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DOI:
10.57938/499f8618-d877-4a1a-bd94-e7ddc092dd2f

Published: 01/01/2011

Document Version:
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Bauer, F., Bremberger, C., Luptacik, M., & Schmitt, S. (2011). *Regulatory impact of environmental standards on the eco-efficiency of firms*. Forschungsinstitut für Regulierungsökonomie, WU Vienna University of Economics and Business. Working Papers / Research Institute for Regulatory Economics No. 2011,3
https://doi.org/10.57938/499f8618-d877-4a1a-bd94-e7ddc092dd2f

Regulatory impact of environmental standards on the eco–efficiency of firms

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Abstract

In this paper we propose one approach to implement environmental standards into Data Envelopment Analysis (DEA) and in this way to measure its regulatory impact on eco–efficiency of firms. As one basic feature of DEA models lies in the exogeneity of inputs, desirable and undesirable outputs, it is not possible to introduce environmental constraints for these parameters directly into existing DEA models. Therefore, we implement the environmental standard in a bounded–variable way, which allows constraints on the efficiency frontier. The regulatory impact is assessed as difference in eco–efficiency scores before and after fictive introduction of an environmental standard. Furthermore, we distinguish between weak and strong disposability of undesirable outputs and develop according models.

Assessing the regulatory impact of environmental standards in advance provides support for environmental policy makers in choosing appropriate instruments and in adjusting the intensity of regulation. Moreover, the procedure can be applied in a wide range of markets, as the proposed model framework offers several options. Policy makers can choose between different environmental standards and different disposability assumptions.

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1 Introduction

In today's political debates the concept of sustainability has become indispensable. The basic idea behind this concept is that natural resources are finite and that ecological issues – in particular pollution – cannot be ignored any more. In many cases the destruction of ecological capital leads contemporaneously to an increase in gross domestic product and if there are no costs associated with the former, long-term environmental costs are completely excluded from economic analysis. Therefore, one of the most striking challenges in (environmental) economics is the internalisation of negative external effects. Various concepts and models try to deal with this issue. Our paper enters into the discussion as we refer to implementing environmental standards in evaluating the eco–efficiency[1] of different firms in a particular industry in order to give incentives for less pollutant production. Moreover, in this way it is possible to measure the regulatory impact on firms by comparing eco–efficiency scores before and after a fictive introduction of an environmental standard. This can provide support for the environmental policy makers in choosing appropriate instruments and intensity of regulation.

As it is rather difficult to quantify pollution, emissions or other undesirable outputs in monetary units, we refer to data envelopment analysis (DEA), a non-parametric approach for multilateral productivity comparisons. With this approach, which is extended in several ways, it is now possible to ascertain the eco–efficiency of firms.

The remainder of the article is organised as follows. The next section provides a brief literature overview in DEA with a special focus on the measurement of eco–efficiency and the effects of regulatory standards. Section 3 presents our basic idea using a fictive example of eight DMUs, herein several variants of DEA–models that deal with undesirable outputs in the context of eco–efficiency are applied and discussed. In section 4 we show how to implement our idea by extending common slack–based measure models in the DEA field. Finally, the most important findings are summarised and drawn together in a principal conclusion.

2 Literature

In efficiency analysis each firm, called decision making unit (DMU) in the Data envelopment analysis (DEA) framework, is compared with the best practice frontier constructed by the whole sample. Thereby, the relative technical efficiency of every DMU can be computed. DEA, going back to Charnes et al. (1978), is a linear programming technique to estimate the efficiency frontier, which is extensively applied in both, academic literature and practical world. It is also widely used for environmental analysis, where undesirable outputs such as pollution or emissions play a key role.[2] Since undesirable outputs are jointly produced with desirable outputs the incorporation into the measurement of overall performance is intensively discussed. A seminal

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[1] Korhonen and Luptacik (2004) define eco-efficiency according to Heinz Felsner: *We are looking for eco–efficient solutions such that the goods and services can be produced with less energy and resources and with less waste and emission.*

[2] For a survey of DEA studies in the area of energy and environment, see Zhou et al. (2008).

paper in this context is the one from Färe et al. (1989), who have introduced the differentiation between strong and weak disposability of outputs.The basic idea behind their concept is that, given a certain amount of inputs, the higher the ratio between desirable and undesirable output the higher is efficiency. In other words, firms should be penalised for the production of bad outputs whereas higher production of (good) outputs, as usually, should have a positive effect on efficiency. Färe et al. (1996) introduce an environmental performance indicator based on the decomposition of overall productivity into a pollution index and a productive efficiency index. A comprehensive survey on the measurement of environmental performance is provided by Tyteca (1996), who suggests three DEA model variations which also take undesirable outputs into account. Moreover, a number of recent studies developed further extensions of Färe et al. (1989). Lozano and Gutierrez (2011) develop a modified slack–based DEA model which assumes joint weak disposability of the desirable and undesirable outputs to compare the efficiencies of airports. In another study Yang and Pollitt (2010) point out that the assumption of a uniform disposability for all undesirable outputs brings different results in comparison to a model that builds on technically correct disposability features for all undesirable outputs. Their model specification is applied to a set of Chinese coal-fired power plants.

In literature different possibilities are distinguished how to include bad outputs into the DEA–framework. According to Korhonen and Luptacik (2004) undesirable outputs can either be seen as bad outputs or as inputs. While the explanation for the former is straightforward, undesirable outputs can also be interpreted as inputs since both incur costs for a DMU. Within this logic a DMU is trying to produce a given output with minimal inputs and undesirable outputs. The main result of Korhonen and Luptacik (2004) was that the efficiency frontier, unlike the efficiency scores of single firms, is independent of the way of including undesirable outputs.

