf{y}_o^b-\beta g_{y^b}\right)\leq \mathbf{z}\,\mathbf{B} && (iii) \\
&\mathbf{ez}=1 && (iv) \\
&\mathbf{z}\geq 0 && (v)
\end{aligned}
\qquad (12)
$$

Computation of program (12) yields the *DDF* under the axiom of strong disposal of *bads* (*SDB*), i.e., when, in absence of regulation, firms do not face costs for the *free* (strong) disposal of bad outputs. Furthermore, *SDB* has been introduced transforming the equality (11)-(*iii*) into the inequality (12)-(*iii*) and removing the parameter δ.

Figure 1 provides some intuition of the evaluation of programs (11) and (12) based on a simple diagram. In order to make things easier, let us assume that all productive units present the same inputs vector to produce one good output and one bad output. Also, let us consider that the direction vector takes only the good output expansion direction. Formally, this direction vector is:

$$\mathbf{g}=\left(-g_x,g_{y^g},-g_{y^b}\right)=\left(0,1,0\right) \qquad (13)$$

[Figure 1 about here]

Being productive unit *A* inefficient[5], by expanding to the maximum level of good output with the same level of bad output, the *DDF* computed assuming that environmental rules prevent free disposal of *bads*, i.e., the solution to program (11), locates point *A* on the technological frontier at point $A'=A+\vec{D}_A^{WDB}$. In contrast, when there is not environmental regulation and firms can dispose of *undesirables* at no cost, program (12) finds point $A''=A+\vec{D}_A^{SDB}$ as the benchmark for the good output of productive unit *A*. Nevertheless, as it is technologically infeasible for productive unit *A* to reach point *A"*, in real terms its benchmark is *B* (note that $y_B^g=y_{A''}^g$), but the strong disposability axiom, i.e., lack of environmental rules, permits to freely dispose the increase in bad outputs, which is measured by $\left(y_B^b-y_A^b\right)$.

[5] Notice that, under the particular direction vector considered, technical inefficiencies should be interpreted as output-oriented inefficiencies, because this vector expands *goods* for given endowment of inputs.

Having these results and following Picazo-Tadeo *et al.* (2005), we define the *regulatory impact index* as the difference between efficient projections of good output on both *regulated* and *unregulated* technological frontiers. Formally, for decision making unit *O*, this index is:

$$Regulatory\ impact\ index = \left(\vec{D}_O^{SDB} - \vec{D}_O^{WDB} \right) \qquad (14)$$

The regulatory impact index of expression (14) measures losses of good output due to regulation and takes values equal or greater than zero. Value zero means that environmental regulations are not binding and regulation is not hindering strong disposability of undesirable outputs. Conversely, a positive index indicates that regulation hinders free disposal of *bads*.

Let us assume now that the situation is the symbolized in *Figure 2*, where the biggest polluter is not the biggest producer. We call it *the complex situation*. In this new scenario, productive unit *B* continues being the *maximiser* of the good output, but units *C* and *D* generate a greater amount of bad output, while producing a lower level of good output.

[Figure 2 about here]

In spite of the fact that economic literature on the measurement of environmental performance runs into hundreds of papers, few attempts have been made to explain why we might observe productive units like *C* and *D*. Perhaps, the easiest way to justify this behaviour that apparently seems to be somewhat counter-intuitive, is to affirm that, although observed, these observations are simply outliers due to measurement error. Furthermore, despite that the theoretical framework of efficiency measurement assumes that all observations have access to the same technology, it can be argued that points like *C* and *D* could be representing productive units using older, and also dirtier, technologies. Our perspective here is a little different since we consider that, at least, two additional reasons could justify the existence of such points.

- On the one hand, imagine a technology generating a fixed level of bad output, irrespective of the level of production of the good output (being similar to what a fixed input is). If, in the short term basis, a drop in the demand implies that units *C* and *D* use a poor level of their productive capacity, these units are going to be inefficient because of their sub-activity, although this sub-activity does not imply any reduction in their environmental impact.

- Figure 2 could be expressive of the short run, being the long-run situation what is presented in *Figure 3*. In this new picture, we observe the extension of the efficient frontier until unit *E* (the biggest producer with the highest environmental impact), but, from the short-run perspective, we do not observe the presence of productive unit *E*.

[Figure 3 about here]

In the empirical illustration we carry out in the next section, we have a cross-section dataset for a sample of Spanish tile producers, so that we deal with a *complex situation* corresponding to the short-run situation symbolised in *Figure 2*. In this case, application of programs (11) and (12) to units *C* and *D* yields the following results: $\vec{D}_C^{WDB} = \vec{D}_C^{SDB} > 0$ and $\vec{D}_D^{WDB} = \vec{D}_D^{SDB} = 0$.

