Estimating the efficiency of American petroleum refineries under varying assumptions of the disposability of bad outputs

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Abstract

Purpose – The paper aims to describe and compare multiple methods for estimating the technical efficiency of 113 US oil refineries in operation in 2006 and 2007, considering undesirable output in a production process.

Design/methodology/approach – A technology that satisfies weak disposability between desirable and undesirable outputs is constructed by allowing different abatement factors across all refineries. Several measures based on data envelopment analysis approaches are implemented and compared to study the impact of disposability assumptions and to investigate the effects of using non-uniform abatement factors. A hyperbolic efficiency measure is used to analyze the potential output loss of each refinery due to environmental regulations.

Findings – The results indicate that domestic refineries can improve efficiencies regardless of the disposability assumptions and that environmental regulations reduce the amount of potentially desirable outputs produced by some facilities. However, refineries in the western USA appear to be the most affected by regulations. In general, efficient refineries are less likely to be affected.

Research limitations/implications – Undesirable outputs are limited to toxic release. Undesirable outputs generated from refining crude oil, such as greenhouse gases, can be used when data are available. The desirable outputs in this paper do not include premium products, such as lubricants, which could raise the efficiency estimates of complex refineries.

Originality/value – To the authors' knowledge, this paper is the first implementation of the weakly disposable technology constructed by different uniform abatement factors. Further, the paper investigates the effects of various disposability assumptions on efficiency estimation. The result clearly identifies refineries that use their resources efficiently. The paper suggests that the data may be used to augment managerial decision-making regarding benchmarking and best practices.

Keywords Energy, Environmental testing, Petroleum refining, United States of America

Paper type Research paper

1. Introduction

Oil refineries are one of the principal stationary pollution sources along with chemical plants, coal-fired power plants, metal mining plants and other heavy industry. Petroleum refineries are a significant contributor to total US greenhouse gas emissions. Environmental Integrity Project and the Sierra Club comment on the current Environmental Protection Agency (EPA) standard of performance for refineries and conclude that refineries are responsible for about 14.3 per cent of industrial emissions and about 4 per cent of US emissions of CO_2 from fossil fuel combustion (EIPSC-SC, 2005). Refineries are the second largest industrial source of sulfur dioxide, the third

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largest industrial source of nitrogen oxides and the largest stationary source of volatile organic compound emissions (Saha and Gamkhar, 2005). The refinery industry is a significant contributor to toxic releases such as nitrate compounds, sulfuric acid, aromatic hydrocarbons and ammonia. These toxic emissions by refineries can be harmful to both the environment and to the humans.

Petroleum refining, one of the most heavily regulated of US industries (Saha and Gamkhar, 2005), is subject to federal regulations, i.e. the Clean Air Act, Clean Water Act, Resource Conservation and Recovery Act, Emergency Planning and Community Right-to-Know Act (EPCRA), Occupational Safety and Health Administration Health Standards and Process Safety Management Rules (EPAOC, 1995; ECMSIG-NCMS, 2004) and a plethora of state and local regulations depending on locale.

Prior studies cite environmental regulation as one of the reasons for refinery closures during the 1990s due to the rise in capital expenditures for the facility upgrades required to comply with new environmental guidelines (Saha and Gamkhar, 2005). A report from the US Department of Energy (DOE) states that the share of total US refinery's capital expenditures for pollution abatement increased from just over 10 per cent before the Clean Air Act Amendments of 1990 to over 40 per cent in 1997 (Energy Information Administration, EIA, 1997).

As concerns grow regarding climate change, oil refineries will also be subject to more regulation of CO_2 emissions. Other policy matters now being debated and legislated include pollution controls set by the EPA, establishment of a national market-based emissions permit system and self-regulatory compliance programs. Many studies have examined the impact of environmental compliance costs and regulations on productivity. Some researchers find that environmental regulation reduces productivity because it directly or indirectly makes inputs more expensive, while others conclude that such regulation can enhance productivity. For example, EPA reports that some companies which reduced their toxic chemical releases and increased their efficiency at the same time experienced increased profits (EPA, 2003). Moreover, one analysis of the paper industry finds a win-win potential to reduce inputs and pollution simultaneously without reducing productivity (Boyd and McClelland, 1999). An empirical analysis of South Coast oil refineries concludes that despite the heavy regulation in the region, abatement costs can still increase productivity (Berman and Bui, 2001). Porter's hypothesis (Boyd and McClelland, 1999) states that well-designed environmental regulations may introduce an innovative effect, i.e. new technologies and environmental improvements, making firms more efficient in production. However, few studies find evidence to support this hypothesis. Thus, it is important to develop new methods to evaluate efficiency and benchmark performance while considering pollution.

