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Efficiency Measurement when Producers Control Pollutants: A Non-Parametric Approach

[illegible]

Abstract: [illegible]

Keywords: *Data Envelopment Analysis; Directional Output Distance Function; Pollution Control; Allocatable Inputs; Weak Disposability Axiom*
JEL-codes: *D24; Q52; C61*

1. INTRODUCTION

[illegible] (Shepherd, 1970) [illegible]

[illegible] *the imposition of a fine, or more likely in the present case through diversion of given inputs to cleanup of the bad output”* [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

2. POLLUTION CONTROL ACTIVITIES AND THEIR IMPLICATIONS FOR EFFICIENCY MEASUREMENT

[illegible]

[illegible]

[illegible]

[illegible] $x \in \Re_+^N$ [illegible] $y \in \Re_+^M$ [illegible] $b \in \Re_+^K$ [illegible] U [illegible] $(K \times N)$ [illegible] V [illegible] $(K \times M)$ [illegible] K [illegible]

$$b = Ux - Vy \qquad (1)$$

[illegible] b [illegible] b [illegible]

[illegible] $a \in \Re_+^K$ [illegible]

$$b = Ux - Vy - a \qquad (2)$$

[illegible][1]

[1] [illegible]

[illegible]

1. [illegible]
2. [illegible]

[illegible]

[illegible] *does not assume that purification* [illegible] *inputs are used at the expense of production inputs* [illegible] *through diversion of given inputs to cleanup of the bad output"* [illegible]

[illegible]

[illegible]

[illegible] *allocative* [illegible]

[illegible] *no relevance* [illegible]

3. THEORETICAL UNDERPINNINGS

[illegible]

[illegible] $P(x)$ [illegible] x [illegible] $\Re_+^N$ [illegible] x [illegible]

$$P^T\left(x\right) = \left\{y : x \text{ can produce } y\right\}$$ [illegible]

[illegible]

[illegible]

output sets, and free disposability of inputs and desirable outputs are assumed to apply. These properties are described in more detail in Färe and Primont (1995).

The traditional production model does not account for the generation of undesirable outputs (as well as their reduction). One may expect that emission reductions take place at the expense of desirable outputs for given inputs. The discussion in section 2 suggests that this is the case when emissions are reduced by pollution control. In this case, production possibilities for desirable outputs should depend on pollution control efforts. In the following, I present two alternative models that attempt to deal with this issue.

3.2 The weak disposability model

This section provides a short summary of the model framework of Färe et al. (2005). Let $P^W(x)$ be an output set containing desirable and undesirable outputs:

$$P^W(x) = \{(y,b) : x \text{ can produce } (y,b)\} \tag{4}$$

With the exception of free disposability of undesirable outputs, Färe et al. (2005) impose the axioms of traditional production model on the output set form equation 4. Two non-conventional axioms are also added to capture that some of the outputs are undesirable:

$$\text{(i) if } (y,b) \in P^W(x) \text{ and } b = 0, \text{ then } y = 0$$
$$\text{(ii) if } (y,b) \in P^W(x) \text{ and } 0 \le \theta \le 1, \text{ then } (\theta y, \theta b) \in P^W(x)$$

Axiom (i), null-jointness (Shephard and Färe, 1974), implies that undesirable outputs are unavoidable when desirable outputs are being produced. Axiom (ii) is known as weak disposability of desirable and undesirable outputs. It implies that proportional output reductions always are feasible. This axiom allows modelling costly emission reductions since desirable outputs must be forgone to reduce undesirable outputs. The model thereby considers inputs used for reducing emissions productive[4].

Using equation 2 (controlled emission), together with axiom (ii), it is straightforward to show that the weak disposability axiom suggests that emission reductions take place by pollution control (Rødseth, 2011):

$$\theta[b + vy] = ux - a \tag{5}$$

[4] The weak disposability model does however not rule out regions of the output set where undesirable outputs can be reduced while simultaneously increasing desirable outputs.

[illegible] y [illegible] b [illegible] x [illegible] y [illegible] b [illegible] x [illegible] $(1-\theta)(b+vy)$ [illegible] y [illegible] b [illegible]

[illegible]

[illegible]

[illegible]

$$P^A(x;a)=\{y : x \text{ can produce } y \text{ for given } a\}$$

[illegible] a [illegible]

$$P^A\left(x;a^1\right)\subseteq P^A\left(x;a^2\right) \text{ if } a^1 \geq a^2$$

[illegible] $P^A\left(x;a^2\right)$ [illegible] $P^A(x;0)=P^T(x)$ [illegible]

[illegible]

[illegible] *vice versa* [illegible] *a priori* [illegible] *whether* [illegible] *possibly* [illegible]

3.2 [illegible]

[illegible] g_y

[illegible] $\Re_+^M$ [illegible]

$$\vec{D}_O^T\left(x, y; g_y\right) = \max\left\{\beta^T : \left(y + \beta^T g_y\right) \in P^T\left(x\right)\right\}$$
$$\vec{D}_O^A\left(x, y; a, g_y\right) = \max\left\{\beta^A : \left(y + \beta^A g_y\right) \in P^A\left(x; a\right)\right\} \qquad (8)$$
$$\vec{D}_O^W\left(x, y, b; g_y, 0\right) = \max\left\{\beta^W : \left(y + \beta^W g_y, b\right) \in P^W\left(x\right)\right\}$$

[illegible]

$$y \in P^T\left(x\right) \text{ if and only if } \vec{D}_O^T\left(x, y; g_y\right) \geq 0$$
$$y \in P^A\left(x; a\right) \text{ if and only if } \vec{D}_O^A\left(x, y; a, g_y\right) \geq 0 \qquad (9)$$
$$y \in P^W\left(x\right) \text{ if and only if } \vec{D}_O^W\left(x, y, b; g_y, 0\right) \geq 0$$

[illegible] y, [illegible] g.