Nevertheless, it is obvious that, for productive units *C* and *D*, the right benchmark is *B*, as it is demonstrated that it is possible to produce more good outputs with a lower level of bad outputs. The problem is that nor the strong neither the weak disposability axioms help us to determine the existence of such situations. In order to manage such situations, it is worth to define a new axiom concerning the consideration of bad outputs as strongly disposable detrimental inputs. Formally:

g) *Adaptation of the axiom of strong disposability of inputs to bad outputs (SDIB).*

$$\forall \mathbf{y}^b \in \mathbf{R}_+^B,\ \ if \left(\mathbf{y}^b, \mathbf{y}^g \right) \in S \Rightarrow \left(\mathbf{y}'^b, \mathbf{y}^g \right) \in S,\ \mathbf{y}'^b \geq \mathbf{y}^b \tag{15}$$

It is possible to produce the same amount of good output generating a bigger quantity of bad output. This axiom accepts that it is possible the existence of environmental inefficiency.

Although it is habitual to model *by-products* that come jointly with production of goods as undesirable or bad outputs, Pitman (1981) already modelled *undesirables* as detrimental inputs in production processes, arguing that the relationship between any environmentally detrimental variable and desirable outputs is quite similar to the relationship that exists between conventional inputs and outputs. Other recent papers that also adopt this view are Tyteca (1997), Reinhard *et al.* (1999, 2002) and Prior (2005).

According to this new technological consideration, a new linear program can be derived to determine the *DDF* for productive unit *O* as:

$$\vec{D}_O^{SDIB}\left(\mathbf{x}_o,\mathbf{y}_o^g,\mathbf{y}_o^b;-g_x,g_{y^g},-g_{y^b}\right)=Max\,\beta$$

subject to:

$$\begin{aligned}
&\left(\mathbf{x}_o-\beta g_x\right)\geq \mathbf{z}\,\mathbf{J} && (i)\\
&\left(\mathbf{y}_o^g+\beta g_{y^g}\right)\leq \mathbf{z}\,\mathbf{G} && (ii)\\
&\left(\mathbf{y}_o^b-\beta g_{y^b}\right)\geq \mathbf{z}\,\mathbf{B} && (iii)\\
&\mathbf{ez}=1 && (iv)\\
&\mathbf{z}\geq 0 && (v)
\end{aligned} \qquad (16)$$

In this case, the axiom of *SDIB* has been introduced thought the inequality in restriction (16)-*(i)*. Let us, then, return to the situation depicted in *Figure 2*, and apply program (16) to productive units *C* and *D*, orienting the direction to expand the good output while maintaining observed levels of inputs and *bads*, i.e., we continue assuming that the direction vector is that of expression (13). It is worth noting that in both cases the good output can be respectively expanded to $C''=B=C+\vec{D}_C^{DSIB}$ and $D''=B=D+\vec{D}_D^{DSIB}$. This is an information very useful for the managers of these firms, however, the regulator should also know that firms *C* and *D* are producing a level of bad output over to they would require, even in the case they maximize their production of the good output. Summing up, if there appear situations similar to productive units *C* and *D*, even without limiting the production of the good output, the regulator could achieve a effective reduction in the aggregate level of the bad output, i.e., $\left(y_C^b-y_B^b\right)+\left(y_D^b-y_B^b\right)$.

Generalising the procedure, when evaluating the efficiency of firms taking into account the environmental impact of the bad outputs, it could be possible the existence of *complex situations* similar to productive units *C* and *D*. For a decision making unit *O*, testing for this situation makes it necessary the definition of the following algorithm:

1. Using a direction vector that expands desirable outputs while maintaining inputs and bad outputs, i.e., the direction vector adopted is that of expression (13), compute the distances $\vec{D}_O^{WDB}$, $\vec{D}_O^{SDB}$ and $\vec{D}_O^{SDIB}$, from the solution of programs (11), (12) and (16).

2. Then, compare the *DDF* computed under both *SDB* and *SDIB* axioms, that is, match distance $\vec{D}_O^{SDB}$ up with $\vec{D}_O^{SDIB}$.

   a. If $\vec{D}_O^{SDB}>\vec{D}_O^{SDIB}$, then the maximal increase in the good outputs requires the increase in the bad outputs. In this case, the impact of a regulation on the bad outputs side can be conventionally determined according to expression (14), through the comparison of *DDF* computed under *SDB* and *WDB*, i.e., distances $\vec{D}_O^{SDB}$ and $\vec{D}_O^{WDB}$.

b. If $\vec{D}_O^{SDB} < \vec{D}_O^{SDIB}$, then the maximal increase in the good outputs reduces the level of the bad outputs. In these circumstances, the regulator can define rules to control the production of bad outputs that do not constrain the maximization of the good outputs. Consequently, $\left(O + \vec{D}_O^{SDIB}\right)$ can be the right target to achieve.

c. Finally, if $\vec{D}_O^{SDB} = \vec{D}_O^{SDIB}$, then the maximal increase in the good outputs can be achieved with no restrictions on the bad outputs side, and $\left(O + \vec{D}_O^{SDB}\right)$ can be a target according to the environmental perspective.