The output/input ratio is normally calculated to quantify a firm's productivity. Efficiency can be obtained by comparing to the best practice behavior. Generally, firm performance can be measured relative to a production frontier. If the firm operates under the frontier, it is said that this firm is inefficient. A number of studies apply this approach to perform benchmarking among firms in different industries and service sectors (Fare *et al.*, 1989; Hua *et al.*, 2007; Pathomsiri *et al.*, 2008). An important issue to evaluate efficiency for an oil refinery is that the pollution should be taken into account because oil refineries use a significant amount of their resources to abate pollution. Furthermore, this pollution is an undesirable output which has a shadow price in the sense that refineries have to spend more money on abatement processes, and this undesirable output can cause the company to pay more taxes or lose goodwill of the customer or surrounding community if a high level of pollution is generated. Accounting for undesirable outputs in a production process allows for a more complete efficiency measure for the oil refining industry.

In this paper, we compare the relative performance of different methods to estimate production frontiers and evaluate efficiency when undesirable outputs are taken into account. Notably, we show one of the first applications of a weak disposability model with non-uniform abatement factors. Several measures based on a data envelopment analysis (DEA) approach are implemented and compared to understand the value of recognizing non-uniform abatement factors. A unique data set of 113 US petroleum refineries allows a comprehensive picture of the output loss of refineries due to environment constraints.

The paper is organized as follows. Section 2 discusses a literature review of efficiency measurement when considerable undesirable output is presented. Section 3 describes a method of estimating production frontiers based on the assumption of weak disposability of undesirable outputs. Further, the effects of orientation on efficiency are investigated. Section 4 describes plant-level data for 113 US oil refineries. Section 5 presents the results of applying the proposed method to the unique data set. Section 7 concludes and offers suggestions for future research.

2. Literature review

Varied approaches for incorporating undesirable outputs into a production technology using the framework of DEA exist in the literature. Fare *et al.* (1989) modify the Farrell measure and use hyperbolic efficiency measures to equiproportionately increase desirable outputs and reduce undesirable outputs to estimate the efficiency levels of 30 US paper mills. Scheel (2001) proposes a new set of efficiency measures which adjust both desirable and undesirable outputs. These measures assume that any change of output levels involves both desirable and undesirable outputs. Seiford and Zhu (2002) use the invariance property concept to modify the variable returns-to-scale DEA model to address undesirable outputs for the same 30 paper mills analyzed in Fare *et al.* The authors apply a linear monotone decreasing inversion to the undesirable output(s) and transforming the variable(s) to standard outputs. Fare and Grosskopf (2004) comment that the method proposed in Seiford and Zhu (2002) does not satisfy weak disposability, and they suggest an alternative which applies the directional distance function to evaluate the performance of firms in the presence of undesirable outputs. Other DEA applications addressing undesirable outputs are Dyckhoff and Allen (2001), Hua *et al.* (2007) and Pathomsiri *et al.* (2008).

