Analyzing Interplant Marginal Abatement Cost Differences: A Directional Output Distance Function Approach[•]

by

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Abstract.

The purpose of this paper is to compute and evaluate producers' marginal abatement costs (MACs). These costs are obtained by calculating shadow prices of bad outputs from the production technology, which is represented by the estimated directional output distance function. To be more specific, this paper considers the Swedish pulp industry when the regulatory authority has granted each producing plant a maximally allowed emission level. In each case, area residents and other parties concerned have been allowed to express their views, which possibly prepared the way for other factors than prescribed by environmental law, to influence the stringency of the finally allowed emission levels and, therefore, the MACs. The main focus is on whether the calculated MACs reveal that differences between counties in, e.g., economical characteristics, were influential when the authority, during 1983-1990, restricted 12 geographically scattered pulp plants regarding emissions. The result indicates that the MACs vary between many of the plants and that county differences were taken into account when imposing environmental restrictions on the plants.

Key words: bad output, environmental regulation, marginal abatement cost, shadow price, parametric directional output distance function

JEL classification: C61, D24, L51, Q53, R38

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1 INTRODUCTION

Many types of human activities have negative side effects on the environment. These effects may be due to bad outputs, i.e., undesirable by-products from production processes. The effects are, from a societal point of view, considered excessive if no corrective measures are undertaken. Public authorities are therefore called upon to regulate the performance of polluting industries. Regulations, for instance, in the form of producer specific quotas that specify maximum levels of bad output discharges, are legislated to limit the environmental damages. In fulfilling these requirements, the industrial producers face abatement costs, which can be evaluated. The evaluation of abatement efforts may expose information that is useful. Such information can be obtained by computing the producers' marginal abatement costs (MACs), or shadow prices, of bad outputs. This is at the core of this paper.

Computed bad output shadow prices can be used for several purposes; (a) since these prices become visible and are interpreted as MACs, producers may be informed about these prices. Each producer then gets an indication of her/his abatement efforts in comparison with that of others. If markets for pollution rights exist, the producers can also use the MAC information to determine whether it is worthwhile to buy or sell rights; (b) traditional productivity measures can be extended to include polluting emissions when analyzing productivity growth of producing plants, sectors, or countries; (c) one can study whether the existing environmental regulations are cost efficient, i.e., whether they are imposed so that environmental goals are achieved at minimum abatement cost to society; (d) one can analyze why MACs may vary between producers, in purpose to more thoroughly understand the environmental policy in effect. Earlier studies on this subject, overviewed in Section 3, have mainly focused on the first three purposes, while this paper mainly focuses on the last.

Specifically, producers' MACs are studied in order to find out which factors that may have influenced the pursued environmental policy in Sweden. In particular, the pulp and paper industry is under study. To limit the emissions into water, the environmental authority has granted each production plant permits that specify maximally allowed emission levels. During the handling of each such case, area residents and other parties concerned have been allowed to express their views, which may have created possibilities for other factors than those regulated by the environmental legislation to influence the granted permits and, therefore, the MACs. By studying the MACs, this paper seeks the answer to whether regional differences mattered when environmental regulations were imposed on 12 geographically scattered Swedish pulp plants during 1983-1990.

As a first step, shadow prices, reflecting MACs of bad outputs, are estimated for each pulp plant and compared to each other through non-parametric tests to establish whether MACs vary significantly between plants. The approach adopted to compute these prices originates from Färe et al. (2002), where bad outputs are treated differently compared to earlier studies discussed in Section 3. The model is founded on production theory where the technology is represented by the directional output distance function, from which the shadow prices are derived. The distance function is specified using a quadratic flexible functional form and computed by a linear programming technique. In a second step, the computed MACs are regressed on a set of variables in an attempt to explain why MACs may vary across plants. In this paper, hypotheses concerning variables that vary between regions, such as tax base, population density, employment in the pulp and paper industry, and unemployment, are suggested. Also, fixed and time specific effects are included.

The paper is structured as follows. In the next section a background to the issue at study is given. Section 3 provides an overview of the development of bad output shadow-pricing models. The theoretical framework including the underlying production technology, the directional output distance function, and the shadow-pricing model is provided in Section 4. In Section 5 the empirical model is given. First, the directional output distance functional form and the technique to estimate this form is provided. Then, a model for testing why MACs vary is suggested. Data are described in Section 6, and the empirical results are presented in Section 7. Finally, Section 8 summarizes and concludes.

2 BACKGROUND

A substantial part of the emissions into the Gulf of Bothnia, the Bothnian Sea, and the Baltic Sea originates from the Swedish pulp and paper industry. To ensure a better quality of these waters, the National Licensing Board for Environment Protection, NLBEP, has imposed emission standards in the form of non-tradable permits on the production plants.[1] During the time period under study, 1983-1990, the NLBEP was a central government authority that assessed environmentally hazardous activity and acted under the Environment Protection Act (Miljöskyddslagen,1969:387).[2]

The pulp and paper plants were obliged to apply for permits when they wished to increase production or alter emission quotas. The applications were sent to the NLBEP, which, in a manner of court procedure, assessed whether the plants were allowed to make these alterations. However, before the NLBEP granted a permit, the received application was sent on to other authorities and organizations for review. The Environmental Protection Agency, the County Administrative Board, the Municipal Environment and Health Protection Committee were allowed to comment on all cases. Also, regional and local agents, e.g., residents, politicians, and industry and plant representatives were given the opportunity to express their opinions. When the written investigation of a plant was completed, the NLBEP held an on-site meeting and inspection of the plant. These meetings were advertised in advance in local newspapers, and were open to all who considered themselves affected.

Factors that the NLBEP were prescribed to take into consideration in the granting procedure were provided by the Environment Protection Act. In practice, the plants' technological possibilities of abating and the sensitivity to emissions in the

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[1] The National Licensing Board for Environment Protection (2003).

[2] The Environment Protection Act is no longer in effect. The Environmental Code (Miljöbalken, 1998:808) applies from January 1, 1999, where differently aimed Acts, including the Environment Protection Act, have been co-coordinated. At the same time, five environmental courts, located in the cities of Stockholm, Umeå, Vänersborg, Växjö, and Östersund replaced the NLBEP. However, in general, the Environmental Code and the introduction of new courts have not altered the procedure of granting non-tradable emission permits (The Swedish Environmental Protection Agency, 2003).

affected surrounding environment were considered. This means that all other economic factors, private as well as social, were not supposed to be considered. All plants, independently of geographical location, were supposed to be treated equally in context of the Environment Protection Act.[3]

The procedure of letting area residents and other parties express their views could create an opening for other economic factors to influence the procedure of granting non-tradable emission permits. For instance, for plants in review that are located in high unemployment areas, it may be argued that society benefits from less stringent environmental restrictions if this implies that the plants can keep up, or even increase, the employment rate. In this case, society faces a trade-off between employment and environmental quality that should be optimized. This means that plants located in such areas may face lower MACs of bad outputs. This paper addresses this and similar issues by statistically testing whether there are any significant relationships between regional labor market characteristics and the pulp plants' MACs. Hypotheses regarding regional population density and tax base are also tested.