Summing up, our algorithm allows to identify productive units showing a particular environmental behaviour, characterised by a quite unsuccessful economic and environmental performance. Identification of these *complex situations* can provide both firms managers and policy-makers with meaningful information to improve firms' environmental performance and, also, to get better designs of environmental policies. Section three illustrates our methodology applying it to a sample of Spanish ceramic tile producers.

3. Dataset and empirical illustration

The dataset we use to illustrate our methodology is the same as in Picazo-Tadeo *et al.* (2005), and belongs to a cross-section sample of thirty five ceramic tile producers located at the region of Valencian, on the Spanish Mediterranean coast. The information comes from the *Valencian Region Inventory of Industrial Wastes* conducted in 1995 by the *Department of Environment of the Valencian Regional Government*. All firms in the sample share the same productive process, producing ceramic goods through the use of an intermediate input, clay, kaolin, felspar and limestones, and two primary production factors, labour and capital. The production process also generates two undesirable products, watery mud and used oil. Output is measured in monetary units, while labour and capital factors are respectively proxied by energy consumption and the number of workers. Finally, intermediate input and bad outputs are all measured in physical units. Descriptive statistics for the data are presented in *Table 1*.

[Table 1 about here]

In order to apply our algorithm to this dataset and testing for the possible existence of *complex situations*, we have computed the *DDF* of expressions (11), (12) and (16) assuming, as proposed, a direction that expands desirable output while maintaining inputs and bad outputs[6], i.e., the direction vector is that of expression (13). Under this direction vector, the expression for the *DDF* becomes:

$$\vec{D}\left(\mathbf{x},\mathbf{y}^g,\mathbf{y}^b;0,1,0\right)=\text{Sup}\left[\beta\middle|\left(\mathbf{x},\ \mathbf{y}^g+\beta,\ \mathbf{y}^b\right)\in S\right] \tag{17}$$

This distance measures the extent to which a firm could increase its production of good output, while maintaining inputs and *bads*. In other words, given their endowment of inputs, it could be possible for *inefficient* tile firms to move to cleaner environmental-friendly productive plans that would enable them to produce more ceramic pavements while holding the same amount of watery mud and used oil. Since the amount of ceramic pavements increases with constant amount of *bads*, the ratio of each bad output per unit of good output will decrease.

Comparing the *DDF* computed under the assumptions of *SDB* and *SDIB*, i.e., the solutions to programs (11) and (12), shows, on the one hand, that 29 firms (out of 35) present a behaviour corresponding to the *basic situation* depicted in *Figure 1* (see *Table 2*). For these firms, the maximal increase in their production of ceramic pavements, requires an increase in the production of watery mud and used oil. When no regulation is assumed and wastes can be freely disposed, the aggregate desirable output produced by these firms could be augmented by 25 per cent, figure that amounts to 64,915 thousands of euros, with an average of 2,238 thousands per firm. Besides, eleven firms behave efficiently in this *unregulated* scenario, i.e., their computed *DDF* equals to zero. In opposition, when it is assumed a *regulated* scenario and disposing wastes becomes a costly activity, the maximum attainable aggregate expansion of *goods* goes down to 16,982 thousands of euros (586 euros per firm), showing that environmental regulations have an opportunity cost measurable in terms of a lower feasible expansion of desirable outputs. In this case, the reduced production of ceramic pavements due to inefficiency represents 6.5 per cent of the total good output produced by these firms. In the *regulated* scenario, twenty two tile firms show an efficient behaviour.

[Table 2 about here]

[6] Notice that this direction changes the left hand side of restrictions *(i)*, *(ii)* and *(iii)* in expressions (11), (12) and (16) to $\mathbf{x}_o$, $\left(\mathbf{y}_o^g+\beta\right)$ and $\mathbf{y}_o^b$, respectively.

For these ceramic firms behaving according what we have termed the *basic situation*, the impact of environmental regulation can be conventionally computed as stated by expression (14), i.e., as the difference between the potential increases of ceramic pavements under both the *unregulated* and *regulated* scenarios. Figures on regulatory impacts are reported on the third column of *Table 2*. When it is assumed that environmental rules prevent free disposal of *bads*, in aggregate terms these 'well behaved' producers would have to renounce to a potential increase of desirable output of 47,933 thousands of euros (1,653 per firm). This figure amounts to 18.5 per cent of their observed aggregated production of ceramic pavements.

On the other hand, comparison of *DDF* computed under the *SDB* and *SDIB* axioms also reveals that the behaviour of the six remaining firms (decision making units 1, 7, 11, 13, 24 and 27) corresponds to what we have denominated the *complex situation* depicted in *Figure 2* (see the last column of *Table 2*). In particular, firm number 13 displays a behaviour analogous to productive unit *C*, while firms 1, 7, 11, 24 and 27 are productive units similar to point *D*. The traditional approach to the measurement of the impact of environmental regulations on firms performance, i.e., the simple comparison of *DDF* computed under both *SDB* and *WDB*, would lead to assess that, given their respective inputs vectors, no chance exists for the five firms type *D* to attain increases of their production of ceramic pavements, neither under the *unregulated* scenario nor under the *regulated* one. On the contrary, by behaving efficiently, the only firm type *C* in our sample (decision making unit number 13) could increase its production of ceramic pavements by 1,821 thousands of euros, under both the *unregulated* and *regulated* scenarios. Accordingly, environmental regulation is not binding for productive units type *C* and *D*, and their regulatory impact index equals to zero.