[illegible]

$$\vec{D}_O^T\left(x, y; g_y\right) \geq \vec{D}_O^A\left(x, y; a, g_y\right) \qquad (10)$$

[illegible]

[illegible]

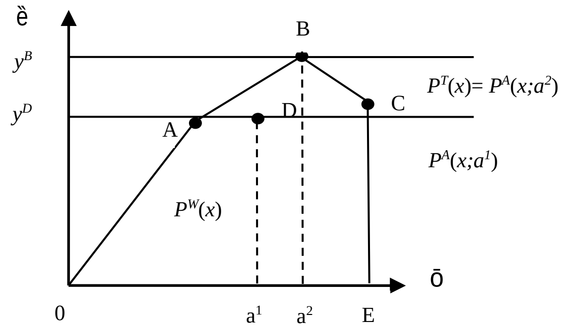

Figure 1: *The three technologies*

[illegible] $P^T(x)$, $P^W(x)$, and $P^A(x;a)$ [illegible]

[illegible]

[illegible]

[illegible]

ŜŦŦ2ǋǖă I·™Φ CǋƵ2Ƴ ŦλƎdzǋŜ ϻΣ λǘ λă ŎŧŜI·ǋ ǘKI·ǘ 2ƴŧè 2ƴŜ ǇǋƵ2ŘdzŎŜǋΣ !Σ ŘλăǇƭI·èă I· KλƎKŜǋ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ŜŦŦ2ǋǘ ǘKI·ƴ ǇǋƵ2ŘdzŎŜǋ 5Φ ¢KŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ Ƴ2ŘŜŧ ǿλŧŧ ǘKŜǋŜŦ2ǋŜ 2ƴŧè Ŏ2ƳǇI·ǋŜ ǘKŜ ǇŜǋŦ2ǋƳI·ƴŎŜ 2Ŧ ǇǋƵ2ŘdzŎŜǋ 5 όλƴ ǘŜǋƳă 2Ŧ ŜÈǇI·ƴăλ2ƴă 2Ŧ ŘŜăλǋI·ōŧŜ 2dzǘǇdzǘăύ ǘ2 ǘKŜ ǇŜǋŦ2ǋƳI·ƴŎŜ 2Ŧ ǇǋƵ2ŘdzŎŜǋ !Φ {λƴŎŜ ǇǋƵ2ŘdzŎŜǋ 5Ωă ŘŜăλǋI·ōŧŜ 2dzǘǇdzǘΣ y^DΣ λă ăŧλƎKǘŧè KλƎKŜǋ ǘKI·ƴ ǇǋƵ2ŘdzŎŜǋ !Ωă 2dzǘǇdzǘΣ ǇǋƵ2ŘdzŎŜǋ 5 λă Ŏ2ƴăλŘŜǋŜŘ ǘŜŎKƴλŎI·ŧ ŜŦŦλŎλŜƴǘ ōè ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ Ƴ2ŘŜŧΦ bŜÈǘΣ Ŏ2ƴăλŘŜǋ ǇǋƵ2ŘdzŎŜǋ .Φ Ǉǘ λă ŎŧŜI·ǋ ǘKI·ǘ λǘă ǇŜŜǋăΣ ǇǋƵ2ŘdzŎŜǋă ! I·ƴŘ 5Σ ŘλăǇƭI·è KλƎKŜǋ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ŜŦŦ2ǋǘă ǘKI·ƴ ǇǋƵ2ŘdzŎŜǋ .Σ ōdzǘ ǇǋƵ2ŘdzŎŜǋ .Ωă 2dzǘǇdzǘΣ y^BΣ ōè ŦI·ǋ ŜÈŎŜŜŘă y^DΦ ƫǋ2ŘdzŎŜǋ . λă ǘKŜǋŜŦ2ǋŜ I·ŧă2 Ŏ2ƴăλŘŜǋŜŘ ŜŦŦλŎλŜƴǘΦ ƫǋ2ŘdzŎŜǋ /Ωă Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ŜŦŦ2ǋǘă I·ƴŘ ǇǋƵ2ŘdzŎǘλ2ƴ 2Ŧ ǘKŜ ŘŜăλǋI·ōŧŜ 2dzǘǇdzǘ I·ǋŜΣ 2ƴ ǘKŜ 2ǘKŜǋ KI·ƴŘΣ ŧ2ǿŜǋ ǘKI·ƴ ǘK2ăŜ 2Ŧ ǇǋƵ2ŘdzŎŜǋ .Φ ƫǋ2ŘdzŎŜǋ / λă ǘKŜǋŜŦ2ǋŜ Ŏ2ƴăλŘŜǋŜŘ λƴŜŦŦλŎλŜƴǘ ōè ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ Ƴ2ŘŜŧΦ Ǉƴ ădzƳƳI·ǋèΣ ǇǋƵ2ŘdzŎŜǋă !Σ . I·ƴŘ 5 I·ǋŜ Ŏ2ƴăλŘŜǋŜŘ ǘ2 ōŜ ǘŜŎKƴλŎI·ŧ ŜŦŦλŎλŜƴǘ ōè ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ Ƴ2ŘŜŧΦ