Before outlining the theoretical model, including the concept of shadow-pricing of bad outputs, an overview of the development of the estimation of bad output shadow prices is provided in the next section.[4]

3 SHADOW-PRICING MODELS

One of the first attempts to analyze producer environmental performance from an estimated bad output shadow price was made by Pittman (1981). He studied 30 pulp and paper plants in Wisconsin and Michigan in 1976. The purpose was partly to investigate whether the pollution control requirements, set by the authorities, were cost efficient. Pittman specified a restricted profit maximization problem where one of the restrictions was plant specific quotas specifying maximum allowed levels of biological oxygen demand (BOD) discharge into the waters. The

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[3] The Swedish Environmental Protection Agency (2003).
[4] Readers not interested may go directly to Section 4.

Lagrange multiplier of that restriction, reflecting the shadow price, or the MAC, of BOD, was then econometrically estimated in a system of equations. This means that Pittman assumed that each plant discharged exactly as much BOD as it was allowed to. One of the findings was that the shadow price differed substantially between plants and it was interpreted such that the pollution control regulations allocated abatement resources inefficiently. A conclusion was, therefore, that either an effluent charge or a market for transferable discharge permits would potentially result in a more efficient resource allocation. A striking feature of the Pittman model is that the pollutant BOD is treated in the same way as conventional inputs. Pittman (1983) presented an alternative use of bad output shadow prices, where the estimates were used in the construction of a multi-factor productivity index. The hypothesis was that differences in conventionally measured productivity (excluding information on pollutants) among different plants could be explained by the failure to account for pollution control behavior. However, his empirical results clearly rejected the hypothesis, but he found that productivity measures, which ignore information on pollutants, might yield misleading results from a societal point of view.

Färe et al. (1993) characterized the structure of production technology with the Shephard multi-output distance function, which is dual to the revenue function. Using this approach, duality theory is exploited and shadow prices of outputs are derived from the distance function using Shephard’s dual lemma. A major difference compared to the Pittman approach is that emissions are here treated as undesirable by-products from production processes. Estimated shadow prices then reflect the trade-off between good and bad outputs. This means that information on environmental restrictions imposed on producers are not needed in this case and, consequently, there is no need to assume that producers are satisfying these requirements when estimating shadow prices. Färe et al. (1993) computed the output distance function on the Pittman (1981, 1983) data by employing a parametric linear programming technique. Their findings coincided with Pittman’s in the sense that shadow prices varied between plants and, given the plants geographical proximity, this suggested that the environmental regulations in effect were not allocating resources efficiently.

Coggins and Swinton (1996) used the Färe et al. (1993) approach to calculate the shadow price, or MAC, of sulfur dioxide (SO_2) for 14 Wisconsin coal-burning electric utility plants during 1990-1992. They suggested that the shadow price could be interpreted as the market value of a SO_2 emission allowance to the plants in the study. Coggins and Swinton noted that the estimated sample average shadow price was close to prices at which actual trades between utilities had occurred, and that the shadow price varied widely across the sample. This variability was further confirmed by Swinton (1999), who pointed out that the variability also highlighted a dramatic difference in MACs among plants using different abatement strategies, as installing scrubber capital or purchasing low-sulfur fuel.

Reig-Martínez et al. (2001) used the Färe et al. (1993) approach on 18 Spanish ceramic pavement producers in 1995. They observed that shadow prices of watery muds and used oil differed significantly across the sample. Due to the closely knitted geographical location of these producers, Reig-Martínez et al. (2001) found it reasonable to assume that marginal social benefits from reducing emissions were similar between the producers. Therefore, they concluded that the existing situation was not efficient in terms of allocating resources and that a market of emission permits could be developed. Reig-Martínez et al. (2001) used the calculated shadow prices to construct a labor productivity deviation index (PDI), which compares a conventional form of labor productivity to an extended form of the same. The calculated PDI showed that the conventional index overestimated labor productivity by 12 percent on average in terms of revenues per labor unit. Their major point was that producers that are less productive in conventional terms might be relatively productive when taking the environment issue into account.

Färe et al. (2002) suggest a directional output distance function approach to calculate shadow prices of bad outputs. Unlike the Shephard output distance function used in the studies discussed above, which expands both good and bad outputs to the output frontier, this function allows for a simultaneous expansion of good outputs and contraction of bad outputs (see Figure 1 in Section 4). Consequently, this new approach will, in comparison with the Shephard approach, imply different shadow prices of bad outputs. Färe et al. (2002) apply the approach to the U.S. agricultural sector for the period 1960-1996. They calculate shadow prices of two indices that capture the effects on drinking water of pesticides leaching into the ground water, and of pesticide runoff into the surface water. The resulting shadow prices are then used to calculate the pollution cost for leaching and for runoff. Their results indicate that these costs are significant, averaging about 17.5 percent of the revenues from good outputs.

4 THEORY

The shadow-pricing model adopted in this paper, which allows for the calculation of shadow prices of bad outputs, originates from Färe et al. (2002).[5] The theoretical framework that constitutes the basis of this model is founded on the underlying production technology, here the output possibilities set, and the directional output distance function, which is defined on this set. The distance function then inherits the properties from the output set and is, therefore, an adequate representative of the production technology. By exploiting the duality theory, the shadow-pricing model can then be derived from the distance function by using the envelope theorem. To begin the theoretical outline, the output possibilities set is first discussed.

4.1 Underlying production technology

Formally, let $y = (y_1, ..., y_M) \in \Re_+^M$ and $b = (b_1, ..., b_J) \in \Re_+^J$ be vectors of good outputs and bad outputs, respectively, and let $x = (x_1, ..., x_N) \in \Re_+^N$ denote a vector of inputs. Then, the production technology is generally characterized by the output possibilities set as

$$P(x) = \{(y, b) : x \text{ can produce } (y, b)\} \tag{1}$$

[5] A similar shadow-pricing model was introduced already in Färe et al. (2001). However, on that occasion, bad outputs were not included.

which further is assumed to satisfy some theoretical properties. It is assumed to be convex, closed and bounded, i.e. compact, with $P(0) = \{0,0\}$. Furthermore, inputs are freely disposable, i.e., if $x' \geq x$ then $P(x') \supseteq P(x)$, which states that if inputs are changed, but not decreased, the new output set contains the original.

The general idea about how to theoretically draw a distinction between good and bad outputs is introduced by the following technological properties. First, outputs are assumed to be weakly disposable, i.e.,

$$\text{if } (y,b) \in P(x) \text{ and } 0 \leq \theta \leq 1, \text{ then } (\theta y, \theta b) \in P(x) \tag{2}$$

This implies that, given a fixed input vector, a reduction in any output is always feasible by reducing the production of all other outputs proportionally. In addition, good outputs are assumed to be freely disposable, i.e.,

$$\text{if } (y,b) \in P(x) \text{ and } y' \leq y, \text{ then } (y',b) \in P(x), \tag{3}$$

which means that, holding input quantities constant, a good output can always be reduced without reducing any other output. Thus, the theoretical distinction between a good and a bad output is that a good output is freely disposable, which is sufficient for being weakly disposable, and a bad output is only weakly disposable. This means that it must be costly to reduce bad outputs, holding inputs constant, since it has to be accomplished by reducing all good outputs, at least proportionally. Obviously, since the cost for reducing bad outputs then must be in terms of forgone revenue from good outputs, each bad output commands its own shadow price at the margin. In these circumstances, when defining the directional output distance function on the output possibilities set, $P(x)$, it appears natural to exploit the duality between the distance function and the revenue function, when deriving the shadow-pricing model.