In addition to the incorporation of undesirable outputs into the calculation of efficiency, it is also possible to include regulatory standards. The first paper dealing with the impact of regulation in the efficiency analysis was conducted by Färe and Logan (1992). Using rate-of-return regulation, the authors were able to determine the relationship between measures of regulated and unregulated firms. The idea of implementing standards into the DEA framework was introduced by Golany and Roll (1994). These standards do not necessarily have to be observed from the real operations, but reflect both optimal output levels and corresponding minimal inputs.

One of the most important topics in recent environmental research is the question how emissions can be reduced in order to meet predetermined climate goals, like for example the Kyoto-protocol. There are different possibilities to decrease emissions, see e.g. Helfand (1991) or Luptacik (2009). First, the absolute amount of emissions can be reduced with the consequence that all emissions producing firms are treated equally independently of what they have done in the past in order to cut emissions. A second possibility is intensity-regulation introduced by Dudenhöffer (1984). Here, the emissions per unit of input have to be set below a predefined benchmark, whereby those firms which have already invested in less polluting technologies in the past have an advantage. Third, emissions per unit of output should not be higher than a given value. In this case, it is not clear that the level of emission will fall, since emissions can increase as long as output rises.

3 Extensions of eco–efficiency models — our basic idea

In order to internalise negative external effects of pollution, we want to include environmental standards in the efficiency evaluation of firms. This should help to identify the impact of introducing environmental standards as regulatory constraint.

Data Envelopment Analysis (DEA), as one of the most common methods for measuring efficiency, in particular its extensions for eco–efficiency, will constitute the basic framework. Within DEA the efficiency is maximised over the chosen weights, whereas raw data of firms is treated as exogenously given. Therefore, it is not possible to incorporate constraints on inputs, desirable and undesirable outputs directly. Consequently, we will first explain our basic idea and introduce the methodological implementation later (in Section 4). Our idea contains two–steps:

1. Including the environmental standard in the efficiency frontier:

   In general, all possibilities for environmental standards discussed in literature can be included in the DEA framework. As mentioned in the Section 2, Luptacik (2009) and Helfand (1991) distinguish three types of environmental standards:

   - Intensity–regulation (Dudenhöffer (1984)): $\frac{Emission}{Input} \leq \alpha_1$
   - Emission per unit of output: $\frac{Emission}{Output} \leq \alpha_2$
   - Set level of emissions:[3] $Emission \leq \alpha_3$

   As original firm data is exogenously given, we cannot incorporate constraints on inputs, desirable and undesirable outputs directly. Therefore, especially the efficiency–frontier projections of all firms have to fulfil the environmental standard. Figures 1 and 2 give a graphical presentation of the introduction of intensity and emission per unit of output regulation, respectively. Similar to the rate–of–return regulatory constraint implemented by Färe and Logan (1992), the introduced environmental standard cuts the efficiency frontier. Herein, indicating regions not allowed by the regulator due to excessive undesirable outputs (black part of the efficiency frontier). All firms, particularly including the ones lying above the regulatory constraint (given as red line) need to be projected on that part of the efficiency frontier where the environmental standard is guaranteed (blue part of the efficiency frontier).

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[3] Limitation on absolute amount of undesirable outputs.

Figure 1: Intensity regulation

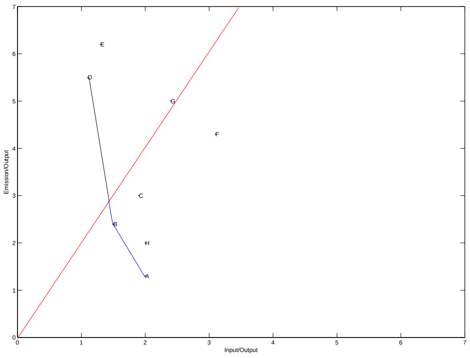
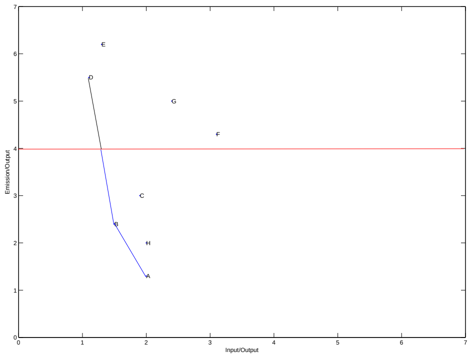


Figure 2: Emission per unit of output regulation



2. Using DEA models for eco–efficiency to compute the regulatory impact:

   In a second step, the regulatory impact of an environmental standard can be assessed as the difference in eco–efficiency scores before and after introducing the standard.[4] This is possible, as we are comparing identical DMUs. Different DEA models for measuring the eco–efficiency of firms can be applied in general. Korhonen and Luptacik (2004) distinguish three input–oriented eco–efficiency models for a radial DEA framework, according to treatment of inputs and emissions:

   - Model A: Undesirable output (emission) is treated as negative output.
   - Model B: Undesirable output is treated as input.
   - Model C: Undesirable output is treated as input and input is treated as negative output.

   Nevertheless, in radial DEA models eco–efficiency scores need not contain all inefficiency information. Additional slacks can appear for single firms which are not accounted in the eco–efficiency score. This might lead to distorted results, as the regulatory impact of the environmental standards is exclusively assessed via the comparison of eco–efficiency scores before and after introducing the regulation. Therefore, slack–based measure models seem to be advantageous for our purpose, as all slacks are included in the eco–efficiency scores.