/2ƳǇI·ǋλƴƎ ǘKŜ ǘKǋŜŜ Ƴ2ŘŜŧăΣ λǘ λă ŎŧŜI·ǋ ǘKI·ǘ ǘKŜè ŘλŦŦŜǋ λƴ ǘŜǋƳă 2Ŧ I·ăăλƎƴλƴƎ ŜŦŦλŎλŜƴǘ ŘŜŎλăλ2ƴ ƳI·ƙλƴƎ dzƴλǘăΦ ¢KŜ ǘǋI·Řλǘλ2ƴI·ŧ ǇǋƵ2ŘdzŎǘλ2ƴ Ƴ2ŘŜŧ Ǉdzǘă ƴ2 ǿŜλƎKǘ 2ƴ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ŜŦŦ2ǋǘă I·ƴŘ ǘKŜǋŜŦ2ǋŜ 2ƴŧè Ŏ2ƴăλŘŜǋă ǇǋƵ2ŘdzŎŜǋ . ǘ2 ōŜ ŜŦŦλŎλŜƴǘΦ ¢KŜ ǿŜI·ƙ ŘλăǇ2ăI·ōλŧλǘè Ƴ2ŘŜŧ I·ƴŘ ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ Ƴ2ŘŜŧ I·Ŏŏ2dzƴǘ Ŧ2ǋ ŜŦŦ2ǋǘă ǘ2 ǋŜŘdzŎŜ ŜƳλăăλ2ƴă ǿKŜƴ ŜǾI·ŧdzI·ǘλƴƎ ǇŜǋŦ2ǋƳI·ƴŎŜΣ ōdzǘ ǘKŜè ǋI·ƴƙ ǇǋƵ2ŘdzŎŜǋă ŘλŦŦŜǋŜƴǘŧèΦ ² KλŧŜ ǘKŜ ǿŜI·ƙ ŘλăǇ2ăI·ōλŧλǘè Ƴ2ŘŜŧ Ŏ2ƴăλŘŜǋă ǇǋƵ2ŘdzŎŜǋă !Σ . I·ƴŘ / ǘŜŎKƴλŎI·ŧ ŜŦŦλŎλŜƴǘΣ ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ǘŜŎKƴ2ŧ2Ǝè Ŏ2ƴăλŘŜǋă ǇǋƵ2ŘdzŎŜǋă !Σ .Σ I·ƴŘ 5 ǘŜŎKƴλŎI·ŧ ŜŦŦλŎλŜƴǘΦ ¢KŜ ǿŜI·ƙŧè ŘλăǇ2ăI·ōŧŜ ǘŜŎKƴ2ŧ2Ǝè λƴŎŧdzŘŜă ǘKŜ Ŏ2ƴǾŜÈ Ŏ2ƳōλƴI·ǘλ2ƴ 2Ŧ ǘKŜ 2dzǘǇdzǘ ǾŜŎǘ2ǋă 2Ŧ ǇǋƵ2ŘdzŎŜǋă ! I·ƴŘ .Σ ǿKλŎK λƳƳŜŘλI·ǘŜŧè ƳŜI·ƴă ǘKI·ǘ ǇǋƵ2ŘdzŎŜǋ 5 λă I·ŧŧ2ŎI·ǘŜŘ λƴ ǘKŜ λƴǘŜǋλ2ǋ 2Ŧ λǘă 2dzǘǇdzǘ ăŜǘΦ ¢KŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ǘŜŎKƴ2ŧ2Ǝè ŘŗŜăΣ 2ƴ ǘKŜ 2ǘKŜǋ KI·ƴŘΣ ǋŜăŜƳōŧŜ I· ŦǋŜŜ ŘλăǇ2ăI·ōŧŜ Kdzŧŧ I·ƴŘ ǘKŜǋŜŦ2ǋŜ I·ŧŧ2ǿă ǇǋƵ2ŘdzŎŜǋ 5 ǘ2 ōŜ I·ŧŧ2ŎI·ǘŜŘ 2ƴ ǘKŜ Ŧǋ2ƴǘλŜǋ 2Ŧ ǘKŜ Ǝǋ2dzǇ 2dzǘǇdzǘ ăŜǘΦ bŜÈǘΣ ǇǋƵ2ŘdzŎŜǋ / λă I·ŧŧ2ŎI·ǘŜŘ 2ƴ ǘKŜ Ŧǋ2ƴǘλŜǋ 2Ŧ ǘKŜ ǿŜI·ƙŧè ŘλăǇ2ăI·ōŧŜ ǘŜŎKƴ2ŧ2ƎèΣ ōdzǘ λƴ ǘKŜ λƴǘŜǋλ2ǋ 2Ŧ ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ǘŜŎKƴ2ŧ2ƎèΦ ¢KŜ ŧI·ǘǘŜǋ ǋŜădzŧǘ λă ădzƳǇŧè ŘdzŜ ǘ2 ǘKŜ ŦI·Ŏǘ ǘKI·ǘ ǇǋƵ2ŘdzŎŜǋ .Ωă Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ŜŦŦ2ǋǘă I·ƴŘ ǇǋƵ2ŘdzŎǘλ2ƴ 2Ŧ ǘKŜ ŘŜăλǋI·ōŧŜ 2dzǘǇdzǘ ōè ŦI·ǋ ŜÈŎŜŜŘ ǘKI·ǘ 2Ŧ ǇǋƵ2ŘdzŎŜǋ /Φ Ǉƴ ǘŜǋƳă 2Ŧ ǘKŜ ǿŜI·ƙŧè ŘλăǇ2ăI·ōŧŜ ǘŜŎKƴ2ŧ2ƎèΣ ǇǋƵ2ŘdzŎŜǋ / λă ŧ2ŎI·ǘŜŘ λƴ I·ǋŜƎλ2ƴ 2Ŧ ǘKŜ ǇǋƵ2ŘdzŎǘλ2ƴ Ŧǋ2ƴǘλŜǋ ǿλǘK I· ƴŜƎI·ǘλǾŜ ǘǋI·ŘŜπ2ŦŦ ōŜǘǿŜŜƴ ǘKŜ ŘŜăλǋI·ōŧŜ I·ƴŘ dzƴŘŜăλǋI·ōŧŜ 2dzǘǇdzǘăΦ ¢Kλă ƳŜI·ƴă ǘKI·ǘ ǘKŜ dzƴŘŜăλǋI·ōŧŜ 2dzǘǇdzǘ ŎI·ƴ ōŜ ǋŜŘdzŎŜŘ ǿKλŧŜ ăλƳdzŧǘI·ƴŜ2dzăŧè λƴŎǋŜI·ăλƴƎ ǘKŜ ŘŜăλǋI·ōŧŜ 2dzǘǇdzǘΣ λΦŜΦ Ǉ2ŧŧdzǘλ2ƴ ǋŜŘdzŎǘλ2ƴ λă Ǉǋ2ŦλǘI·ōŧŜΦ ¢Kλă λă I· Ŏ2dzƴǘŜǋλƴǘdzλǘλǾŜ ǋŜădzŧǘ ǘKI·ǘ Ŏ2ƴǘǋI·Řλŏǘă ŎŧI·ăăλŎI·ŧ ŜŎ2ƴ2ƳλŎ ǘKŜ2ǋè I·ƴŘ ƳI·ƴè ŜƳǇλǋλŎI·ŧ ŜŎ2ƴ2ƳλŎ ăǘdzŘλŜă 2ƴ ǘKŜ 2dzǘǇdzǘ ăŜǘ λă ǘKŜǋŜŦ2ǋŜ 2ǘǘŜƴ Ŏ2ƴăλŘŜǋŜŘ I· ăK2ǋǘŎ2ƳλƴƎ 2Ŧ ǘKŜ ǿŜI·ƙŧè ŘλăǇ2ăI·ōŧŜ ǘŜŎKƴ2ŧ2Ǝè όCDŽǋădzƴŘΣ ннлфΤ ƫλŎI·Î2π¢I·ŘŜ2 I·ƴŘ ƫǋλ2ǋΣ ннлфύΦ ¢Kλă λăădzŜ λăΣ K2ǿŜǾŜǋΣ I·Ǿ2λŘŜŘ ōè ǘKŜ Ǉ2ŧŧdzǘλ2ƴ Ŏ2ƴǘǋ2ŧ ǘŜŎKƴ2ŧ2Ǝè[P]Φ