Finally, the output possibilities set satisfies the property that good outputs are null-joint with the bad outputs, i.e.,

$$\text{if } (y,b) \in P(x) \text{ and } b = 0, \text{ then } y = 0. \tag{4}$$

This means that good outputs cannot be produced without producing bad outputs and, hence, the general idea of bad outputs being undesirable by-products is theoretically modeled.

4.2 The directional output distance function

The directional output distance function is defined on $P(x)$, as

$$D(x,y,b;g) = \max_{\beta}\{\beta : (y + \beta \cdot g_y, b - \beta \cdot g_b) \in P(x)\} \tag{5}$$

where the solution, β^*, gives the maximum expansion and contraction of good outputs and bad outputs, respectively. The vector $g = (g_y, -g_b)$ specifies in what direction an output vector, $(y,b) \in P(x)$, is scaled so as to reach the boundary of the output set at $(y + \beta^* \cdot g_y, b - \beta^* \cdot g_b) \in P(x)$, where $\beta^* = D(x,y,b;g)$. The output possibilities set can be recovered from the distance function in the sense that[6]

$$(y,b) \in P(x) \text{ if and only if } D(x,y,b;g) \geq 0 \tag{6}$$

The distance function takes the value of zero for technically efficient output vectors on the boundary of $P(x)$, whereas positive values apply to technically inefficient output vectors below the boundary. The higher the value the more inefficient the output vector. Finally, the directional output distance function satisfies the translation property, i.e.,[7]

[6] This is valid if $P(x)$ satisfies g-disposability, i.e., if $(y,b) \in P(x)$ then $(y-g_y,b+g_b) \in P(x)$. The concept of g-disposability is defined and more thoroughly discussed in Chung (1996, p. 29-34).

[7] A proof of this statement can be found in Chung (1996, p. 111).

$$D(x, y+\alpha \cdot g_y, b-\alpha \cdot g_b; g) = D(x, y, b; g) - \alpha \tag{7}$$

where α is a positive scalar.

4.3 The shadow-pricing model

When deriving the output shadow-pricing model from the directional output distance function the duality between the distance function and the revenue function is exploited. Let $p = (p_1,..., p_M) \in \Re_+^M$ and $q = (q_1,..., q_J) \in \Re_+^J$ represent prices of good and bad outputs, respectively. The revenue function is then defined on the underlying production technology as[8]

$$\begin{aligned} R(x, p, q) &= \max_{y,b}\{py - qb : (y,b) \in P(x)\} \\ &= \max_{y,b}\{py - qb : D(x, y, b; g) \geq 0\}, \qquad \text{(by using (6))} \end{aligned} \tag{8}$$

Duality means that if the revenue function is generated from the underlying production technology represented by the directional output distance function, as in (8), the directional output distance function can be recovered from the revenue function. This duality is formally established in Färe et al. (2002) and it is shown that the directional output distance function can be expressed as

$$D(x, y, b; g) = \min_{p,q}\{(R(x, p, q) - (py - qb))/(pg_y + qg_b)\} \tag{9}$$

To get the explicit output shadow-pricing model, the envelope theorem is first applied to (9), which yields

$$\nabla_y D(x, y, b; g) = -\frac{p}{(pg_y + qg_b)} \leq 0, \qquad (pg_y + qg_b) > 0 \tag{10a}$$

[8] Note that the shadow prices, q, take non-negative values and are here considered as the cost faced when reducing bad outputs, b.

$$\nabla_b D(x, y, b; g) = \frac{q}{(pg_y + qg_b)} \geq 0, \qquad (pg_y + qg_b) > 0 \qquad (10b)$$

The absolute shadow prices of good and bad outputs could then be derived from (10a) and (10b), respectively. Unfortunately, the value of $(pg_y + qg_b)$ is not known since it consists of the shadow prices not yet calculated. However, if it is assumed that at least one of the good outputs, e.g., y_m, is sold in a perfectly competitive market, its observed price, p_m, can be taken to be the absolute shadow price. If this is the case, the absolute shadow prices of all bad outputs can be calculated as[9]

$$q_j = -\left(\frac{\partial D(x, y, b; g)}{\partial b_j} \bigg/ \frac{\partial D(x, y, b; g)}{\partial y_m} \right) \cdot p_m, \qquad j = 1, ..., J \qquad (11)$$

where the negative of the expression within brackets is the marginal rate of transformation between the $j:th$ bad output and the $m:th$ good output, MRT_{jm}. The shadow price q_j then equals the revenue loss, from decreased sales of y_m, that has to be faced when reducing b_j marginally.

The shadow-pricing model is illustrated in Figure 1. The output possibilities set is given by $P(x)$ and the technically inefficient output vector (y, b) is produced.

[9] Regarding this mode of procedure, see, e.g., Färe et al. (1993).

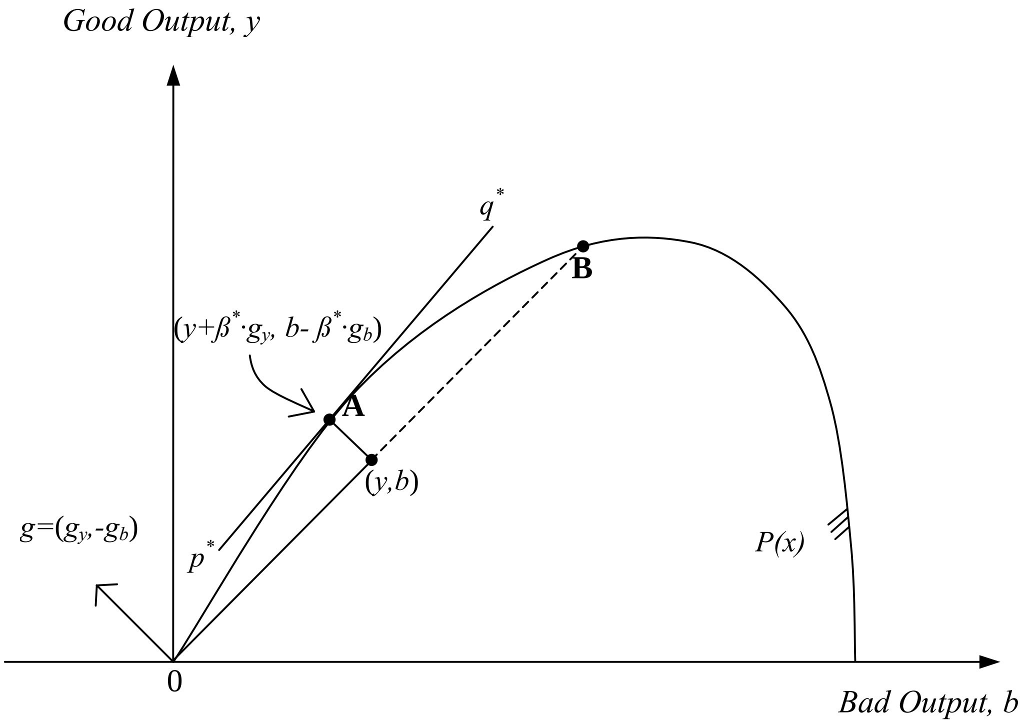

Figure 1 The shadow-pricing model

The directional output distance function in (5) scales (y,b) until it reaches the boundary of $P(x)$ at A. This particular point has a supporting hyper plane interpreted as a shadow price relation, $q^* - p^*$, which counts for (y,b), and can be calculated using the formula in (11). The illustration in Figure 1 also shows that the shadow price valid for the output mix (y,b) differs depending on which distance function that is used. For instance, the standard Shephard output distance function identifies the shadow price relation at point B.