4 Methodological approach

In this section we introduce our idea to evaluate the regulatory impact of environmental standards into the common DEA framework. We will illustrate the ideas using sample data. As our extensions are beyond common solver software packages, we generated all results by solving the models in GAMS (General Algebraic Modeling System).

As argued before, SBM models are more advantageous than radial models for our purpose, because all slacks are accounted in the eco–efficiency score. Therefore, we use the Undesirable

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[4] Note that the regulatory impact can be computed for single firms (difference in single eco-efficiency scores) and the whole industry (difference in average eco–efficiency scores).

Output Model from Cooper et al. (2007) and a slack–based measure version of Model B from Korhonen and Luptacik (2004) as starting points.

In order to create a slack–based measure version of Model B from Korhonen and Luptacik (2004), we translate Model B from the radial DEA to the SBM framework keeping input orientation and constant returns to scale. Equation (1) presents the translated Model B, which is called SBM Model B in the remaining text.[5]

SBM version of Model B:

$$\min_{\lambda,s^-,s^b} \quad \rho = \quad 1 - \frac{1}{m+s_2}\left(\sum_{i=1}^{m}\frac{s_i^-}{x_{io}} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right) \tag{1}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o^b = Y^b\lambda + s^b$$

$$y_o^g \leq Y^g\lambda$$

$$\lambda, s^-, s^b \geq 0$$

We implement the regulatory constraint for environmental standards by the idea of bounded variables, which allows constraints on efficiency–frontier projections. The effect of the environmental standard is a cut of the efficiency frontier, indicating regions not allowed by the regulator due to excessive undesirable outputs. In evaluating the regulatory impact of environmental standards it is crucial to distinguish between a strong and weak disposability assumption of undesirable outputs. With $\mathbf{v}$ as the vector for good outputs, $\mathbf{w}$ as undesirable output vector, $\mathbf{x}$ as input vector, $\mathbf{P}(\mathbf{x})$ as production technology, and $0 \leq \theta \leq 1$ Shepard (1970) and Kuosmanen (2005) define undesirable outputs as strongly disposable if:
$(\mathbf{v}, \mathbf{w}) \in \mathbf{P}(\mathbf{x})$ implies $(\mathbf{v}, \theta\mathbf{w}) \in \mathbf{P}(\mathbf{x})$,
as weakly disposable via outputs if:
$(\mathbf{v}, \mathbf{w}) \in \mathbf{P}(\mathbf{x})$ implies $(\theta\mathbf{v}, \theta\mathbf{w}) \in \mathbf{P}(\mathbf{x})$,
and weakly disposable via inputs if:
$(\mathbf{v}, \mathbf{w}) \in \mathbf{P}(\mathbf{x})$ implies $(\mathbf{v}, \theta\mathbf{w}) \in \mathbf{P}((2-\theta)\mathbf{x})$.

This means that strongly disposable undesirable outputs can be reduced costless, whereas weakly disposable undesirable outputs can only be decreased when simultaneously decreasing outputs or increasing inputs proportionally.

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[5] The Undesirable Output Model from Cooper et al. (2007) is provided in Appendix A.

4.1 Strong disposability assumption

If strong disposability of undesirable outputs is assumed, the regulatory impact of environmental standards can be assessed as the difference of eco–efficiency scores between standard SBM models (*SBM Model B* from Equation (1) and the *Undesirable Output Model* from Cooper et al. (2007)) and modified versions including the environmental standard. Herein, all environmental standards (intensity, emission per unit of output and level–of–emission regulation) can be implemented in a bounded–variable way.

4.1.1 SBM Model B

In order to extend the *SBM Model B* by the environmental standard we add a fourth constraint constituting that projections on the efficiency frontier need to fulfil the environmental standard. In Equation (2) the environmental standard is given as emission per unit of output regulation.[6] This extended SBM Model B is called *SBM Model B bounded* in the remaining text.

<u>SBM Model B including bounded variables:</u>
(*Emission per unit of output regulation*)

$$\min_{\lambda, s^-, s^b} \quad \rho = \quad 1 - \frac{1}{m + s_2}\left(\sum_{i=1}^{m} \frac{s_i^-}{x_{io}} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{ro}^b}\right) \tag{2}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o = Y^b\lambda + s^b$$

$$y_o^g \leq Y^g\lambda$$

$$0 \leq Y^b\lambda \leq \alpha_2 Y^g\lambda$$

$$\lambda, s^-, s^b \geq 0$$

Sample data In Section 4 we will illustrate our ideas using — for simplicity and without loss of generality — an example of eight firms using one input to produce one desirable output and one type of emission. Table 1 summarises the data of treated DMUs. As we will deal with emission per unit of output as well as intensity regulation, the last two columns give the according measures under consideration, respectively.

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[6] For intensity or level–of–emission regulation, $0 \leq Y^b\lambda \leq \alpha_1 X\lambda$ or $0 \leq Y^b\lambda \leq \alpha_3$ have to be inserted as environmental standard respectively.