[P] hƴŜ ǋŜŦŜǋŜŜ Ǉ2λƴǘŜŘ 2dzǘ ǘKI·ǘ ǘKŜ λăădzŜ 2Ŧ ƴŜƎI·ǘλǾŜ ăKI·Ř2ǿ ǇǋλŎŜă ŎI·ƴ I·ŧă2 ōŜ ǋŜă2ŧǾŜŘ ōè I·ăădzƳλƴƎ ǘKI·ǘ Ǉ2ŧŧdzǘI·ƴǘă I·ǋŜ ŦǋŜŜŧè ŘλăǇ2ăI·ōŧŜ λƴǇdzǘă ό2ǋ Ŏ2ăǘŧè ŘλăǇ2ăI·ōŧŜ 2dzǘǇdzǘăύΦ ¢Kλă I·ǇǇǋ2I·ŎK ǘ2 Ƴ2ŘŜŧλƴƎ dzƴŘŜăλǋI·ōŧŜ 2dzǘǇdzǘă λă ŜÈǇŧ2ǋŜŘ ōè I I·λŧdz I·ƴŘ ±ŜŜƳI·ƴ όннлмύΣ ōdzǘ KI·ă ōŜŜƴ Ŏǋλǘλ Ŏλ ÎŜŘ ōè CǋŅŜ I·ƴŘ Dǋ2ăă ǐ2ǇŦ όнллоύ Ŧ2ǋ ōŜλƴƎ λƴŎ2ƴăλăǘŜƴǘ ǿλǘK ǇKèăλŎI·ŧ ŧI·ǿăΦ