5 THE EMPIRICAL MODEL

5.1 The functional form of the distance function

Following Färe et al. (2001, 2002), the directional output distance function is parameterized by using a (additive) quadratic flexible functional form. Accordingly, for producer k in time period t, the technology to be estimated is written as

$$D^{kt}\left(x^{kt}, y^{kt}, b^{kt}; g\right) = \alpha_0 + \sum_{n=1}^{N}\alpha_n x_n^{kt} + \sum_{m=1}^{M}\beta_m y_m^{kt} + \sum_{j=1}^{J}\gamma_j b_j^{kt}$$
$$+ \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N}\alpha_{nn'} x_n^{kt} x_{n'}^{kt} + \sum_{n=1}^{N}\sum_{m=1}^{M}\delta_{nm} x_n^{kt} y_m^{kt} + \sum_{n=1}^{N}\sum_{j=1}^{J}\eta_{nj} x_n^{kt} b_j^{kt}$$
$$+ \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M}\beta_{mm'} y_m^{kt} y_{m'}^{kt} + \sum_{m=1}^{M}\sum_{j=1}^{J}\mu_{mj} y_m^{kt} b_j^{kt} \tag{12}$$
$$+ \frac{1}{2}\sum_{j=1}^{J}\sum_{j'=1}^{J}\gamma_{jj'} b_j^{kt} b_{j'}^{kt}$$
$$+ \kappa_k + \tau_t$$

where κ and τ represent producer and time specific effects, respectively.

5.2 A technique for estimating the distance function

As in Färe et al. (2001, 2002), the distance function in (12) is estimated by a linear programming technique.[10] Specifically, by assuming the directional vector $g = (1_1,...1_M; -1_1,...,-1_J)$ the parameters in (12) are chosen to[11]

$$\text{minimize} \sum_{k=1}^{K}\sum_{t=1}^{T}\left[D^{kt}\left(x^{kt}, y^{kt}, b^{kt}; 1, -1\right) - 0\right] \tag{13}$$

subject to

$$D^{kt}\left(x^{kt}, y^{kt}, b^{kt}; 1, -1\right) \geq 0, \quad k = 1,...,K, \quad t = 1,...,T \tag{i}$$

$$D^{kt}\left(x^{kt}, y^{kt}, 0; 1, -1\right) < 0, \quad k = 1,...,K, \quad t = 1,...,T \tag{ii}$$

$$\frac{\partial D^{kt}\left(x^{kt}, y^{kt}, b^{kt}; 1, -1\right)}{\partial y_m} \leq 0, \quad k = 1,...,K, \quad t = 1,...,T, \quad m = 1,...,M \tag{iii}$$

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[10] Färe et al. (2001, 2002) refer to the work of Aigner and Chu (1968).

[11] The directional vector g = (1,-1) is chosen for the sake of simplicity. It is then not needed to be included in the parameterization. An alternative would be the vector $g = (y,-b)$, which has been chosen when estimating the directional output distance function by non-parametric piecewise linear programming techniques, see, e.g., Chung et al. (1997).

$$\frac{\partial D^{kt}\left(x^{kt}, y^{kt}, b^{kt}; 1, -1\right)}{\partial b_j} \geq 0, \quad k = 1, \ldots, K, \quad t = 1, \ldots, T, \quad j = 1, \ldots, J \tag{iv}$$

$$\frac{\partial D^{kt}\left(\bar{x}, \bar{y}, \bar{b}; 1, -1\right)}{\partial x_n} \geq 0, \quad n = 1, \ldots, N \tag{v}$$

$$\begin{aligned}
&\sum_{m=1}^{M} \beta_m - \sum_{j=1}^{J} \gamma_j = -1, \\
&\sum_{m'=1}^{M} \beta_{mm'} - \sum_{j=1}^{J} \mu_{mj} = 0, \qquad m = 1, \ldots, M \\
&\sum_{j'=1}^{J} \gamma_{jj'} - \sum_{m=1}^{M} \mu_{mj} = 0, \qquad j = 1, \ldots, J \\
&\sum_{j=1}^{J} \eta_{nj} - \sum_{m=1}^{M} \delta_{nm} = 0, \qquad n = 1, \ldots, N
\end{aligned} \tag{vi}$$

$$\begin{aligned}
&\alpha_{nn'} = \alpha_{n'n}, \quad n \neq n' \\
&\beta_{mm'} = \beta_{m'm}, \quad m \neq m' \\
&\gamma_{jj'} = \gamma_{j'j}, \quad j \neq j'
\end{aligned} \tag{vii}$$

The directional output distance function inherits its properties from the output possibilities set, $P(x)$. Therefore, to ensure that the functional form of the distance function in (12) satisfies these properties, the minimization problem in (13) is solved subject to restrictions (i) – (vii). The restrictions in (i) impose the property in (6), which constrain each producer to operate on, or below, the boundary of $P(x)$. The null-jointness property in (4) is imposed by the restrictions in (ii) and states that good outputs cannot be produced without producing bad outputs. This statement means that, for $y > 0$, the output bundle $(y,0)$ is not technically feasible, which then formally can be stated as $(y,0) \notin P(x)$ if and only if $D(x, y, 0; g) < 0$. The monotonicity conditions in (10a) and (10b) are imposed by the restrictions in (iii) and (iv), respectively. Notice that, by (iii), the property in (3), i.e., free disposability of good outputs, is satisfied. This property can equivalently be stated as: $y' \leq y$ implies $D(x, y', b; g) \geq D(x, y, b; g)$. Inputs are also assumed to be freely disposable, i.e., if $x' \geq x$ then $D(x', y, b; g) \geq D(x, y, b; g)$ and, hence, monotonicity on the inputs is imposed by the restrictions in (v). This is done at the mean level of data. The translation property in (7) is ensured by the restrictions in (vi) and, finally, the restrictions in (vii) impose symmetry.

5.3 Tests concerning variability in MACs

Once the parameters of the directional output distance function are estimated, shadow prices of bad outputs can be calculated for each individual plant, k, in each period, t, by applying the shadow-pricing formula in (11). This also means that MACs for a particular bad output can be compared between plants. To establish whether these costs vary significantly between plants, non-parametric tests can be performed. Independent of time, the Kruskal-Wallis H statistic is used to test the null hypothesis that the MAC samples of two different plants are drawn from the same population, and the alternative that they are not. The test procedure is repeated for every possible two-plant combination in the study. The Kruskal-Wallis statistic is asymptotically distributed as chi-square under the null hypothesis with, in this case, one degree of freedom.[12]

Calculating shadow prices of bad outputs also makes it possible to parametrically test hypotheses of why the MAC of a particular bad output varies between plants. A general model for testing such hypotheses can be formulated as follows:

$$\frac{q_j^{kt}}{p_m^{kt}} = \phi + \zeta Z^{rt} + \rho_k + \psi_t + \varepsilon^{kt}, \qquad j = 1,...,J \tag{14}$$

where $q_j^{kt} \big/ p_m^{kt}$ is the previously calculated MAC of the $j:th$ bad output in terms of the $m:th$ good output, Z is a vector of variables for region r in period t, while ρ_k and ψ_t represent plant specific fixed effects and time specific effects, respectively. The fixed effects are modeled by plant dummies to capture the effects from factors provided by the Environment Protection Act and considered

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[12] For a detailed description of the Kruskal-Wallis test, see, e.g., Mendenhall et al. (1990, pp. 697-702).

by the NLBEP when granting maximally allowed emission levels, i.e., each plant's technological possibilities to abate and the sensitivity to emissions in the affected surrounding environment.[13, 14] The last term on the right-hand side, ε, is an error term that is uncorrelated with all other right-hand side variables and uncorrelated in time and across plants. The parameters to be estimated are ϕ, ζ, ρ_k, where $k = 2,...,K$, and ψ_t, where $t = 2,...,T$.