Nevertheless, computation of the *DDF* for tile firms showing a *complex behaviour* under the axiom of *SDIB*, i.e., considering *bads* as strong disposable detrimental inputs, displays a picture somewhat different. In the light of this new technological consideration, these six productive units could attain an aggregate increase in their production of ceramic pavements of 13,026 thousands of euros, without additional consumption of inputs, with an average per firm of 2,171 thousands of euros. Doubtless, this is an information of great interest for the managers of these firms. Nonetheless, regulating authorities should also be aware that these tile firms are producing a level of bad output over to they would require, even in the case they maximize their production of ceramic pavements. In this situation, an effective reduction in the aggregate level of watery mud and used oil could be achieved by environmental-friendly regulations, without limiting the production of the good output.

4. Concluding remarks

Environmental performance is a major matter of concern for both firms' managers and academics in the field of environmental economics. Besides, the growing recognition of the environment as a public good in the industrialised countries has stimulated wide-ranging legislation aimed at achieving predetermined standards of environmental quality. This setting calls for new methods to evaluate the environmental performance of firms and the impact of environmental-friendly regulations on their productive activity.

In this paper we propose the use of directional distance functions to test for the existence of firms behaving accordingly to what we call *complex situations*, corresponding to productive units showing a quite unsuccessful economic and environmental performance. We show that when the biggest polluter is not the greater producer, by enforcing adequate environmental regulations, public authorities could achieve an effective reduction on the production of *bads*, without affecting the level of *goods*. Furthermore, we illustrate our methodological proposal with an empirical application to a sample of cross-section data of Spanish tile producers.

Acknowledgements

We are indebted to Francesc Hernández-Sancho for data availability. Andrés J. Picazo-Tadeo gratefully acknowledges the financial aid received from the *Spanish Ministry of Science and Technology* (project AGL2003-07446-C03-03). Diego Prior received financial aid from the *Spanish Ministry of Science and Technology* (project SEC2003-04770). The usual disclaimer applies.

References

Allen, K., 1999, DEA in the ecological context: an overview. In: Westermann, G. (Ed.), *Data Envelopment Analysis in the service sector*. Gabler Edition Wissenschaft, Germany, 203-235.

Ball, V.E. Lovell, C.A.K., Nehring, R.F., Somwaru, A., 1994, Incorporating undesirable outputs into models of production: an application to US agriculture. *Cahiers d'Economique et Sociologie Rurales* 31, 59-73.

Ball, V.E., Färe, R., Grosskopf, S., Nehring, R.F., 2001, Productivity of the US agricultural sector: the case of undesirable outputs. In: Hulten, Ch., Dean, E.R., Harper, M.J. (Eds.), *New developments in productivity measurement*. *NBER*. The University of Chicago Press.

Banker, R.D., Charnes, A., Cooper, W.W., 1984, Some models for estimating technical and scale inefficiencies in Data Envelopment Analysis. *Management Science* 30, 1078-1092.

Brännlund, R., Färe, R., Grosskopf, S., 1995, Environmental regulation and profitability: an application to Swedish pulp and paper mills. *Environmental and Resource Economics* 6, 23-36.

Chambers, R.G., Chung, Y., Färe, R., 1998, Profit, directional distance functions and Nerlovian efficiency. *Journal of Optimization Theory an Applications* 98, 351-364.

Chung, Y., Färe, R., Grosskopf, S., 1997, Productivity and undesirable outputs: a directional distance function approach. *Journal of Environmental Management*, 51, 229-240.

Coggins, J.S., Swinton, J.R., 1996, The price of pollution: a dual approach to valuing SO_2 allowances. *Journal of Environmental Economics and Management* 30, 58-72.

Färe, R., Grosskopf, S., Lovell, C.A.K., 1994, *Production Frontiers*. Cambridge University Press, Cambridge.

Färe, R., Grosskopf, S., 2000, Theory and application of directional distance functions. *Journal of Productivity Analysis* 13, 93-103.

Färe, R., Grosskopf, S., 2004, *New directions: efficiency and productivity*. Kluwer Academic Publishers, Boston/London/Dordrecht.

Färe, R., Grosskopf, S., Lovell, C.A.K., Pasurka, C., 1989, Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach. *The Review of Economics and Statistics* 71, 90-98.

Färe, R., Grosskopf, S., Lovell, C.A.K., Yaisawarng, S., 1993, Derivation of shadow prices for undesirable outputs: a distance function approach. *The Review of Economics and Statistics* 75, 374-380.

Färe, R., Grosskopf, S., Tyteca, D., 1996, An activity analysis model of the environment performance of firms: application to fossil-fuel-fired electric utilities. *Ecological Economics* 18, 161-175.

Färe, R., Primont, D., 1995, *Multi-output production and duality: theory and applications*. Kluwer Academic Publishers.