4. DATASET AND EMPIRICAL IMPLEMENTATION

I·ŘŘλůλ2ÿ ů2 ŦŹťŧ2ǿλÿƎ CŊŊŜ Ŝů I·ťΦ όнллтōύ ōè ŜȄŎťdzŘλÿƎ LJťI·ÿůă Ŧ2Ŋ ǿKλŎK Ÿ2ŊŜ ůKI·ÿ лΦлллм LJŜŊŐŜÿů 2Ŧ ůKŜ ŜÿŜŊƎè λÿLJdzůă Ŏ2ŸŜ ŦŊ2Ÿ 2ůKŜŊ ă2dzŊŎŜă ůKI·ÿ Ŧ2ăăλť ŦdzŜťăΦ a 2ăů 2Ŧ ůKŜ LJťI·ÿůă ůKI·ů ăI·ůλăŦè ůKŜăŜ ŎŊλůŜŊλI· KI·ǾŜ I· ÿŜƎťλƎλōťŜ Ŏ2ÿădzŸLJůλ2ÿ 2Ŧ LJŜůŊ2ťŜdzŸ ŦdzŜťăΦ ¢2 I·Ǿ2λŘ ÎŜŊ2ă λÿ ůKŜ λÿLJdzů ŘI·ůI·Σ L Ř2 ÿ2ů Ŏ2ÿăλŘŜŊ Ŏ2I·ť ƎI·ăΣ I·ÿŘ LJŜůŊ2ťŜdzŸ ăŜLJI·ŊI·ůŜťèΣ ōdzů I·ƎƎŊŜƎI·ůŜ ůKŜ KŜI·ů Ŏ2ÿůŜÿů όŸŸ . ¢¦ ăύ 2Ŧ Ŏ2I·ť I·ÿŘ LJŜůŊ2ťŜdzŸ λÿů2 2ÿŜ λÿLJdzů όůKŜ άKλƎKπLJ2ťťdzůλÿƎέ ŦdzŜťύ ůKI·ů λă Ŏ2ÿădzŸŜŘ ů2ƎŜůKŜŊ ǿλůK ÿI·ůdzŊI·ť ƎI·ă όůKŜ άť2ǿπLJ2ťťdzůλÿƎέ ŦdzŜťύΦ

9L ! пфлскфнл LJŊ2ǾλŘŜă Ÿ2ÿůKťè λÿŦ2ŊŸI·ůλ2ÿ 2ÿ ŦdzŜť Ŏ2ÿădzŸLJůλ2ÿ I·ÿŘ ÿŜů ƎŜÿŜŊI·ůλ2ÿ 2Ŧ ŜťŜŎůŊλŎλůèΦ L I·ƎƎŊŜƎI·ůŜ ůKλă λÿŦ2ŊŸI·ůλ2ÿ dzLJ ů2 I·ÿÿdzI·ť Ŏ2ÿădzŸLJůλ2ÿ I·ÿŘ ƎŜÿŜŊI·ůλ2ÿ Ŧ2Ŋ ŜI·ŎK LJťI·ÿůΦ LÿŦ2ŊŸI·ůλ2ÿ I·ō2dzů ůKŜ LJťI·ÿůăΩ ƎŜÿŜŊI·ůλÿƎ ŎI·LJI·Ŏλůè λă 2ōůI·λÿŜŘ ŦŊ2Ÿ 9L ! ăůI·ůλăůλŎă 2ÿ ŎI·LJI·ŎλůèΦ ¢KŜ Ŧ2ŊŸ C9w / м LJŊ2ǾλŘŜă λÿŦ2ŊŸI·ůλ2ÿ I·ō2dzů ůKŜ I·ǾŜŊI·ƎŜ ÿdzŸōŜŊ 2Ŧ ǿ2Ŋʅ ŜŊă I·ů ůKŜ LJťI·ÿůăΦ ¦ ÿŦ2ŊůdzÿI·ůŜťèΣ ťI·ō2Ŋ ŘI·ůI· λă 2ÿťè I·ǾI·λťI·ōťŜ Ŧ2Ŋ нс 2Ŧ ůKŜ рп LJťI·ÿůă λÿ ůKŜ ŘI·ůI·ăŜůΦ ! ŸI·?2Ŋ LJŊ2ōťŜŸ ǿλůK ŜȄŎťdzŘλÿƎ LJťI·ÿůă ůKI·ů Ř2 ÿ2ů ŊŜLJ2Ŋů ťI·ō2Ŋ ŦŊ2Ÿ ůKŜ ăI·ŸLJťŜ λă ůKI·ů ůKŜ Ŧ2ťť2ǿλÿƎ ŊŜŘdzŎůλ2ÿ λÿ ăI·ŸLJťŜ ăλÎŜ ŊŜŘdzŎŜă ůKŜ I·ōλťλůè ů2 ŘλăŎŊλŸλÿI·ůŜ I·Ÿ2ÿƎ LJ2ǿŜŊ LJťI·ÿůăΦ L ůKŜŊŜŦ2ŊŜ I·LJLJťè I· ŸŜůK2Ř ŘŜǾŜť2LJŜŘ ōè Ÿdz2ăŸI·ÿŜÿ όнллфύ ůKI·ů KI·ÿŘťŜă Ÿλăăλÿƽ ŘI·ůI· λÿ 59!Φ Ÿdz2ăŸI·ÿŜÿ ădzƎƎŜăůă ŊŜLJťI·ŎλÿƎ Ÿλăăλÿƽ λÿLJdzů ǾI·ťdzŜă ōè I· άădzŦŦλŎλŜÿůťè ťI·ŊƎŜ ÿdzŸōŜŊέΣ ădzŎK ůKI·ů ůKŜ ăKI·Ř2ǿ LJŊλŎŜ 2ÿ ůKŜ ťI·ō2Ŋ Ŏ2ÿăůŊI·λÿů λă ÎŜŊ2 Ŧ2Ŋ I·ťť LJťI·ÿůă ǿλůK Ÿλăăλÿƽ ťI·ō2Ŋ ŘI·ůI· όλΦŜΦ ădzŎK ůKI·ů ůKŜ Ÿλăăλÿƽ λÿLJdzů λă ŜŦŦŜŎůλǾŜťè ŜȄŎťdzŘŜŘ ŦŊ2Ÿ ůKŜ I·ÿI·ťèλă ǿKŜÿ ŜǾI·ťdzI·ůλÿƽ ůKŜ ŜŦŦλŎλŜÿŎè 2Ŧ LJťI·ÿůă ǿλůK Ÿλăăλÿƽ ŘI·ůI·ύΦ L Ŏ2ÿăλŘŜŊ I· ǿλŘŜ ŊI·ÿƎŜ 2Ŧ LJ2ăăλōťŜ άťI·ŊƎŜ ÿdzŸōŜŊăέ Ŧ2Ŋ ůKŜ Ÿλăăλÿƽ ťI·ō2Ŋ ǾI·ťdzŜă I·ÿŘ Ŏ2ÿŎťdzŘŜ ůKI·ů тΦлл9ЪмлλăădzŦŦλŎλŜÿů ů2 ăI·ůλăŦè Ÿdz2ăŸI·ÿŜÿΩă ŎŊλůŜŊλ2ÿΦ {ŜŎ2ÿŘΣ L ŜăůλŸI·ůŜ ůKŜ LJŊ2ŘdzŎůλ2ÿ Ÿ2ŘŜťă ǿλůK I·ÿŘ ǿλůK2dzů ťI·ō2Ŋ ů2 Ŏ2ÿăλŘŜŊ ǿKŜůKŜŊ ťI·ō2ŊΣ ůKŜ 2ÿťè λÿLJdzů Ŏ2ÿăλŘŜŊŜŘ ůKI·ů LJ2ăăλōťè ŎI·ÿ ōŜ I·ťť2ŎI·ůŜŘ ů2 ō2ůK ŜťŜŎůŊλŎλůè ƎŜÿŜŊI·ůλ2ÿ I·ÿŘ LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ťΣ I·ŦŦŜŎůă ůKŜ ŘλŦŦŜŊŜÿŎŜă ōŜůǿŜŜÿ ůKŜ ůǿ2 LJŊ2ŘdzŎůλ2ÿ Ÿ2ŘŜťă ůKI·ů ůI·ʅŜ LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ť ŜŦŦ2Ŋůă λÿů2 I·ŎŎ2dzÿů I·ÿŘ ůKŜ ůŊI·ŘλůλŸ2ÿI·ť LJŊ2ŘdzŎůλ2ÿ Ÿ2ŘŜťΦ