6 DATA

The directional output distance function is estimated using data on the Swedish pulp and paper industry gathered by Statistics Sweden and the Swedish Environmental Protection Agency. The data set available is an unbalanced panel that contains annual information on eleven plants producing sulfate pulp and one plant producing sulfite pulp. It extends over the period 1983-1990 with a total of 86 observations. To produce the good output, pulp, y_1, each plant is assumed to use four inputs; wood fiber, x_1, labor, x_2, electricity, x_3, and capital, x_4. The capital stock is approximated using a perpetual inventory method based on information about investment in machinery and buildings.[15] Bad outputs are oxygen-demanding substances, b_1, and suspended solids, b_2. The former is collected as discharges of biological (BOD) and chemical (COD) oxygen demand. However, since BOD is a subset of COD, the emissions of BOD are converted into COD by using the conversion factor 3.5.[16] Descriptive statistics for the inputs and outputs are provided in Table A1 in the Appendix.

For the purpose of testing hypotheses regarding the variability of MACs, in accordance with equation (14), some additional information is needed. This

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[13] An alternative to the fixed effects would be to model random effects. However, the random effects model was rejected in this case since the fixed effects model explains the variability of the MAC variable to a much greater extent.

[14] Region dummies that capture effects from omitted variables belonging to vector Z are not included. The reason is that for some regions there are data available on only one plant. This means that the fixed and the region effects cannot be separated since they both are captured, and controlled for, by the plant dummy coefficients, ρ_k.

[15] See, e.g., Berndt (1996).

[16] The Swedish Environmental Protection Agency (1990).

information concerns variables that are motivated by the argument that they may influence economic policy, which also should involve the environment. To start with, environmental quality is a normal good and income is relatively high in Sweden. This should be reflected in a relatively high demand for environmental quality, possibly varying across counties due to differences in income. Higher income allows people to financially support, and/or actively commit to, environmental movements. Also, higher income allows people to spend more time on environmental activities on their own, e.g., trying to influence the environmental authority that handles and grants the pulp plants' emission permits. The hypothesis tested is, therefore, whether the county tax base per resident, *Rtaxbase*,[17] is positively correlated with the pulp plants' MACs, which reflect the stringency of environmental regulation. The county population density, *Rpopdens*, will also be included since regional, or point, emissions harm more people the higher the density near the polluting source. The hypothesis tested is whether there is a positive correlation between population density and pulp plants' MACs. Pressure from the people possibly affects the authority to grant lower maximally allowed emission levels, leading to higher MACs.

Furthermore, the analysis will focus on variables that describe the regional labor market. If the pulp plant in review is located in a high unemployment area, locally committed politicians may argue that society benefits from less stringent environmental regulation, if it implies that the plant can maintain, or even increase, the employment rate. Therefore, the hypothesis tested is whether there is a negative correlation between the county unemployment rate, *RUE*, and pulp plants' MACs, indicating laxer environmental regulation when *RUE* increases. Finally, an employment variable is included. If the pulp and paper industry employs a relatively large number of people in the county, it is relatively important to its economy. In this case not only the plant and industry representatives can be expected to act protective in favor of the plant in review, but also local politicians. The hypothesis tested is whether there is a negative correlation between industry employment, *RIE*, and pulp plants' MACs, i.e., whether a laxer environmental policy is pursued as *RIE* increases. The data on the

[17] The tax base is defined as added income minus pension fee and basic allowance.

variables at the county level are published in Statistics Sweden's annual statistics and descriptive statistics are provided in Table A2 in the Appendix.

7 RESULTS

The system of equations in (13) is estimated using mean normalized input and output data. By the quadratic flexible functional form of the objective function and the imposed restrictions, the estimated directional output distance function satisfies the theoretical properties that are imposed on the production technology. Its parameter estimates are provided in Table A3 in the Appendix.

To obtain shadow prices, or MACs, of bad outputs, the distance function is differentiated with respect to output variables in accordance with the shadow-pricing formula in (11). These calculations generate MAC estimates for all of the 86 observations. Table 1 provides the correlation coefficients between estimated MACs of emissions in units of pulp, q/p_1, emissions per unit produced pulp, b/y_1, and estimated technical output efficiency scores, $D(\cdot)$.[18]

Table 1 Correlation coefficients

	q_1/p_1	**q_2/p_1**	**b_1/y_1**	**b_2/y_1**	**D(.)**
q_1/p_1	1.000				
q_2/p_1	-0.617	1.000			
b_1/y_1	-0.602	-0.499	1.000		
b_2/y_1	-0.243	-0.013	0.212	1.000	
D(.)	-0.181	0.305	0.226	0.007	1.000

The coefficient reflecting the correlation between oxygen-demanding substances, b_1/y_1, and its shadow price, q_1/p_1, has the expected negative sign. This is also confirmed for suspended solids, b_2/y_1, and its shadow price, q_2/p_1. Translating the interpretation made in Reig-Martínetz et al. (2001), plants that produce a greater quantity of emissions per unit pulp are probably those relying on technical

[18] Descriptive statistics of these variables are provided in Table A2 in the Appendix.

equipment less adapted to minimizing their emergence.[19] Therefore, investments to reduce emissions have a relatively small cost in comparison with their yields, in terms of reduced sales of pulp. This is reflected in lower shadow prices, or MACs, of bad outputs. Furthermore, when q_1/p_1 increases then q_2/p_1 decreases, which, together with the correlation coefficients commented on above, shows that plants increase b_2/y_1 when reducing b_1/y_1. This contradicts the positive correlation coefficient, 0.212, in Table 1. However, when regressing b_2/y_1 on b_1/y_1, together with dummies capturing fixed effects from plants differing in, e.g., output mixes, a significant and negative sign indicates that b_2/y_1 increases when b_1/y_1 is decreased. Furthermore, $D(\cdot)$ is positively correlated with both b_1/y_1 and b_2/y_1, which indicates that when plants increase technical efficiency by moving towards the technology frontier, i.e., when $D(\cdot)$ decreases, they reduce emissions per unit produced pulp. Additionally, $D(\cdot)$ is negatively correlated with q_1/p_1, which indicates that plants increase efficiency in such a way that the MACs are increased. However, this is not the case concerning the relationship to q_2/p_1, where the correlation coefficient is positive, indicating that MACs decrease when plants become more efficient. This is another indication of plants increasing b_2/y_1 when reducing b_1/y_1, which also, possibly, is confirmed by descriptive statistics in Table A1 in the Appendix.

Table 2 provides arithmetic averages for each plants' relative shadow prices of mean normalized oxygen-demanding substances, q_1/p_1, and suspended solids, q_2/p_1, as well as absolute shadow prices per ton oxygen-demanding substances, q_1, and suspended solids, q_2. Values at mean of the data are also provided.