Färe, R., Grosskopf, S., Pasurka, C.A., 2003, Estimating pollution abatement costs: a comparison of 'stated' and 'revealed' approaches, *Working Paper Oregon State University*. http://oregonstate.edu/dept/econ/research/working_papers.php.

Farrell, M., 1957, The measurement of productive efficiency. *Journal of the Royal Statistics Society. Series A* 120, 253-282.

Grosskopf, S., 1986, The role of the reference technology in measuring production efficiency. *The Economic Journal* 96, 499-513.

Hernández-Sancho F., Picazo-Tadeo, A., Reig-Martínez, E., 2000, Efficiency and environmental regulation. *Environmental and Resource Economics* 15, 365-378.

Picazo-Tadeo, A.J., Reig-Martínez, E., Hernández-Sancho, F., 2005, Directional distance functions and environmental regulation. *Resource and Energy Economics*, in press.

Pittman, R.W., 1981, Issues in pollution control: interplant cost differences and economies of scale. *Land Economics*, 57, pp. 1-17.

Pittman, R.W., 1983, Multilateral productivity comparisons with undesirable outputs. *Economic Journal* 93, 883-891.

Prior, D., 2005, Efficiency and total quality management in health care organisations. A dynamic frontier approach. *Annals of Operations Research*, in press.

Reig-Martínez, E., Picazo-Tadeo, A., Hernández-Sancho, F., 2001, Shadow prices and distance functions: an analysis for firms of the Spanish ceramic pavements industry. *International Journal of Production Economics* 69, 277-285.

Reinhard, S, Lovell, C.A.K, Thijssen, G., 2002, Analysis of environmental efficiency variation. *American Journal of Agricultural Economics* 84, 1054-1065.

Reinhard, S., Lovell, C.A.K., Thijssen, G., 1999, Econometric estimation of technical and environmental efficiency: an application to Dutch dairy farms. *American Journal of Agricultural Economics*, 81, 44-60.

Shephard, R.W., 1970, *Theory of cost and production functions*. Princeton University Press, Princeton.

Shephard, R.W., Färe, R., 1974, The law of diminishing returns. *Zeitschrift für Nationalökonomie* 34, 69-90.

Swinton, J.R., 1998, At what cost do we reduce pollution? Shadow prices of SO_2 emissions. *Energy Journal* 19, 63-83.

Tyteca, D., 1996, On the measurement of the environmental performance of firms: a literature review and a productive efficiency perspective. *Journal of Environmental Management* 46, 281-308.

Tyteca, D., 1997, Linear programming models for the measurement of environmental performance of firms: concepts and empirical results. *Journal of Productivity Analysis* 8, 175-189.

Zofio, J.L., Prieto, A., 2001, Environmental efficiency and regulatory standards: the case of CO2 emissions from the OECD industries. *Resource and Energy Economics* 23, 63-93.

Table 1.- Sample description.

Variable	*Measurement unit*	*Mean*	*Standard deviation*
Desirable output			
Ceramic pavements	Euros (thousands)	8,814.1	11,470.0
Undesirable outputs			
Watery mud	Tons	1,725.9	3,411.6
Used oil	Kilograms	1,537.4	2,460.5
Inputs			
Clay, kaolin, felspar and limestones	Tons	58,182.3	102,559.3
Labour	Number of workers	87.0	101.5
Capital	Kilowatts-hour (thousands)	3,408.4	4,006.8

Table 2.- Computed distance functions, regulatory impacts and type of firms.

	Bads as undesirable outputs			*Bads as strong disposable inputs*	
Firm	*Unregulated scenario (SDB)*	*Regulated scenario (WDB)*	*Regulatory impact index*	*SDIB*	*Firm type*
1	0	0	0	1,151	*D*
2	0	0	0	0	-
3	3,918	0	3,918	0	-
4	2,624	1,208	1,416	1,208	-
5	0	0	0	0	-
6	1,113	184	929	228	-
7	0	0	0	2,274	*D*
8	16,274	11,551	4,723	11,551	-
9	0	0	0	0	-
10	0	0	0	0	-
11	0	0	0	3,171	*D*
12	0	0	0	0	-
13	1,821	1,821	0	4,269	*C*
14	0	0	0	0	-
15	433	0	433	0	-
16	12,215	0	12,215	0	-
17	0	0	0	0	-
18	2,693	0	2,693	0	-
19	1,327	0	1,327	0	-
20	1,149	0	1,149	535	-
21	7,270	539	6,731	759	-
22	2,011	700	1,311	588	-
23	0	0	0	0	-
24	0	0	0	1,479	*D*
25	0	0	0	0	-
26	1,449	0	1,449	0	-
27	0	0	0	682	*D*
28	336	0	336	0	-
29	0	0	0	0	-
30	3,241	0	3,241	0	-
31	2,461	0	2,461	375	-
32	596	0	596	0	-
33	3,703	1,880	1,823	1,999	-
34	2,102	920	1,182	920	-
35	0	0	0	0	-

Figure 1.- Weak and strong disposability of bad outputs (I): the *basic situation*.