Table 1: Data of DMUs

	Input	**Emissions**	**Output**	$\frac{Emission}{Output}$	$\frac{Emission}{Input}$
A	20	13	10	1.3	0.7
B	15	24	10	2.4	1.6
C	19	30	10	3	1.6
D	11	55	10	5.5	5
E	13	62	10	6.2	4.8
F	31	43	10	4.3	1.4
G	24	50	10	5	2.1
H	20	20	10	2	1

Table 2 presents the eco–efficiency scores, ranks and reference sets of *SBM Model B* and *SBM Model B bounded* with an environmental standard of $\alpha_2 = 3.5$ for the sample data. The results of the two models are rather similar, except for the circumstance that all eco–efficient projections in *SBM Model B bounded* meet the environmental standard. Consequently, DMU D is no longer a valid projection possibility at the efficiency frontier, which now ends at the intersection with the regulatory constraint ($\tilde{\mathrm{D}}$).[7] Therefore, DMU D also has to be projected on point $\tilde{\mathrm{D}}$ and thus faces an efficiency loss of 24% as regulatory impact. Similarly DMU E which is projected close to D in SBM Model B, has to be projected on $\tilde{\mathrm{D}}$ in *SBM Model B bounded*, which causes an efficiency loss of 5 percentage points. The efficiency of DMU G is not changing because although DMU G is not fulfilling the emission per unit of output regulation, its projection on the efficiency frontier (point A) does. Therefore, the optimal projection of DMU G is not altered by the environmental standard. Summing up, the average regulatory impact over all eight firms is calculated as an efficiency loss of 3 percentage points.

Table 2: Eco–efficiency Results — Emission per unit of output regulation

	SBM Model B			**SBM Model B bounded**			**Regulatory Impact**
	Score	**Rank**	**Ref**	**Score**	**Rank**	**Ref**	
DMU A	1	1	A	1	1	A	
DMU B	1	1	B	1	1	B	
DMU C	0.75	6	A,B	0.75	6	A,B	
DMU D	1	1	D	0.76	3	$\tilde{\mathrm{D}}$	0.24
DMU E	0.82	5	B,D	0.77	5	$\tilde{\mathrm{D}}$	0.05
DMU F	0.47	8	A	0.47	8	A	
DMU G	0.55	7	A	0.55	7	A	
DMU H	0.83	4	A	0.83	4	A	
∅ Efficiency	0.80			0.77			**0.03**

To evaluate the regulatory impact of the emission per unit of output regulation it is necessary

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[7] For a graphical illustration see Figure 2.

to solve *SBM Model B bounded* for different values of α_2. If α_2 is for instance set to 1.5, the overall regulatory impact accounts to 12 percentage points, which is around four times the effect of an environmental standard of $\alpha_2 = 3.5$. For $\alpha_2 = 1$, which would indicate that outputs and undesirable outputs need to be equal, it would be most efficient for all firms to cease production and leave the market. Detailed information about efficiency scores and regulatory impacts of different environmental standards can be found in Appendix B.

4.1.2 Undesirable Output Model

The *Undesirable Output Model* from Cooper et al. (2007) is extended in a similar way. Again, one additional constraint on the set of possible projections is added. This fourth constraint constitutes that projections on the efficiency frontier need to fulfil the environmental standard. In Equation (3) the environmental standard is given as intensity regulation.[8] This modified model is called *Undesirable Output Model bounded* in the remaining text.

Undesirable Output Model including bounded variables:
(*Intensity regulation*)

$$\min_{\lambda, s^-, s^+} \quad \rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)} \tag{3}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o^b = Y^b\lambda + s^b$$

$$y_o^g = Y^g\lambda - s^g$$

$$0 \leq Y^b\lambda \leq \alpha_1 X\lambda$$

$$\lambda, s^-, s^g, s^b, s_r^{WD} \geq 0$$

Table 3 presents the eco–efficiency scores, ranks and reference sets of the *Undesirable Output Model* and *Undesirable Output Model bounded* with an environmental standard of $\alpha_1 = 2$ for the sample data. All eco–efficient projections in the *Undesirable Output Model bounded* meet the environmental standards. This causes a necessary projection and resulting efficiency loss for DMU D of 23% as regulatory impact.[9] DMU E is also projected to $\tilde{\text{D}}$ and faces an efficiency loss of 4 percentage points. The average regulatory impact of an intesity regulation of $\frac{Emission}{Input} \leq 2$ over all eight firms is calculated as an efficiency loss of 3 percentage points.

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[8] For emission per unit of output or level–of–emission regulation, $0 \leq Y^b\lambda \leq \alpha_2 Y^g\lambda$ or $0 \leq Y^b\lambda \leq \alpha_3$ have to be inserted as environmental standard respectively.

[9] DMU D is again projected on the intersection between efficiency frontier and environmental standard ($\tilde{\text{D}}$). For a graphical illustration see Figure 1.

Table 3: Eco–efficiency Results — Intensity regulation

	Undesirable Output Model			**Undesirable Output Model bounded**			**Regulatory Impact**
	Score	**Rank**	**Ref**	**Score**	**Rank**	**Ref**	
DMU A	1	1	A	1	1	A	
DMU B	1	1	B	1	1	B	
DMU C	0.72	6	B	0.72	6	B	
DMU D	1	1	D	0.77	5	$\tilde{D}$	0.23
DMU E	0.80	5	D	0.76	4	$\tilde{D}$	0.04
DMU F	0.40	8	B	0.40	8	B	
DMU G	0.49	7	B,D	0.49	7	B,$\tilde{D}$	
DMU H	0.84	4	A,B	0.84	3	A,B	
∅ Efficiency	0.78			0.75			**0.03**

In order to evaluate the regulatory impact of intensity regulation, α_1 in the *Undesirable Output Model bounded* is varied. If α_1 is for instance set to 0.7, the overall regulatory impact accounts to 4 percentage points, but the individual impacts differ. The big efficiency losers are DMU B, D and E and due to the necessary projection of firm B DMUs C, F and G gain efficiency. For $\alpha_1 \leq 0.7$, all firms chose to cease production and leave the market. Detailed information about efficiency scores and regulatory impacts of different intensity regulations can be found in Appendix C.