[19] Reig-Martínez et al. (2001) apply a Shephard output distance function approach.

Table 2 Shadow prices of bad outputs (standard deviations in parentheses)

Plant	q_1/p_1 mean normalized	q_1 SEK/ton	q_2/p_1 mean normalized	q_2 SEK/ ton
1	0.092 (0.016)	2755.1 (474.6)	0.001 (0.001)	530.2 (302.8)
2	0.178 (0.077)	5344.1 (2319.1)	0.0004 (0.0002)	238.5 (94.7)
3	0.284 (0.010)	8549.3 (302.1)	0.001 (0.0002)	366.2 (100.3)
4	0.293 (0.022)	8832.5 (653.4)	0.0004 (0.0002)	224.8 (124.9)
5	0.209 (0.013)	6276.7 (379.9)	0.002 (0.0004)	876.9 (248.5)
6	0.316 (0.033)	9505.1 (1001.5)	0.0005 (0.0004)	265.3 (203.9)
7	0.200 (0.029)	6027.1 (876.8)	0.0004 (0.0002)	263.1 (137.0)
8	0.053 (0.046)	1583.6 (1398.3)	0.001 (0.002)	827.3 (904.4)
9	0.030 (0.023)	898.0 (692.1)	0.004 (0.001)	2214.8 (354.3)
10	0.177 (0.014)	5314.2 (429.8)	0.0004 (0.0003)	230.7 (194.5)
11	0.143 (0.012)	4313.7 (348.8)	0.003 (0.001)	1689.5 (364.7)
12	0.093 (0.009)	2792.8 (282.4)	0.003 (0.0002)	1674.1 (88.4)
Average	0.168 (0.097)	5068.0 (2909.6)	0.001 (0.001)	793.8 (749.6)
At mean	0.161	4844.7	0.001	583.4

The estimated relative shadow prices can be interpreted as MACs in terms of mean normalized units of reduced pulp, y_1. When reducing emissions of b_1 by one unit, the 'at the mean' producing plant diverted resources that could have been used to produce 0.161 units of y_1. The corresponding figure for b_2 is 0.001. In this case, one unit of y_1 = 255.5 thousand tons, b_1 = 34.9 thousand tons, and b_2 = 1.8 thousand tons. However, shadow prices can be transformed as to count for original units, resulting in the relative shadow price of b_1, 0.161*(255.5/34.9) = 1.179, and of b_2, 0.001*(255.5/1.8) = 0.142. These relative shadow prices can further be multiplied with the mean price of y_1, 4110.3 SEK/ton (1990 constant prices), to obtain absolute shadow prices of b_1 and b_2.[20] Consequently, the price of b_1 is 4844.7 SEK/ton and the price of b_2 is 583.4 SEK/ton. The corresponding sample averages are 5068.0 and 793.8 SEK/ton, respectively. Note that q_1/p_1 is

[20] It is assumed that pulp, y_1, is sold on a perfectly competitive market.

generally higher than q_2/p_1, which could be due to b_1 being more stringently regulated than b_2 and that, as earlier conjectured, plants increase b_2 when decreasing b_1.

Furthermore, as seen from Table 2, the shadow prices of bad outputs seem to vary across plants. This is also confirmed by the results of Kruskal-Wallis tests provided in Appendix, Tables A4a and A4b. Each plant is compared to all other plants, one by one, and concerning q_1/p_1 they differ in roughly 82 percent of the cases. For q_2/p_1 the figure is about 61 percent. To investigate which factors that possibly cause MACs to vary, a fixed effects model, in accordance with equation (14), is applied. The hypotheses tested are related to variables that vary across counties; unemployment in proportion to the labor force, *RUE*, employment in the pulp and paper industry (SNI 34) in proportion to total employment, *RIE*, tax base per resident, *Rtaxbase*, and population density, *Rpopdens*. The parameter estimates of the finally chosen model specifications and their corresponding t-values are displayed in Table 3.[21]

At the 5 percent significance level only one of the variables that vary between counties contributes to the variability of q_1/p_1. The estimated coefficient for *Rpopdens* shows a negative sign, which contradicts the tested hypothesis. People possibly experience utility from the industry operating in the county that outweighs the negative influences from emissions of oxygen-demanding substances.

[21] F-statistics have been calculated to test the joint effect from the time dummy variables. In the case of explaining the variability of q_2/p_1, time effects were rejected at the 5 percent significance level. A time trend hypothesis was also tested and rejected.

Table 3 The fixed effects models explaining relative shadow prices of mean normalized oxygen-demanding substances, q_1/p_1, and suspended solids, q_2/p_1

		Dependent variable, q_1/p_1		**Dependent variable, q_2/p_1**	
Coefficient	**Variable**	**Estimate**	**t-value**	**Estimate**	**t-value**
ϕ	*intercept*	1.3801	2.5382	-0.0052	-0.9553
ζ_1	*RIE*	-1.2006	-0.6003	-0.1059	-2.6313
ζ_2	*RUE*	-0.2811	-0.2630	-0.0036	-0.2124
ζ_3	*Rtaxbase*	-0.8595	-1.4515	-0.0058	-1.5706
ζ_4	*Rpopdens*	-0.0228	-2.6309	0.0003	2.2192
ρ_2	*plant 2*	-0.1592	-1.3932	0.0063	2.8468
ρ_3	*plant 3*	0.1593	3.7874	0.0023	2.9371
ρ_4	*plant 4*	-0.1437	-0.8690	0.0096	3.1564
ρ_5	*plant 5*	-0.2286	-1.3826	0.0107	3.5266
ρ_6	*plant 6*	-0.1097	-0.6620	0.0096	3.1581
ρ_7	*plant 7*	-0.2332	-1.4102	0.0097	3.1757
ρ_8	*plant 8*	-0.4303	-2.2676	0.0126	3.4642
ρ_9	*plant 9*	-0.4530	-2.3876	0.0150	4.1252
ρ_{10}	*plant 10*	-0.4724	-1.8218	0.0119	2.3904
ρ_{11}	*plant 11*	0.4648	3.0176	-0.0018	-0.8299
ρ_{12}	*plant 12*	0.2115	2.6946	0.0011	0.8117
ψ_{84}	*1984*	0.0010	0.0856	-	-
ψ_{85}	*1985*	0.0146	0.8911	-	-
ψ_{86}	*1986*	0.0579	1.7366	-	-
ψ_{87}	*1987*	0.0865	1.6360	-	-
ψ_{88}	*1988*	0.1018	1.6844	-	-
ψ_{89}	*1989*	0.1477	1.9147	-	-
ψ_{90}	*1990*	0.1616	2.2063	-	-
Adjusted R-squared		0.9392		0.8345	
Number of observations		86		86	

Regarding q_2/p_1 there are two county variables that significantly explain its variability. The variable *RIE* reflects the size of the pulp and paper industry, and the estimated coefficient shows a negative sign. In accordance with the formulated hypothesis, the larger the industry the more successful the plant and the industry representatives are in affecting the regulatory authority to grant higher maximally allowed emission levels of suspended solids, leading to lower MACs. Also, politicians may argue for relatively lax environmental regulation in their efforts to maintain the positive dynamic effects the industry has on the regional economy. Furthermore, the positive influence of *Rpopdens* on q_2/p_1 confirms the tested hypothesis. People feel uncomfortable with emissions of suspended solids, and the higher the density the more successful people are in influencing the regulatory authority.[22]

Finally, it is evident from Table 3 that a larger part of the plant dummy coefficients are significant, which indicates that the regulatory authority, guided by the Environment Protection Act, accounted for differences in plants' possibilities of abating and the sensitivity to emissions in the affected surrounding environment, when granting emission permits. However, since county dummies are excluded the plant dummies may also capture county specific effects from variables that vary across counties and that are not being modeled.