The important concept of weak disposability of undesirable output under variable returns-to-scale (VRS) has been debated recently. Weak disposability of output states that it is only possible to reduce undesirable outputs by decreasing desirable outputs. Conventionally, in a DEA framework, this has been modeled by using strict equality constraints on undesirable outputs. However, Hailu and Veeman (2001) propose a procedure to estimate the inner and outer bound of a non-parametric technology to incorporate undesirable outputs which they argue is preferable to the weakly disposable DEA model. Commenting on Hailu and Veeman, Fare and Grosskopf (2003) propose a new model to construct a weakly disposable production possibility set under VRS. An abatement factor is introduced for both desirable and undesirable output constraints to allow for the simultaneous contraction of desirable and undesirable outputs. Kuosmanen (2005) argues that the single abatement factor in Fare and Grosskopf (2003) is an unintended limiting assumption. In reality, firms face different abatement costs, whereas Fare and Grosskopf's model assumes that all firms apply the same uniform abatement factor. Kuosmanen shows how a weakly disposable technology can be modeled by using different non-uniform abatement factors across firms. Kuosmanen and Podinovski (2008) demonstrate numerically that a single abatement factor does not suffice to model a weakly disposable production set and prove that Kuosmanen technology is the correct minimum extrapolation technology under weak disposability and VRS assumptions. To the best of our knowledge, the work presented in this paper is the first implementation of Kuosmanen (2005) to a practical application.

In weak disposability models, the issue of non-negative shadow prices along some portions of the frontier is of concern. Fare *et al.* (1993), Hailu and Veeman (2001) and Lee *et al.* (2002) either restrict or use the method to ensure non-positive shadow prices of undesirable outputs. Fare *et al.* (1993) use a parametric translog form of distance function and restrict non-negative shadow prices of undesirable outputs in one constraint when analyzing pulp and paper mills in Michigan and Wisconsin. Hailu and Veeman (2000) treat undesirable outputs as inputs by using an inequality sign in undesirable output constraints to ensure that there will be no frontier constructed with negative shadow prices. Lee *et al.* (2002) use a directional distance function where the directional vector decreases both desirable and undesirable outputs to estimate shadow prices of NO_x, total suspended particulates and SO_2 in the Korean electric power industry. However, a few papers report non-negative shadow prices of undesirable outputs, such as Hetemaki (1996), Reinhard (1999) and van Ha *et al.* (2008). Reinhard (1999) measures firms' technical efficiency by using output distance function and projecting inefficiency firms to the frontiers where shadow prices of undesirable outputs are non-negative. Hetemaki (1996) observes that, theoretically, there are no axioms that require non-positive shadow prices of undesirable outputs and reports average positive shadow prices of total suspended solids (TSS) from Finish pulp plants. van Ha *et al.* (2008) study the technical efficiency and the shadow prices of biochemical oxygen demand, chemical oxygen demand and TSS of household-level paper-recycling units in Vietnam, reporting that the average shadow prices of all undesirable outputs have positive values. In our data set, the observations projected to the portions of the frontier with non-negative shadow prices are identified. A purpose of measuring technical inefficiency is to estimate an upper bound on economic efficiency. A tighter bound is derived by considering the implications for allocative efficiency along frontiers that have non-negative shadow prices for bad outputs.

When considering undesirable outputs in the production processes, other authors have proposed alternatives to Kuosmanen's weak disposability model. Many studies employ the concept of material balance originally proposed by Ayres and Kneese (1969) as a condition when modeling joint production of desirable and undesirable outputs. Murty and Russell's (2002) method models pollution-generating technologies by explicitly specifying a mathematical function characterizing the pollution generating mechanism. Assuming the material inputs are not freely disposable, Murty and Russell (2002), Forsund (2009) and Ebert and Welsch (2007) argue that the material balance condition excludes the possibility of the resulting production technology satisfying either strong or weak disposability between desirable and undesirable outputs. Inspired by engineering, Forsund (2009) uses the concept, factorially determined multi-output production (Frisch, 1965), to propose a theoretical model when considering pollutants, similar to Murty and Russell (2002) who separate desirable generating function from undesirable outputs' generating function. Note that only material inputs are related to desirable and undesirable outputs with a material balance condition equation. Unlike general production transformation functions, the marginal productivities of inputs in material balance function are sign unrestricted depending on the types of inputs. For example, the marginal productivities in undesirable outputs of capital and labor could be zero but have positive marginal productivities in desirable outputs.