4.2 Weak disposability assumption

If weak disposability of undesirable outputs is assumed, standard SBM models (*SBM Model B* from Equation (1) and the *Undesirable Output Model* from Cooper et al. (2007)) first have to be adopted. The regulatory impact of environmental standards can subsequently be assessed as the difference of eco–efficiency scores between the adopted standard SBM models including weak disposability of undesirable outputs and extended versions additionally including the environmental standard.

In order to guarantee that the model accounts for weak disposability of undesirable outputs, we add a weak disposability constraint. This means that if a firm has to lower its emissions in order to be efficient, it simultaneously has to decrease outputs (weak disposability via outputs) or to increase inputs (weak disposability via inputs). Weak disposability via outputs is more often treated in literature, see e.g. Yang and Pollitt (2010), Shepard (1970) and Kuosmanen (2005), and refers to short–term reductions of undesirable outputs within one production technology with constant emission–coefficient. Contrary to this, weak disposability via inputs refers to long–term changes in the production technology, achieved through investments which in turn increase inputs.

As the input–oriented *SBM Model B* does not include output slacks, it is only possible to implement weak disposability via inputs. The *Undesirable Output Model* is non–oriented and thus includes slacks for inputs, undesirable outputs and desirable outputs. Nevertheless, undesirable outputs are treated as outputs wherefore weak disposability can only be implemented via outputs. Consequently, the two versions of weak disposability are separated in the two available SBM models.

4.2.1 SBM Model B

Equation (4) presents our extensions for weak disposability via inputs in *SBM Model B*. The fourth constraint assures that the relative decrease in undesirable outputs is accompanied by a proportional increase in inputs. A necessary input increase results in a positive slack for weak disposability (s_r^{WD}) which enters the objective function. Any weak disposability slack will lower the efficiency of the respective firm. This model is called *SBM Model B weak* in the remaining text.

SBM Model B including weak disposability via inputs:

$$\min_{\lambda,s^-,s^b} \quad \rho = \quad 1 - \frac{1}{m+2s_2}(\sum_{i=1}^{m} \frac{s_i^-}{x_{io}} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{ro}^b} + \sum_{i,r=1}^{s_2} \frac{s_r^{WD}}{x_{io}}) \tag{4}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o = Y^b\lambda + s^b$$

$$y_o^g \leq Y^g\lambda$$

$$\frac{s_r^b}{y_{ro}^b} = \frac{s_r^{WD}}{x_{io}}$$

$$\lambda, s^-, s^b, s_r^{WD} \geq 0$$

Subsequently the environmental standard is implemented in a bounded–variable way as described in Section 4.1. Equation (5) presents the *SBM Model B extended*, which contains an environmental standard in the fourth constraint and weak disposability in the fifth constraint. In order to distinguish direct and indirect effects of environmental standards, it is advantageous to implement the regulatory and the weak disposability constraint for different variables. This means, as weak disposability refers to inputs within the SBM Model B framework, emission per unit of output or level–of–emission regulation can be used as environmental standards. The fourth constraint here, shows an emission per unit of output regulation.[10]

SBM Model B including bounded variables and weak disposability via inputs:
(*Emission per unit of output regulation*)

$$\min_{\lambda,s^-,s^b} \quad \rho = \quad 1 - \frac{1}{m+2s_2}(\sum_{i=1}^{m} \frac{s_i^-}{x_{io}} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{ro}^b} + \sum_{i,r=1}^{s_2} \frac{s_r^{WD}}{x_{io}}) \tag{5}$$

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[10] Recall that for a level–of–emission regulation the environmental standard has to be formulated as $0 \leq Y^b\lambda \leq \alpha_3$.

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o = Y^b\lambda + s^b$$

$$y_o^g \leq Y^g\lambda$$

$$0 \leq Y^b\lambda \leq \alpha_2 Y^g\lambda$$

$$\frac{s_r^b}{y_{ro}^b} = \frac{s_r^{WD}}{x_{io}}$$

$$\lambda, s^-, s^b, s_r^{WD} \geq 0$$

Table 4 presents the eco–efficiency scores, ranks and reference sets of *SBM Model B weak* and *SBM Model B extended* for the sample data. The results of the two models were again generated using GAMS and are almost identical.[11] Again, DMU D is no longer a valid projection possibility at the efficiency frontier and consequently has to be projected on point D̃. The regulatory impact on DMU D increases from an efficiency loss of 24% under strong disposability to 32% under weak disposability. Same holds for DMU E where the regulatory impact increases from 5 to 7 percentage points. Consequently, the average regulatory impact over all eight firms is calculated as an efficiency loss of 5 percentage points, also higher than under a strong disposability assumption for undesirable outputs.

The increased regulatory impact shows that, when accounting for weak disposability the firms have to undertake additional effort in order to fulfil the environmental standard. This result highlights the importance of accounting for weak disposability when assessing the strength of certain environmental regulations.[12]

Again, different values of α_2 are considered in order to evaluate the regulatory impact of the environmental standard. If α_2 is for instance set to 1.5, the overall regulatory impact accounts to 16 percentage points, which is around three times the effect of an environmental standard of $\alpha_2 = 3.5$. For $\alpha_2 = 1$ it would again be most efficient for all firms to cease production and leave the market. Detailed information about efficiency scores and regulatory impacts of different environmental standards when accounting for weak disposability in the SBM Model B framework can be found in Appendix D.

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[11] Recall that the environmental standard was set to $\frac{Y^b}{Y^g} \leq 3.5$.