8 SUMMARY AND CONCLUSIONS

The purpose of this paper is to compute and evaluate shadow prices of bad outputs. The background is that many types of human activities have negative side effects on the environment. These effects may be due to produced bad outputs, i.e., undesirable by-products from different production processes. Therefore, to limit the environmental damages, public authorities are called upon to regulate the performance of polluters. If the regulations force producers to increase the sharpness of their abatement efforts, they also face increased abatement costs that can be studied. For instance, computed shadow prices, i.e., marginal abatement costs (MACs) of bad outputs, can be used to find out which factors that influence the regulatory authority's stringency of environmental regulations to be imposed on polluters.

In this paper, the Swedish pulp and paper industry during 1983-1990 is being studied. To limit its emission into the water, the regulatory authority, which by

[22] One explanation to why *RUE* does not contribute significantly to the variability of the MACs may be that there were no substantial unemployment during the sample period.

law was prescribed to consider the polluters' technological possibilities of abating and the sensitivity to emissions in the affected surrounding environment, granted each producing plant permits that specify maximally allowed emission levels. However, during the handling of each such case, area residents and other parties concerned were allowed to express their views, which possibly introduced additional factors which may influence the amount of finally granted permits and, therefore, the MACs. This paper seeks the answer to whether also regional differences in, e.g., economical characteristics, were important when the authority restricted 12 geographically scattered pulp plants with respect to emissions.

As a first step, shadow prices, reflecting MACs of oxygen-demanding substances and suspended solids, are computed for each pulp plant and compared to each other through non-parametric tests. These tests reveal that MACs vary significantly between plants. The approach adopted to compute these prices originates from Färe et al. (2002). The model is founded on production theory, where technology is represented by the directional output distance function, from which the shadow prices are derived. The distance function is specified using a quadratic flexible functional form and estimated by a linear programming technique. In a second step, the computed MACs are regressed on a set of variables in an attempt to explain their variation across plants. Hypotheses concerning variables such as regional tax base and population density, and variables describing the situation on the regional labor market, are suggested. Also fixed and time specific effects are modeled. The fixed effects are included to capture the effects from factors prescribed by environmental law, such as differences across plants regarding technological possibilities to abate, and the sensitivity to emissions in the affected surroundings, where each plant is located.

The result indicates that there are regional factors, not regulated by environmental law, which may influence the actually pursued environmental policy. For instance, the larger the relative size of the pulp and paper industry in the county the lower the MAC of suspended solids for plants located in that county. This indicates that these plants were targets of laxer environmental regulation. Also, a higher county population density seems to have created opportunities for people to influence the actual policy pursued. This study shows that population density had a different influence on the two types of emissions. In the case of oxygen-demanding substances, the density contributed negatively to the plants' MACs, indicating that plants located in counties with higher density were targets of laxer environmental regulation. On the other hand, in the case of suspended solids, the density contributed positively to the plants, MACs. That is, plants located in counties with higher population density were more stringently regulated.

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APPENDIX

Table A1 Definitions and mean statistics for variables included as arguments in the directional output distance function (standard deviations in parentheses)

Variable	1983	1984	1985	1986	1987	1988	1989	1990
y_1	249.8 (150.8)	254.8 (142.7)	248.8 (139.9)	248.2 (143.0)	256.9 (146.8)	253.4 (155.4)	273.1 (153.4)	263.0 (144.6)
b_1	41.1 (36.5)	39.5 (34.6)	37.7 (33.7)	32.1 (24.3)	32.5 (25.2)	33.3 (25.1)	33.5 (25.6)	28.5 (22.0)
b_2	1.1 (1.1)	1.1 (0.9)	1.2 (1.0)	1.3 (1.2)	1.2 (1.3)	3.0 (4.5)	2.7 (4.7)	3.4 (4.6)
x_1	1348.8 (663.6)	1356.9 (602.9)	1303.5 (624.2)	1314.3 (648.6)	1332.1 (651.4)	1292.3 (685.2)	1436.1 (704.0)	1360.3 (624.1)
x_2	720.2 (335.0)	680.8 (295.7)	678.2 (309.4)	655.6 (320.9)	649.5 (332.0)	638.2 (348.9)	671.8 (330.3)	702.9 (360.8)
x_3	202.6 (117.6)	205.1 (115.3)	203.4 (116.8)	203.7 (118.8)	208.9 (120.7)	209.9 (125.7)	226.8 (116.2)	229.7 (127.1)
x_4	2032.7 (1493.9)	1917.7 (1326.5)	1959.5 (1353.0)	1966.1 (1356.9)	2006.4 (1362.2)	2034.6 (1468.3)	2292.8 (1527.4)	2813.7 (1601.4)

Variable	1983-1990		
	mean	**min**	**max**
y_1	255.5 (140.9)	61.0	597.6
b_1	34.9 (28.0)	1.1	111.2
b_2	1.8 (2.8)	0.1	15.0
x_1	1340.4 (624.3)	313.9	2588.0
x_2	672.2 (314.7)	184.0	1365.0
x_3	210.4 (114.9)	25.4	458.3
x_4	2096.6 (1389.1)	551.6	5482.5

y_1 = pulp, 1000 tons
b_1 = oxygen-demanding substances, 1000 tons
b_2 = suspended solids, 1000 tons
x_1 = wood fiber, 1000 m^3
x_2= labor, 1000 hours worked
x_3 = electricity, Mwh
x_4 = capital, millions SEK (1990 constant price)

Table A2 Definitions and mean statistics for variables that appear in the result section (standard deviations in parentheses)

Variable	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**
q_1/p_1	0.143 (0.098)	0.150 (0.094)	0.155 (0.097)	0.169 (0.101)	0.173 (0.103)	0.179 (0.104)	0.180 (0.097)	0.206 (0.101)
q_2/p_1	0.002 (0.002)	0.002 (0.002)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
b_1/y_1	1.187 (1.004)	1.075 (0.840)	1.048 (0.816)	0.906 (0.540)	0.872 (0.449)	0.890 (0.397)	0.869 (0.364)	0.768 (0.285)
b_2/y_1	0.619 (0.520)	0.590 (0.401)	0.773 (0.747)	0.706 (0.582)	0.658 (0.597)	1.411 (1.726)	1.166 (1.460)	1.626 (1.953)
D(.)	0.016 (0.029)	0.024 (0.028)	0.036 (0.039)	0.026 (0.027)	0.023 (0.031)	0.034 (0.044)	0.027 (0.035)	0.027 (0.037)
RIE	0.039 (0.013)	0.036 (0.013)	0.036 (0.013)	0.036 (0.013)	0.036 (0.013)	0.036 (0.013)	0.038 (0.014)	0.036 (0.014)
RUE	0.044 (0.011)	0.041 (0.010)	0.037 (0.007)	0.035 (0.009)	0.025 (0.008)	0.020 (0.007)	0.016 (0.003)	0.021 (0.009)
Rtaxbase	0.625 (0.057)	0.626 (0.050)	0.635 (0.051)	0.672 (0.055)	0.704 (0.057)	0.713 (0.060)	0.733 (0.054)	0.749 (0.069)
Rpopdens	19.444 (12.350)	22.917 (14.475)	23.000 (14.691)	22.917 (14.513)	22.917 (14.513)	23.273 (15.434)	25.800 (14.374)	18.750 (11.374)
q_1	4317.3 (2935.3)	4524.7 (2831.5)	4667.8 (2904.8)	5098.4 (3031.4)	5196.0 (3104.8)	5390.4 (3121.8)	5414.7 (2920.5)	6213.3 (3040.9)
q_2	957.1 (937.8)	967.5 (899.1)	851.4 (833.7)	710.5 (623.2)	736.9 (659.2)	785.4 (760.2)	785.5 (821.4)	495.4 (508.6)