¢KŜ Ŧ2ŊŸ 9L ! птст όō2λťŜŊύ LJŊ2ǾλŘŜă λÿŦ2ŊŸI·ůλ2ÿ 2ÿ ůKŜ ů2ůI·ť ÿdzŸōŜŊ 2Ŧ K2dzŊă bh₌ Ŏ2ÿůŊ2ť ǿI·ă λÿ ăŜŊǾλŎŜ ŘdzŊλÿƎ нллрΦ L Ŏ2ÿăλŘŜŊ ůKλă ǾI·ŊλI·ōťŜ ů2 ōŜ I· ădzλůI·ōťŜ LJŊ2Ȅè Ŧ2Ŋ ůKŜ LJťI·ÿůăΩ ŜŦŦ2Ŋůă ů2 Ŏ2ÿůŊ2ť bh₌ ŜŸλăăλ2ÿăΦ hůKŜŊ I·ǾI·λťI·ōťŜ ŸŜI·ădzŊŜă Ŏ2dzťŘ I·ťă2 ōŜ dzăŜŘΣ ōdzů L Ŏ2ÿăλŘŜŊ ůKŜŸ ů2 ōŜ ťŜăă ŊŜťλI·ōťŜΦ C2Ŋ ŜȄI·ŸLJťŜΣ 9L ! птст LJŊ2ǾλŘŜă λÿŦ2ŊŸI·ůλ2ÿ 2ÿ ůKŜ I·ǾŜŊI·ƎŜ I·ÿÿdzI·ť bh₌ ŊŜŸ2ǾI·ť ŊI·ůŜΦ ¢KŜ ŊŜŸ2ǾI·ť ŊI·ůŜ ŘŜLJŜÿŘă 2ÿ ůKŜ ŘŜăλƎÿ 2Ŧ ůKŜ ƎŜÿŜŊI·ůλÿƎ dzÿλťůè I·ÿŘ ůKŜ LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ť ŜǀdzλLJŸŜÿůΣ ǿKλŎK ŸŜI·ÿ ůKI·ů LJI·ŊI·ŸŜůŜŊă ădzŎK I·ă ō2λťŜŊ ůèLJŜ I·ÿŘ ăλÎŜ ůKI·ů I·ŊŜ ÿ2ů ŘλŊŜŎůťè ŊŜťI·ůŜŘ ů2 ŊŜă2dzŊŎŜă ŜŸLJť2èŜŘ ů2 LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ť LJťI·è I· λŸLJ2ŊůI·ÿů Ŋ2ťŜ λÿ ŘŜůŜŊŸλÿλÿƎ bh₌ ŊŜŸ2ǾI·ťΦ ! ťůŜŊÿI·ůλǾŜťèΣ ůKŜ I·Ÿ2dzÿů 2Ŧ bh₌ ŊŜŸ2ǾŜŘ ōè LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ť ŎI·ÿ ōŜ ŎI·ťŎdzťI·ůŜŘ ōè ŜăůλŸI·ůλÿƎ dzÿŎ2ÿůŊ2ťťŜŘ ŜŸλăăλ2ÿă όōè I·LJLJťèλÿƎ ŜŸλăăλ2ÿ ŦI·Ŏů2Ŋă ŊŜLJ2ŊůŜŘ λÿ ůKŜ I·LJLJŜÿŘλŎŜă 2Ŧ 9L ! Ωă 9ťŜŎůŊλŎ t2ǿŜŊ ! ÿÿdzI·ťύ I·ÿŘ ădzōůŊI·Ŏůλÿƽ Ŏ2ÿůŊ2ťťŜŘ ŜŸλăăλ2ÿă όǿKλŎK I·ŊŜ ŊŜLJ2ŊůŜŘ ōè 9ÿǾλŊ2ÿŸŜÿůI·ť tŊ2ůŜŎůλ2ÿ ! ƎŜÿŎèΩă ό9t ! ύ /ťŜI·ÿ ! λŊ a I·Ŋʅ Ŝůă ŘI·ůI·ōI·ăŜύΦ ¢KŜ LJŊ2ōťŜŸ ǿλůK ůKλă I·LJLJŊ2I·ŎK λă ůKI·ů I·ÿè ŜŊŊ2Ŋă λÿ ůKŜ ŜăůλŸI·ůŜă 2Ŧ dzÿŎ2ÿůŊ2ťťŜŘ ŜŸλăăλ2ÿă ŊŜădzťů λÿ ōλI·ăŜŘ ŜăůλŸI·ůŜă 2Ŧ LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ťΦ I ŜÿŎŜΣ L Ŏ2ÿăλŘŜŊ ůKŜ ÿdzŸōŜŊ 2Ŧ K2dzŊă 2Ŧ bh₌ Ŏ2ÿůŊ2ť ů2 ōŜ ůKŜ LJŊŜŦŜŊI·ōťŜ LJŊ2Ȅè 2Ŧ ŊŜă2dzŊŎŜă ŜŸLJť2èŜŘ ů2 LJ2ťťdzůλ2ÿ Ŏ2ÿůŊ2ťΦ ¢KŜ ŘI·ůI·ăŜů λă ădzŸŸI·ŊλÎŜŘ ōè ůI·ōťŜ мΦ