[12] Moreover, it is interesting to compare the results of *SBM Model B* in Table 2 and *SBM Model B weak* in Table 4. Although referring to the same firms and efficiency frontier, the average efficiency score decreased from 0.80 to 0.76 when taking into account weak disposability of undesirable outputs.

Table 4: Eco–efficiency Results — Emission per unit of output regulation

	SBM Model B weak			**SBM Model B extended**			**Regulatory Impact**
	Score	**Rank**	**Ref**	**Score**	**Rank**	**Ref**	
DMU A	1	1	A	1	1	A	
DMU B	1	1	B	1	1	B	
DMU C	0.67	6	A,B	0.67	6	A,B	
DMU D	1	1	D	0.68	3	$\tilde{D}$	0.32
DMU E	0.76	5	B,D	0.69	5	$\tilde{D}$	0.07
DMU F	0.42	8	A	0.42	8	A	
DMU G	0.45	7	A	0.45	7	A	
DMU H	0.77	4	A	0.77	4	A	
∅ **Efficiency**	0.76			0.71			**0.05**

Table 5 shows coordinates of the efficiency–frontier projections in *SBM model B extended* for single firms. The fourth column states that all projections fulfil the environmental standard $(\frac{Emission}{Output} \leq 3.5)$, but due to weak disposability firms have to increase their inputs to the *Input weak*–level. Consequently, no inefficient firm can reach the efficiency frontier within one period. This is in line with Lozano and Gutierrez (2011) who also tried to account for weak disposability in SBM models.

Table 5: Efficiency–Frontier Projections

	Emission	Input	Output	$\frac{Emisison}{Output}$	Input weak
DMU A	13	20	10	1.3	20
DMU B	24	15	10	2.4	15
DMU C	15.2	19	10	1.5	28.37
DMU D	28.34	11	8.10	3.5	16.33
DMU E	33.50	13	9.57	3.5	18.97
DMU F	13	20	10	1.3	52.62
DMU G	13	20	10	1.3	41.76
DMU H	13	20	10	1.3	27

4.2.2 Undesirable Output Model

Our weak disposability extensions to the Undesirable Output Model from Cooper et al. (2007) are included in Equation (6), this formulation is called *Undesirable Output Model weak* in the remaining text. The Undesirable Output Model is non–oriented and thus includes slacks for inputs, undesirable outputs and desirable outputs. Nevertheless, undesirable outputs are treated as outputs wherefore weak disposability can only be implemented via outputs. The fourth constraint presents the implementation via output decrease. As soon as a firm needs to decrease emissions for reaching efficiency, it concurrently has to lower outputs proportional which is accounted in the objective function by the weak disposability slack s_r^{WD}.

Undesirable Output Model including weak disposability via outputs:
(*Intensity regulation*)

$$\min_{\lambda,s^-,s^+} \quad \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s_1+2s_2}(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}+\sum_{r=1}^{s_2}\frac{s_r^{WD}}{y_{ro}^g})} \tag{6}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o^b = Y^b\lambda + s^b$$

$$y_o^g = Y^g\lambda - s^g$$

$$\frac{s_r^b}{y_{ro}^b} = \frac{s_r^{WD}}{y_{ro}^g}$$

$$\lambda, s^-, s^g, s^b, s_r^{WD} \geq 0$$

Subsequently, the environmental standard is introduced (fourth constraint in Equation (7)). Again due to clarity reasons, different variables should be used for the regulatory and weak disposability constraint. Therefore, intensity and level–of–emission regulation can be used in combination with weak disposability via outputs. The fourth constraint contains intensity regulation as environmental standard on the efficiency frontier.[13] This model is called *Undesireable Output Model extended* in the remaining text.

Undesirable Output Model including bounded variables and weak disposability:
(*Intensity regulation*)

$$\min_{\lambda,s^-,s^+} \quad \rho = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s_1+2s_2}(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}+\sum_{r=1}^{s_2}\frac{s_r^{WD}}{y_{ro}^g})} \tag{7}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o^b = Y^b\lambda + s^b$$

$$y_o^g = Y^g\lambda - s^g$$

$$0 \leq Y^b\lambda \leq \alpha_1 X\lambda$$

$$\frac{s_r^b}{y_{ro}^b} = \frac{s_r^{WD}}{y_{ro}^g}$$

$$\lambda, s^-, s^g, s^b, s_r^{WD} \geq 0$$

Table 6 presents the eco–efficiency scores, ranks and reference sets when applying the *Undesirable Output Model weak* and the extended version from Equation (7) to the sample data. The

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[13] Recall that for a level–of–emission regulation the environmental standard has to be formulated as $0 \leq Y^b\lambda \leq \alpha_3$.

regulatory impact, given by the average efficiency loss in the industry, accounts to 5 percentage points and DMU D is again most affected from an individual point of view. As the regulatory impact is higher than under a strong disposability assumption, these results once again reveal that accounting for weak disposability is necessary to evaluate the whole regulatory impact of environmental standards.

In doing so, when decreasing α_2 to 0.7 for instance, the only remaining efficient firm is DMU A. Consequently, DMUs D,E and B lose efficiency. But the firms which were formerly projected in B gain efficiency, because the efficiency frontier approaches them. The industry wide efficiency loss is here computed with 8 percentage points, which also gives a higher difference than assuming strongly disposable undesirable outputs. Setting α_2 below 0.7, all firms will cease production and leave the market. Detailed information about efficiency scores and regulatory impacts of different environmental standards when accounting for weak disposability in the Undesirable Output Model framework can be found in Appendix E.