Variable	**1983-1990**		
	mean	**min**	**max**
q_1/p_1	0.168 (0.097)	0.000	0.351
q_2/p_1	0.001 (0.001)	0.000	0.004
b_1/y_1	0.955 (0.625)	0.103	3.597
b_2/y_1	0.913 (1.108)	0.069	5.777
D(.)	0.027 (0.033)	0.000	0.132
RIE	0.037 (0.013)	0.015	0.054
RUE	0.030 (0.013)	0.009	0.066
Rtaxbase	0.680 (0.070)	0.542	0.867
Rpopdens	22.558 (13.720)	3.000	52.000
q_1	5068.0 (2909.6)	0.000	10556.0
q_2	793.8 (749.6)	0.000	2588.4

q_1/p_1 = relative shadow price of mean normalized oxygen-demanding substances in terms of forgone mean normalized units of pulp

q_2/p_1 = relative shadow price of mean normalized suspended solids in terms of forgone mean normalized units of pulp

b_1/y_1 = emissions of mean normalized oxygen-demanding substances per mean normalized unit produced pulp

b_2/y_1 = emissions of mean normalized suspended solids per mean normalized unit produced pulp

$D(x/x^m,y/y^m,b/b^m;1,-1)$ = estimated technical output efficiency scores for mean normalized input and output quantities (the top index *m* denotes the variable at mean)

RIE = employment in the pulp and paper industry (SNI 34) in proportion to total employment in the county

RUE = number of unemployed in proportion to the number of people in the county labor force

Rtaxbase = tax base in the county, 1000 SEK per resident (1990 constant prices)

Rpopdens = residents per km^2 in the county

q_1 = absolute shadow price of one ton oxygen-demanding substances (1990 constant price)

q_2 = absolute shadow price of one ton suspended solids (1990 constant price)

Table A3 Parameter estimates of the directional output distance function when inputs and outputs are mean normalized[23]

Coefficient	**Variable**	**Estimate**	**Coefficient**	**Variable**	**Estimate**
α_0	*intercept*	-0.3118	δ_{21}	x_2y_1	-0.1976
α_1	x_1	0.3139	η_{21}	x_2b_1	-0.1962
α_2	x_2	-0.2946	η_{22}	x_2b_2	-0.0015
α_3	x_3	0.2599	α_{33}	x_3x_3	-0.2684
α_4	x_4	0.5114	α_{34}	x_3x_4	0.3575
β_1	y_1	-0.7182	δ_{31}	x_3y_1	-0.0668
γ_1	b_1	0.2818	η_{31}	x_3b_1	-0.0636
γ_2	b_2	0.0001	η_{32}	x_3b_2	-0.0031
α_{11}	x_1x_1	-1.1588	α_{44}	x_4x_4	-0.0688
α_{12}	x_1x_2	0.8567	δ_{41}	x_4y_1	0.1081
α_{13}	x_1x_3	0.6148	η_{41}	x_4b_1	0.1079
α_{14}	x_1x_4	-0.3391	η_{42}	x_4b_2	0.0001
δ_{11}	x_1y_1	0.0454	β_{11}	y_1y_1	-0.0157
η_{11}	x_1b_1	0.0439	μ_{11}	y_1b_1	-0.0178
η_{12}	x_1b_2	0.0015	μ_{12}	y_1b_2	0.0021
α_{22}	x_2x_2	0.8405	γ_{11}	b_1b_1	-0.0198
α_{23}	x_2x_3	-0.4172	γ_{12}	b_1b_2	0.0020
α_{24}	x_2x_4	-0.5901	γ_{22}	b_2b_2	0.0001

y_1 = pulp, 255.5 thousand tons

b_1 = oxygen-demanding substances, 34.9 thousand tons

b_2 = suspended solids, 1.8 thousand tons

x_1 = wood fiber, 1340.4 thousand m^3

x_2 = labor, 672.2 thousand hours worked

x_3 = electricity, 210.4 Mwh

x_4 = capital, 2096.6 millions SEK (1990 constant price)

[23] The estimates of the plant and time specific effects are left out.

Table A4a The Kruskal-Wallis Test: Comparing shadow prices of oxygen-demanding substances between plants (bold type indicates that the null-hypothesis cannot be rejected)

Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1		10.50	10.50	11.29	11.29	9.60	9.60	**2.48**	10.60	10.50	9.60	**0.01**
2			5.00	7.09	**1.93**	6.61	**1.65**	9.76	10.50	**1.47**	**0.02**	9.80
3				**0.34**	10.50	4.00	9.00	10.50	10.50	9.80	9.00	9.80
4					11.29	**1.35**	9.60	11.29	11.29	10.50	9.60	10.50
5						9.60	**1.07**	11.29	11.29	9.05	9.60	10.50
6							8.31	9.60	9.60	9.00	8.31	9.00
7								9.60	9.60	**2.94**	8.31	9.00
8									**0.62**	10.50	9.60	1.93
9										10.50	9.60	10.50
10											8.16	9.80
11												**0.74**
12												

H_0: the shadow prices of oxygen-demanding substances, q_1/p_1, for the two compared plants, are drawn from the same population

H_A: the shadow prices of oxygen-demanding substances, q_1/p_1, for the two compared plants, are not drawn from the same population

$\chi^2 (1)_{.05} = 3.84$

Table A4b The Kruskal-Wallis Test: Comparing shadow prices of suspended solids between plants (bold type indicates that the null-hypothesis cannot be rejected)

Plant	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1		3.87	**2.63**	4.41	4.41	**3.50**	**3.27**	**0.01**	11.29	4.34	9.60	10.50
2			5.00	**0.00**	10.50	**0.08**	**0.18**	**1.09**	10.50	**0.04**	9.00	9.80
3				4.84	10.50	**0.18**	**1.65**	**0.12**	10.50	**1.80**	9.00	9.80
4					11.29	**0.42**	**0.42**	**0.71**	11.29	**0.00**	9.60	10.50
5						9.60	9.60	**0.71**	11.29	10.50	8.82	10.50
6							**0.03**	**0.27**	9.60	**0.33**	8.31	9.00
7								**0.42**	9.60	**0.08**	8.31	9.00
8									8.04	**0.34**	**2.02**	**1.62**
9										10.50	5.40	6.48
10											9.00	9.80
11												9.00
12												

H_0: the shadow prices of suspended solids, q_2/p_1, for the two compared plants, are drawn from the same population

H_A: the shadow prices of suspended solids, q_2/p_1, for the two compared plants, are not drawn from the same population

$\chi^2 (1)_{.05} = 3.84$