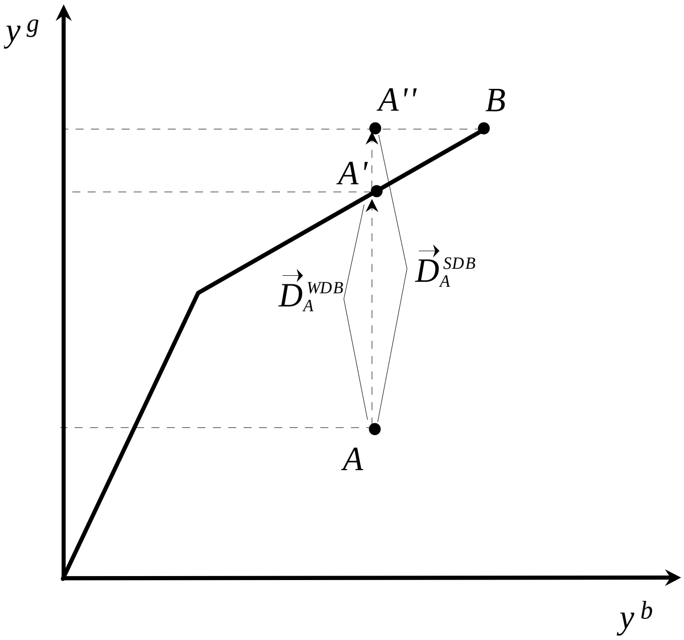


Figure 2.- Weak and strong disposability of bad outputs (II): the *complex situation*.

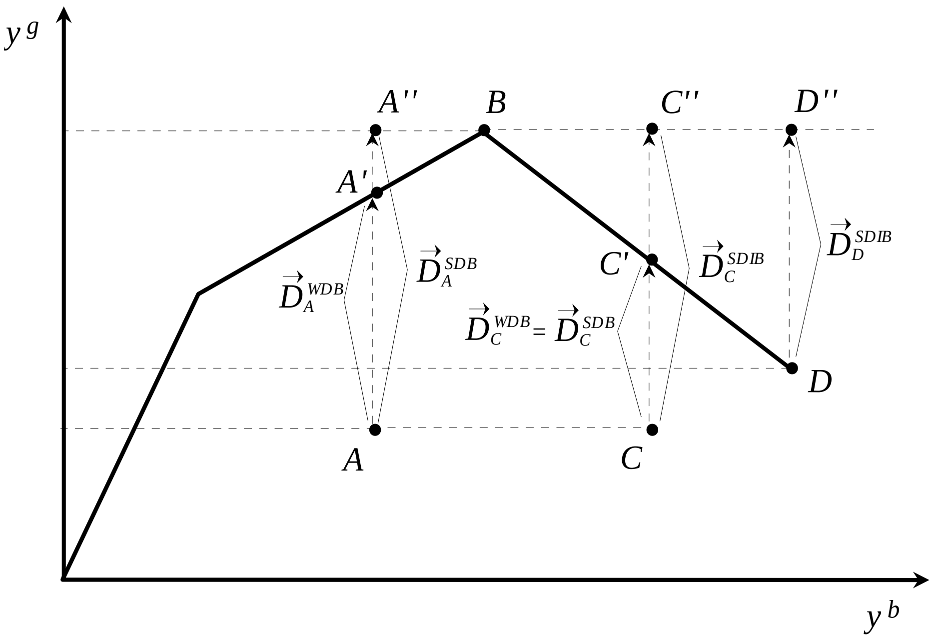
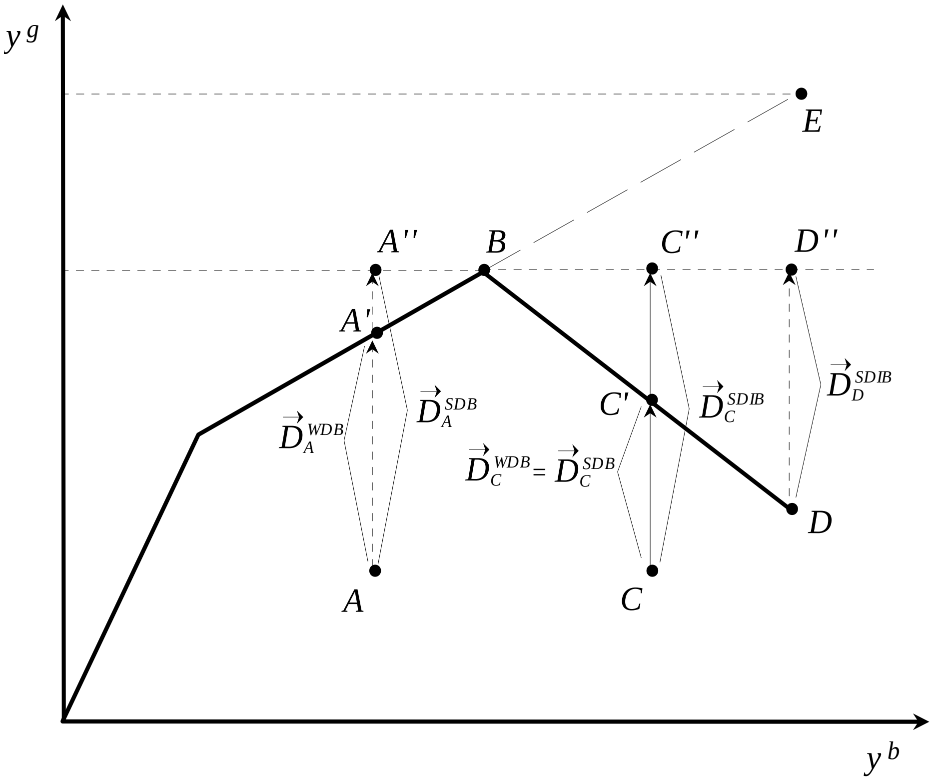