Table 6: Eco–efficiency Results — Intensity regulation

	Undesirable Output Model weak			**Undesirable Output Model extended**			**Regulatory Impact**
	Score	**Rank**	**Ref**	**Score**	**Rank**	**Ref**	
DMU A	1	1	A	1	1	A	
DMU B	1	1	B	1	1	B	
DMU C	0.70	6	B	0.70	6	B	
DMU D	1	1	D	0.71	5	D̃	0.29
DMU E	0.79	5	D	0.72	4	D̃	0.07
DMU F	0.37	8	B	0.37	8	B	
DMU G	0.46	7	B	0.46	7	B	
DMU H	0.81	4	A	0.81	3	A	
∅ Efficiency	0.77			0.72			**0.05**

5 Summary and Conclusion

In this paper we propose one approach to implement environmental standards into the DEA framework and thereby to measure its regulatory impact on eco–efficiency. Herein, we distinguish between strong and weak disposability of undesirable outputs. The presented model extensions can help to assess the regulatory impact of environmental standards in advance. Referring to an industry sample at one point in time, regulators can compare the efficiency scores of the firms when applying a usual SBM model and the extended counterpart to this sample. The difference in eco–efficiency scores can be interpreted as regulatory impact of the environmental standard. The possibility to assess the regulatory impact in advance could provide support for environmental policy makers in choosing appropriate instruments. Additionally, it should help to evaluate and adjust the intensity of regulation before taking political action.

As one basic feature of the DEA models lies in the exogeneity of inputs, desirable and undesirable outputs and the optimisation over weights, it is not possible to introduce constraints for these parameters directly. Therefore, we implement the environmental standard using a bounded

variables framework which allows constraints on the efficiency frontier. The regulatory impact of the environmental standard on a particular firm is determined by the comparison of its eco–efficiency scores before and after fictive introduction of the standard. The regulatory impact for the industry is measured by comparison of average eco–efficiencies.
Assessing the regulatory impact is exclusively based on a comparison of eco–efficiency scores. For that reason, a slack–based measure (SBM) framework, accounting for possible slacks, is more advantageous for our purpose. Herein, two possible models for measuring eco–efficiency are considered: a SBM version of Model B from Korhonen and Luptacik (2004) and the Undesirable Output Model from Cooper et al. (2007). These models constitute the starting point for methodological implementation of an environmental standard into the DEA framework. Moreover, we distinguish between weak and strong disposability of undesirable outputs and develop according models. Herein, weak disposability itself is an extension to common SBM eco–efficiency models.

Especially the huge flexibility in our proposed model framework comprises advantages for regulatory authorities and environmental policy makers. As the regulator can choose between two general SBM model frameworks, three types of environmental standards and two weak disposability versions the model can be adopted to a wide range of industries. Moreover, assessing the regulatory impact of environmental standards in advance can help choosing appropriate instruments and a reasonable intensity of regulation.

The application of our proposed method to assess the regulatory impact of environmental standards in advance would be interesting for different industries and offers large scope for further research. One interesting example is for instance to assess which environmental standard would be most advantageous and effective in reducing emissions in electricity generation.

APPENDIX

A Undesirable Output Model from Cooper et al. (2007)

$$\min_{\lambda, s^-, s^+} \quad \rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)} \tag{8}$$

s.t.:

$$x_o = X\lambda + s^-$$

$$y_o^b = Y^b\lambda + s^b$$

$$y_o^g = Y^g\lambda - s^g$$

$$\lambda, s^-, s^g, s^b, \geq 0$$

B SBM Model B bounded

Table 7: Eco–efficiency Scores — Emission per unit of output regulation

	SBM Model B	**4.5**	**3.5**	**2.5**	**1.5**	**1**
DMU A	1	1	1	1	1	-
DMU B	1	1	1	1	0.75	-
DMU C	0.75	0.75	0.75	0.75	0.75	-
DMU D	1	0.87	0.76	0.75	0.58	-
DMU E	0.82	0.82	0.77	0.76	0.58	-
DMU F	0.47	0.47	0.47	0.47	0.47	-
DMU G	0.55	0.55	0.55	0.55	0.55	-
DMU H	0.83	0.83	0.83	0.83	0.83	-
∅ **Efficiency**	0.80	0.79	0.77	0.76	0.68	-
Regulatory Impact		**0.01**	**0.03**	**0.04**	**0.12**	-

The second column gives the eco–efficiency scores using the standard SBM Model B. Columns 3 to 7 present the eco–efficiency scores using *SBM Model B bounded* for different emission per unit of output regulations ($\frac{Emission}{Output} \leq \alpha_2$). The heading gives the respective value of α_2. The regulatory impact is computed as the deviation of eco–efficiency scores from the average eco–efficiency score of SBM Model B. Note that DMUs A, F, G and H are not affected by the environmental standard. This is because DMU A is eco–efficient under all analysed regulations and each of the remaining DMUs is projected in A. For DMUs D and E the eco–efficiency score is constantly decreasing, indicating that stricter environmental standards cost eco-efficiency. DMU C is projected on the efficiency frontier between A and B. Since DMU B does also not fulfil the environmental standard of $\alpha_2 = 1.5$, the regulatory constraint cuts the efficiency frontier between these two points. But as the eco–efficiency score of DMU C is not changing, the cut must appear between the projection point of DMU C and DMU B. Summing up, the regulatory impact for the whole industry is increasing with strength of regulation.