Table 1: *Summary statistics (54 plants)*

Variable	Mean	Std.Dev	Min	Max
High-polluting fuel (mmBTU)	32129290.0	26575532.0	1438240.0	121000000.0
Low-polluting fuel (mmBTU)	2810866.0	5928644.0	16568.5	32800000.0
Capacity (MW)	807.0	613.4	31.9	2671.4
Labor[i] (Workers)	140.8	74.4	16.0	286.0
Electricity (MwH)	3324180.0	2965044.0	137760.0	14600000.0
Nitrogen (t)	5515.1	4376.1	326.9	19248.5
Pollution control (hrs)	14782.1	11291.6	0.0	56187.0

[i] [illegible]

[illegible] $x^l = \left(x_1^l,..,x_4^l\right) \in \Re_+^4$ [illegible] $y^l \in \Re_+$ [illegible]

$$\vec{D}_O^T\left(x^{l'}, y^{l'}; g_y\right) = \max \beta^T : \quad \sum_{l=1}^{L} \lambda^l y^l \geq y^{l'} + \beta^T y^{l'}$$
$$\sum_{l=1}^{L} \lambda^l x_n^l \leq x_n^{l'}, \qquad \mathrm{n} = 1,\ldots,4 \qquad (11)$$
$$\lambda^l \geq 0, \qquad l = 1,\ldots,L$$

[illegible] $a^l \in \Re_+$ [illegible]

$$\vec{D}_O^A\left(x^{l'}, y^{l'}; a^{l'}, g_y\right) = \max \beta^A : \quad \sum_{l=1}^{L} \lambda^l y^l \geq y^{l'} + \beta^A y^{l'}$$
$$\sum_{l=1}^{L} \lambda^l x_n^l \leq x_n^{l'} \qquad \mathrm{n} = 1,\ldots,4 \qquad (12)$$
$$\lambda^l \geq 0, \qquad \forall l : a^l \geq a^{l'}$$
$$\lambda^l = 0, \qquad \forall l : a^l < a^{l'}$$

[illegible]

$$
\vec{D}_O^W\left(x^{l'}, y^{l'}, b^{l'}; g_y, 0\right) = \max \beta^W : \quad
\begin{aligned}
&\sum_{l=1}^{L} \lambda^l y^l \geq y^{l'} + \beta^W y^{l'} \\
&\sum_{l=1}^{L} \lambda^l b_k^l = b_k^{l'} \\
&\sum_{l=1}^{L} \lambda^l x_n^l \leq x_n^{l'} \qquad n = 1, \ldots, 4 \\
&\lambda^l \geq 0, \qquad l = 1, \ldots, L
\end{aligned}
$$