Figure 3.- Weak and strong disposability of bad outputs (III): the *long-run perspective*.



Edicions / Issues:

95/1 *Productividad del trabajo, eficiencia e hipótesis de convergencia en la industria textil-confección europea*
Jordi López Sintas

95/2 *El tamaño de la empresa y la remuneración de los máximos directivos*
Pedro Ortín Ángel

95/3 *Multiple-Sourcing and Specific Investments*
Miguel A. García-Cestona

96/1 *La estructura interna de puestos y salarios en la jerarquía empresarial*
Pedro Ortín Ángel

96/2 *Efficient Privatization Under Incomplete Contracts*
Miguel A. García-Cestona
Vicente Salas-Fumás

96/3 *Institutional Imprinting, Global Cultural Models, and Patterns of Organizational-Learning: Evidence from Firms in the Middle-Range Countries*
Mauro F. Guillén (The Wharton School, University of Pennsylvania)

96/4 *The relationship between firm size and innovation activity: a double decision approach*
Ester Martínez-Ros (Universitat Autònoma de Barcelona)
José M. Labeaga (UNED & Universitat Pompeu Fabra)

96/5 *An Approach to Asset-Liability Risk Control Through Asset-Liability Securities*
Joan Montllor i Serrats
María-Antonia Tarrazón Rodón

97/1 *Protección de los administradores ante el mercado de capitales: evidencia empírica en España*
Rafael Crespí i Cladera

97/2 *Determinants of Ownership Structure: A Panel Data Approach to the Spanish Case*
Rafael Crespí i Cladera

97/3 *The Spanish Law of Suspension of Payments: An Economic Analysis From Empirical Evidence*
Esteban van Hemmen Almazor

98/1 *Board Turnover and Firm Performance in Spanish Companies*
Carles Gispert i Pellicer

98/2 *Libre competencia frente a regulación en la distribución de medicamentos: teoría y evidencia empírica para el caso español*
Eva Jansson

98/3 *Firm's Current Performance and Innovative Behavior Are the Main Determinants of Salaries in Small-Medium Enterprises*
Jordi López Sintas y Ester Martínez Ros

98/4 *On The Determinants of Export Internalization: An Empirical Comparison Between Catalan and Spanish (Non-Catalan) Exporting Firms*
Alex Rialp i Criado

98/5 *Modelo de previsión y análisis del equilibrio financiero en la empresa*
Antonio Amorós Mestres

99/1 *Avaluació dinàmica de la productivitat dels hospitals i la seva descomposició en canvi tecnològic i canvi en eficiència tècnica*
Magda Solà

99/2 *Block Transfers: Implications for the Governance of Spanish Corporations*
Rafael Crespí, and Carles Gispert

99/3 *The Asymmetry of IBEX-35 Returns With TAR Models*
M.ª Dolores Márquez, César Villazón

99/4 *Sources and Implications of Asymmetric Competition: An Empirical Study*
Pilar López Belbeze

99/5 *El aprendizaje en los acuerdos de colaboración interempresarial*
Josep Rialp i Criado

00/1 *The Cost of Ownership in the Governance of Interfirm Collaborations*
Josep Rialp i Criado, i Vicente Salas Fumás

00/2 *Reasignación de recursos y resolución de contratos en el sistema concursal español*
Stefan van Hemmen Alamazor

00/3 *A Dynamic Analysis of Intrafirm Diffusion: The ATMs*
Lucio Fuentelsaz, Jaime Gómez, Yolanda Polo

00/4 *La Elección de los Socios: Razones para Cooperar con Centros de Investigación y con Proveedores y Clientes*
Cristina Bayona, Teresa García, Emilio Huerta

00/5 *Inefficient Banks or Inefficient Assets?*
Emili Tortosa-Ausina

01/1 *Collaboration Strategies and Technological Innovation: A Contractual Perspective of the Relationship Between Firms and Technological Centers*
Alex Rialp, Josep Rialp, Lluís Santamaria

01/2 *Modelo para la Identificación de Grupos Estratégicos Basado en el Análisis Envolvente de Datos: Aplicación al Sector Bancario Español*
Diego Prior, Jordi Surroca