C Undesirable Output Model bounded

Table 8: Eco–efficiency Scores — Intensity regulation

	Undesirable Output Model	**3**	**2**	**1**	**0.7**	**0.5**
DMU A	1	1	1	1	1	-
DMU B	1	1	1	0.84	0.78	-
DMU C	0.72	0.72	0.72	0.78	0.78	-
DMU D	1	0.83	0.77	0.71	0.70	-
DMU E	0.80	0.84	0.76	0.72	0.70	-
DMU F	0.40	0.40	0.40	0.44	0.47	-
DMU G	0.49	0.49	0.49	0.56	0.60	-
DMU H	0.84	0.84	0.84	0.84	0.85	-
∅ **Efficiency**	0.78	0.77	0.74	0.74	0.74	-
Regulatory Impact		**0.01**	**0.04**	**0.04**	**0.04**	-

The second column gives the eco–efficiency scores using the standard Undesirable Output Model from Cooper et al. (2007). Columns 3 to 7 present the eco–efficiency scores using the *Undesirable Output Model bounded* for different intensity regulations ($\frac{Emission}{Input} \leq \alpha_1$). The heading gives the respective value of α_1. The regulatory impact is computed as the deviation of eco–efficiency scores from the average eco–efficiency score of the Undesirable Output Model from Cooper et al. (2007). Note that for DMUs D and E the eco–efficiency score is constantly decreasing, whereas the eco–efficiency scores of DMU F,G and H are increasing as soon as DMU B is no longer eco–efficient. This is because each of the three firms is projected on the efficiency frontier between A and B. If the environmental standard cuts the efficiency frontier between these two points, the firms face a shorter projection way and thus gain in eco–efficiency. Consequently, the regulatory impact for the whole industry is constant from a distinct strength of regulation on.

D SBM Model B bounded and weak

Table 9: Eco–efficiency Scores — Emission per unit of output regulation

	SBM Model B weak	**4.5**	**3.5**	**2.5**	**1.5**	**1**
DMU A	1	1	1	1	1	-
DMU B	1	1	1	1	0.66	-
DMU C	0.67	0.67	0.72	0.67	0.67	-
DMU D	1	0.82	0.68	0.56	0.44	-
DMU E	0.76	0.76	0.69	0.57	0.44	-
DMU F	0.42	0.42	0.42	0.42	0.42	-
DMU G	0.45	0.45	0.45	0.45	0.45	-
DMU H	0.77	0.77	0.77	0.77	0.77	-
∅ **Efficiency**	0.76	0.74	0.71	0.68	0.60	-
Regulatory Impact		**0.02**	**0.05**	**0.08**	**0.16**	-

The second column gives the eco–efficiency scores using *SBM Model B weak*. Columns 3 to 7 present the eco–

efficiency scores using *SBM Model B extended* for different emission per unit of output regulations ($\frac{Emission}{Output} \leq \alpha_2$). The heading gives the respective value of α_2. The regulatory impact is computed as the deviation of eco–efficiency scores from the average eco–efficiency score of *SBM Model B weak*. Note that DMUs A, F, G and H are not affected by the environmental standard. This is because DMU A is eco–efficient under all analysed regulations and each of the remaining DMUs is projected in A. For DMUs D and E the eco–efficiency score is constantly decreasing, indicating that stricter environmental standards cost eco-efficiency. DMU C is projected on the efficiency frontier between A and B. Since DMU B also has to be projected for $\alpha_2 = 1.5$ the environmental standard cuts the efficiency frontier between A and B. More precisely, the variation in eco–efficiency scores of DMU C indicates that the cut appears between the projection point of DMU C and DMU A. Summing up, the regulatory impact for the whole industry is increasing with strength of regulation on. Due to the weak disposability assumption the eco–efficiency decrease is higher than under strong disposability of undesirable outputs.

E Undesirable Output Model bounded and weak

Table 10: Eco–efficiency Scores — Intensity regulation

	Undesirable Output Model weak	**3**	**2**	**1**	**0.7**	**0.5**
DMU A	1	1	1	1	1	-
DMU B	1	1	1	0.80	0.73	-
DMU C	0.70	0.70	0.72	0.74	0.73	-
DMU D	1	0.79	0.71	0.65	0.64	-
DMU E	0.79	0.80	0.72	0.66	0.64	-
DMU F	0.37	0.37	0.37	0.41	0.44	-
DMU G	0.46	0.46	0.46	0.52	0.52	-
DMU H	0.81	0.81	0.81	0.81	0.81	-
∅ **Efficiency**	0.77	0.74	0.72	0.70	0.69	-
Regulatory Impact		**0.03**	**0.05**	**0.07**	**0.08**	-

The second column gives the eco–efficiency scores using the *Undesirable Output Model weak*. Columns 3 to 7 present the eco–efficiency scores using the *Undesirable Output Model extended* for different intensity regulations ($\frac{Emission}{Input} \leq \alpha_1$). The heading gives the respective value of α_1. The regulatory impact is computed as the deviation of eco–efficiency scores from the average eco–efficiency score of the *Undesirable Output Model weak*. Note that for DMUs D and E the eco–efficiency score is constantly decreasing, whereas the eco–efficiency scores of DMU F and G are increasing as soon as DMU B is no longer eco–efficient. This is because both firms are projected on the efficiency frontier between A and B. If the environmental standard cuts the efficiency frontier between these two points, the firms face a shorter projection way and thus gain in eco–efficiency. The eco–efficiency score of DMU H under weak disposability is not affected, because DMU H is projected on DMU A from the beginning on. Summing up, the regulatory impact for the whole industry is increasing with stricter regulation, this is due to the weak disposability assumption.

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