Using a scientific or engineering approach to estimate a production function is usually appropriate when considering a small-scale production unit such as a machine; however, it is difficult to apply these approaches to larger production units in which several different production processes occur within one unit, such as an oil refinery. Typically, this type of production unit requires several material balance equations. This is supported by Farrell (1957) who states the difficulty in specifying a theoretical production function even via an engineering approach for very complex processes: the more complex the process, the lower the probability that a theoretical function is accurate. Thus, in a larger-scale production unit such as a firm or industry, Farrell suggests that another approach is more appropriate and practical, i.e. using observed data to estimate the best practice frontier.

Moreover, as stated in Coelli *et al.* (2007) and Forsund (2009), when considering undesirable outputs in the production processes, material balance condition only allows the production unit to operate on a frontier, implying that an inefficiency is not allowed. Consider the material input with the material balance equation expressed as $x_m = Av + Bw$ where x_m is a material inputs vector, v is an desirable outputs vector, w is undesirable outputs vector and A and B are conversion parameters. Note that if the material balance equation is affected by the quality of the material input, the desired proportions of the multiple desirable outputs, or different proportions, can be achieved through additional reprocessing, and then multiple material balance equations exist for one facility (i.e. refinery). Further, particularly in the case of reprocessing, there is a link between using non-material inputs to reduce undesirable outputs that are not captured by separately modeling the generation of desirable and undesirable output production functions. The material balance literature does not discuss the aggregation procedure for multiple processes each with their own material balance equation. Also, only under weak disposability of undesirable outputs does a duality exist between the distance function and the technology. Thus, Shephard's (1953) results demonstrate that the dual relationship will not hold under the material balance condition when there are undesirable outputs.

Further, it may be reasonable to assume x_m is freely disposable, implying that in the above material balance equation, v and w can be proportionally contracted while some part of x_m is used to produce both outputs and the remainder can be sold in an open market (assuming minimal friction costs) or used for other purposes, e.g. crude can be stored or sold.

While there is support in the literature for both the material balance approach and the weak disposability approach, it is not clear that one pre-dominates or that the methods are necessarily mutually exclusive. In this paper, we focus on weak disposability methods to clarify the effects of orientation, firm-specific abatement costs and the significance of negative shadow prices for bad outputs. The efficient production frontier is non-parametrically constructed using only observations following production axioms of weak disposability between desirable and undesirable outputs and assuming all inputs are freely disposable. It does not require allocation of inputs to particular pollution-generating mechanisms or information on particular pollution abatement activities as stated in Pasurka (2001).

3. Methodology

First, the notation for describing the input and output vectors and production possibility set is introduced. Input vector $x = (x_1, \ldots, x_N) \in R_+^N$ is used to produce a good output vector $y = (y_1, \ldots, y_M) \in R_+^M$ and an undesirable output vector $b = (b_1, \ldots, b_J) \in R_+^J$. For each firm $k = 1, \ldots, K$, the observed data are represented by vectors $x_k = (x_{k1}, \ldots, x_{kN})$, $y_k = (y_{k1}, \ldots, y_{kM})$ and $b_k = (b_{k1}, \ldots, b_{kJ})$. The production possibility set is defined as $P = \{(x,y,b)$: x can produce $(y,b)\}$. Originally proposed by Shephard (1970), the following axioms are restated regarding production when undesirable outputs are also produced:

- Strong disposability of inputs and desirable outputs
  If $(x,y,b) \in$ P. $0 \leq y' \leq y$ and $x' \geq x$ then $(x',y',b) \in$ P.
- Weak disposability of desirable outputs and undesirable outputs
  If $(x,y,b) \in$ P and $0 \leq \theta \leq 1$, then $(x, \theta y, \theta b) \in$ P.

The maintained assumptions defining the production possibility set for all models are:

- P is convex;
- strong disposability of inputs and desirable outputs exists; and
- there are VRS.