01/3 *Seniority-Based Pay: Is It Used As a Motivation Device?*
Alberto Bayo-Moriones

01/4 *Calidad de Servicio en la Enseñanza Universitaria: Desarrollo y Validación de una Escala de Medida.*
Joan-Lluís Capelleras, José M.ª Veciana

01/5 *Enfoque estructural vs. recursos y capacidades: un estudio empírico de los factores clave de éxito de las agencias de viajes en España.*
Fabiola López-Marín, José M.ª Veciana

01/6 *Opción de Responsabilidad Limitada y Opción de Abandonar: Una Integración para el Análisis del Coste de Capita.*
Neus Orgaz

01/7 *Un Modelo de Predicción de la Insolvencia Empresarial Aplicado al Sector Textil y Confección de Barcelona (1994-1997).*
Antonio Somoza López

01/8 *La Gestión del Conocimiento en Pequeñas Empresas de Tecnología de la Información: Una Investigación Exploratoria*.
Laura E. Zapata Cantú

01/9 *Marco Institucional Formal de Creación de Empresas en Catalunya: Oferta y Demanda de Servicios de Apoyo*
David Urbano y José María Veciana.

02/1 *Access as a Motivational Device: Implications for Human Resource Management*.
Pablo Arocena, Mikel Villanueva

02/2 *Efficiency and Quality in Local Government. The Case of Spanish Local Authorities*
M.T. Balaguer, D. Prior, J.M. Vela

02/3 *Single Period Markowitz Portfolio Selection, Performance Gauging and Duality: A variation on Luenberger's Shortage Function*
Walter Briec, Kristiaan Kerstens, Jean Baptiste Lesourd

02/4 *Innovación tecnológica y resultado exportador: un análisis empírico aplicado al sector textil-confección español*
Rossano Eusebio, Àlex Rialp Criado

02/5 *Caracterización de las empresas que colaboran con centros tecnológicos*
Lluís Santamaria, Miguel Ángel García Cestona, Josep Rialp

02/6 *Restricción de crédito bancario en economías emergentes: el caso de la PYME en México*
Esteban van Hemmen Almazor

02/7 *La revelación de información obligatoria y voluntaria (activos intangibles) en las entidades de crédito. Factores determinantes.*
Gonzalo Rodríguez Pérez

02/8 *Measuring Sustained Superior Performance at the Firm Level*
Emili Grifell - Tatjé, Pilar Marquès - Gou

02/9 *Governance Mechanisms in Spanish Financial Intermediaries*
Rafel Crespi, Miguel A. García-Cestona, Vicente Salas

02/10 *Endeudamiento y ciclos políticos presupuestarios: el caso de los ayuntamientos catalanes*
Pedro Escudero Fernández, Diego Prior Jiménez

02/11 *The phenomenon of international new ventures, global start-ups, and born-globals:what do we know after a decade (1993-2002) of exhaustive scientific inquiry?*
Àlex Rialp-Criado, Josep Rialp-Criado, Gary A. Knight

03/1 *A methodology to measure shareholder value orientation and shareholder value creation aimed at providing a research basis to investigate the link between both magnitudes*
Stephan Hecking

03/2 *Assessing the structural change of strategic mobility. Determinants under hypercompetitive environments*
José Ángel Zúñiga Vicente, José David Vicente Lorente

03/3 *Internal promotion versus external recruitment: evidence in industrial plants*
Alberto Bayo-Moriones, Pedro Ortín-Ángel

03/4 *El empresario digital como determinante del éxito de las empresas puramente digitales: un estudio empírico*
Christian Serarols, José M.ª Veciana

03/5 *La solvencia financiera del asegurador de vida y su relación con el coste de capital*
Jordi Celma Sanz

03/6 *Proceso del desarrollo exportador de las empresas industriales españolas que participan en un consorcio de exportación: un estudio de caso*
Piedad Cristina Martínez Carazo

03/7 *Utilidad de una Medida de la Eficiencia en la Generación de Ventas para la Predicción del Resultado*
María Cristina Abad Navarro

03/8 *Evaluación de fondos de inversión garantizados por medio de portfolio insurance*
Sílvia Bou Ysàs

03/9 *Aplicación del DEA en el Análisis de Beneficios en un Sistema Integrado Verticalmente Hacia Adelante*
Héctor Ruiz Soria

04/1 *Regulación de la Distribución Eléctrica en España: Análisis Económico de una Década, 1987-1997*
Leticia Blázquez Gómez; Emili Grifell-Tatjé

04/2 *The Barcelonnettes: an Example of Network-Entrepreneurs in XIX Century Mexico. An Explanation Based on a Theory of Bounded Rational Choice with Social Embeddedness.*
Gonzalo Castañeda

05/1 *IFRS Adoption in Europe: The Case of Germany.*
Soledad Moya, Jordi Perramon, Anselm Constans

05/2 *Efficiency and environmental regulation: a 'complex situation'*
Andrés J. Picazo-Tadeo, Diego Prior