$b^l \in \Re_+$

5. RESULTS

Table 2: *Efficiency scores*

Plant	Traditional		Pollution Control		Weak Disposable	
	Without labor	With labor	Without labor	With labor	Without labor	With labor
Barry	0.021	0.000	0.000	0.000	0.006	0.000
Green County	0.066	0.027	0.000	0.000	0.053	0.018
Apache S.	0.127	0.127	0.055	0.055	0.069	0.068
Arapahoe	0.000	0.000	0.000	0.000	0.000	0.000
Cameo	0.007	0.000	0.000	0.000	0.000	0.000
Cherokee	0.008	0.000	0.000	0.000	0.000	0.000
Martin Drake	0.000	0.000	0.000	0.000	0.000	0.000
Crist	0.108	0.000	0.000	0.000	0.089	0.000
Lansing Smith	0.000	0.000	0.000	0.000	0.000	0.000
Deerhaven G.S	0.187	0.153	0.187	0.153	0.166	0.152
C.D. McIntosh	0.067	0.067	0.067	0.067	0.055	0.055
Jack McDonough	0.000	0.000	0.000	0.000	0.000	0.000
Yates	0.096	0.073	0.000	0.000	0.080	0.071
Kraft	0.236	0.236	0.236	0.236	0.202	0.202
Harding Street	0.096	0.096	0.019	0.019	0.095	0.095
Sutherland	0.145	0.137	0.145	0.137	0.000	0.000
Riverside	0.319	0.319	0.319	0.319	0.215	0.215
Muscatine #1	0.000	0.000	0.000	0.000	0.000	0.000
Riverton	0.358	0.269	0.357	0.261	0.298	0.267
Quindaro	0.197	0.155	0.197	0.155	0.158	0.153
E.W. Brown	0.133	0.133	0.080	0.080	0.129	0.129
R.S. Nelson	0.250	0.221	0.085	0.085	0.115	0.000
B.C. Cobb	0.069	0.026	0.000	0.000	0.066	0.016
Dan E. Karn	0.126	0.126	0.064	0.064	0.123	0.123
River Rouge	0.034	0.034	0.034	0.034	0.032	0.032
Black Dog	0.057	0.057	0.057	0.057	0.000	0.000
Austin Northeast	0.153	0.153	0.153	0.153	0.036	0.036
Silver Lake	0.256	0.256	0.256	0.256	0.242	0.242
Jack Watson	0.037	0.000	0.037	0.000	0.000	0.000
Hawthorn	0.132	0.132	0.132	0.132	0.000	0.000
Meramec	0.096	0.072	0.069	0.069	0.053	0.000
Blue Valley	0.449	0.449	0.449	0.449	0.313	0.313
James River P.S.	0.183	0.126	0.096	0.096	0.173	0.112
Lon Wright	0.274	0.274	0.274	0.274	0.176	0.176
North Omaha	0.100	0.067	0.061	0.061	0.097	0.050
S.A. Carlson	0.609	0.609	0.598	0.598	0.579	0.579
Asheville	0.071	0.037	0.007	0.007	0.058	0.025
O.H. Hutchings	0.318	0.318	0.318	0.318	0.154	0.154
Hamilton	0.352	0.352	0.352	0.352	0.337	0.337
Muskogee	0.062	0.000	0.021	0.000	0.059	0.000
Northeastern	0.000	0.000	0.000	0.000	0.000	0.000

MT

Urquhart	0.015	0.009	0.015	0.009	0.000	0.000
Chesterfield	0.056	0.037	0.056	0.037	0.039	0.035
Yorktown	0.062	0.017	0.062	0.017	0.016	0.000
South Oak Creek	0.132	0.074	0.132	0.067	0.000	0.000
Pulliam	0.140	0.140	0.099	0.099	0.000	0.000
Weston	0.019	0.019	0.012	0.012	0.007	0.007
Belle River	0.061	0.000	0.061	0.000	0.000	0.000
Trimble County	0.070	0.025	0.070	0.025	0.011	0.000
A.B. Brown	0.053	0.000	0.000	0.000	0.046	0.000
Rodemacher	0.207	0.207	0.207	0.207	0.179	0.178
Southwest P.S	0.135	0.051	0.135	0.051	0.105	0.043
Rawhide	0.073	0.021	0.073	0.021	0.060	0.008
Neil Simpson 2	0.144	0.144	0.144	0.144	0.000	0.000

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Table 3: *Testing for differences in efficiency scores. Test statistic (P-value)*

TESTS	Pollution control - Traditional		Weak Disposable - Traditional	
	Without Labor	With Labor	Without Labor	With Labor
KSM	0.185	0.154	0.278	0.308
	(0.245)	(0.872)	(0.019)	(0.114)
ANOVA	0.790	0.290	3.410	1.520
	(0.377)	(0.590)	(0.068)	(0.224)
WILC	-1.565	-0.571	-2.501	-1.761
	(0.118)	(0.568)	(0.012)	(0.078)
MED	1.815	0.000	4.482	1.923
	(0.178)	(1.000)	(0.034)	(0.166)

[illegible]

[illegible]

6. SUMMARY AND CONCLUSIONS

[illegible]

7. ACKNOWLEDGEMENT

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8. REFERENCES

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