The weak disposability of desirable and undesirable outputs is commonly assumed when one wants to include undesirable outputs into the production process. To construct a weakly disposable technology, we augment the set of maintained assumptions via the weak disposability assumption stated previously. We can model the VRS weakly disposable technology as:

$$\begin{aligned} P_N = \{(x,y,b) : & \\ & \sum_{k \in K} \lambda_k y_{km} \geq y_m, && m = 1, \ldots, M \\ & \sum_{k \in K} \lambda_k b_{kj} = b_j, && j = 1, \ldots, J \\ & \sum_{k \in K} \lambda_k x_{kn} \leq x_n, && n = 1, \ldots, N \\ & \sum_{k \in K} \lambda_k = 1 && \\ & \lambda_k \geq 0, && k = 1, \ldots, K\} \end{aligned} \tag{1}$$

However, Fare and Grosskopf (2003) argue that this technology is not sufficient for modeling weak disposability under the VRS assumption. Rather, they introduce a single abatement factor which can be written as:

$$
\begin{aligned}
P_W = \{(x,y,b) : & \\
& \theta \sum_{k \in K} z_k y_{km} \geq y_{km}, \quad && m = 1, \ldots, M \\
& \theta \sum_{k \in K} z_k b_{kj} = b_{kj}, && j = 1, \ldots, J \\
& \sum_{k \in K} z_k x_{kn} \leq x_{kn}, && n = 1, \ldots, N \\
& \sum_{k \in K} z_k = 1 \\
& z_k \geq 0, && k = 1, \ldots, K \\
& 0 \leq \theta \leq 1 && \}
\end{aligned} \tag{2}
$$

where θ can be interpreted as the single abatement factor across all firms.

Later, Kuosmanen (2005) states that the technology:

- imposes no disposability and technology; and
- is incorrect when modeling the VRS weakly disposable technology.

He proposes:

$$
\begin{aligned}
P_W = \{(x,y,b) : & \\
& \sum_{k \in K} \theta_k z_k y_{km} \geq y_{km}, \quad && m = 1, \ldots, M \\
& \sum_{k \in K} \theta_k z_k b_{kj} = b_{kj}, && j = 1, \ldots, J \\
& \sum_{k \in K} z_k x_{kn} \leq x_{kn}, && n = 1, \ldots, N \\
& \sum_{k \in K} z_k = 1 \\
& z_k \geq 0, && k = 1, \ldots, K \\
& 0 \leq \theta_k \leq 1, && k = 1, \ldots, K\}
\end{aligned} \tag{3}
$$

where θ_k can be interpreted as the abatement factor. This non-linear formulation can be linearized and stated as:

$$
\begin{aligned}
P_W = \{(x,y,b) : & \\
& \sum_{k \in K} \lambda_k y_{km} \geq y_m, \quad && m = 1, \ldots, M \\
& \sum_{k \in K} \lambda_k b_{kj} = b_j, && j = 1, \ldots, J \\
& \sum_{k \in K} (\lambda_k + \mu_k) x_{kn} \leq x_n, && n = 1, \ldots, N \\
& \sum_{k \in K} (\lambda_k + \mu_k) = 1 \\
& \lambda_k, \mu_k \geq 0, && k = 1, \ldots, K\}
\end{aligned} \tag{4}
$$

where μ_k and λ_k can be interpreted as the component of weight z_k related to abatement and unrelated to abatement, respectively. These variables are used to expand the production possibility set; however, this technology is the smallest convex production possibility set under the weak disposability of desirable and undesirable outputs assumption. Based on a weak disposable technology, a multiplicative efficiency measure can be applied to evaluate and benchmark a firm's relative performance.

To check the importance of Kuosmanen's proper characterization of a technology with weakly disposable undesirable outputs when measuring performance, we compare the following methods for evaluating technical efficiency.

3.1 A linear transformation for undesirable outputs

Seiford and Zhu (2002) propose a linear transformation to treat undesirable outputs and then integrate transformed undesirable outputs into the standard Banker, Charnes and Cooper DEA model. To preserve convexity, a linear monotone decreasing transformation $\bar{b}_k = -b_k + w > 0$ is introduced where w is a translation vector to convert undesirable outputs into standard outputs. By applying the two technologies stated above, the efficiency estimates can be calculated using the following linear programs:

$$
\begin{aligned}
T_W = & \max_{\phi,\lambda_k,\mu_k} \gamma \\
& \text{st.} \sum_{k \in K} \lambda_k y_{km} \geq \gamma y_k^o, && m = 1, \ldots, M \\
& \sum_{k \in K} \lambda_k b_{kj}^{-} = \gamma b_k^{-o}, && j = 1, \ldots, J \\
& \sum_{k \in K} (\lambda_k + \mu_k) x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k \in K} (\lambda_k + \mu_k) = 1 \\
& \lambda_k, \mu_k \geq 0, && k = 1, \ldots, K\}
\end{aligned} \tag{5}
$$

$$
\begin{aligned}
T_N = & \max_{\phi,z_k} \gamma \\
& \text{st.} \sum_{k \in K} z_k y_{km} \geq \gamma y_k^o, && m = 1, \ldots, M \\
& \sum_{k \in K} z_k b_{kj}^{-} = \gamma b_k^{-o}, && j = 1, \ldots, J \\
& \sum_{k \in K} z_k x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k \in K} z_k = 1 \\
& z_k \geq 0, && k = 1, \ldots, K\}
\end{aligned} \tag{6}
$$

The programming problem equation (5) uses Kuosmanen's VRS weakly disposable technology and equation (6) uses the technology that implies no disposability according to Kuosmanen. The translation vector w can be arbitrarily selected; however, the least integer value that causes all $\bar{b}_k$ to be greater than zero is used in Seiford and Zhu (2002).

Similar to hyperbolic efficiency, an efficiency estimate equal to 1 implies that the firm operates on the best practice frontier. An efficiency estimate greater than 1 implies the firm operates under the best practice frontier and still has room for improvement.

3.2 A directional output distance function

Following Fare and Grosskopf (2004), the measurement in the direction of vector $g = (g_y, -g_b)$ can be expressed as $D(x,y,b{:}g_y, -g_b) = \max\{\beta{:}\ (y + \beta g_y, b - \beta g_b) \in P(x)\}$. The efficiency estimates for the Kuosmanen technology and the no disposability technology is obtained by solving the following linear programs:

$$
\begin{aligned}
D_W = &\max_{\phi,\lambda_k,\mu_k} \beta \\
&\text{st.} \sum_{k\in K} \lambda_k y_{km} \geq y_k^o + \beta g_y, && m = 1, \ldots, M \\
&\sum_{k\in K} \lambda_k b_{kj} = b_k^o + \beta g_b, && j = 1, \ldots, J \\
&\sum_{k\in K} (\lambda_k + \mu_k) x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
&\sum_{k\in K} (\lambda_k + \mu_k) = 1 \\
&\lambda_k, \mu_k \geq 0, && k = 1, \ldots, K\}
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
D_N = &\max_{\phi,z_k} \beta \\
&\text{st.} \sum_{k\in K} z_k y_{km} \geq y_k^o + \beta g_y, && m = 1, \ldots, M \\
&\sum_{k\in K} z_k b_{kj} = b_k^o + \beta g_b, && j = 1, \ldots, J \\
&\sum_{k\in K} z_k x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
&\sum_{k\in K} z_k = 1 \\
&z_k \geq 0, && k = 1, \ldots, K\}
\end{aligned}
\tag{8}
$$

The efficiency estimate β is a measure of the firm's distance from the best practice. Efficiency is indicated when β equals zero; β greater than zero implies inefficiency. The directional vector $g = (g_y, -g_b)$ is typically arbitrarily selected. One specification of the directional vector is $g = (y, -b)$which implies that each firm determines its own direction based on its current desirable and undesirable output levels. This specification of the directional vector is used in the following analysis.

3.3 A hyperbolic efficiency measure

This is commonly used to evaluate a firm's efficiency considering undesirable outputs because of the measure's ability to expand desirable outputs and reduce undesirable outputs simultaneously at the same rate. The efficiency estimates can be calculated using the following non-linear programs:

$$
\begin{aligned}
H_W = & \max_{\phi,\lambda_k,\mu_k} \phi \\
& \text{st.} \sum_{k\in K} \lambda_k y_{km} \geq \phi y_k^o, && m = 1, \ldots, M \\
& \sum_{k\in K} \lambda_k b_{kj} = (1/\phi) b_k^o, && j = 1, \ldots, J \\
& \sum_{k\in K} (\lambda_k + \mu_k) x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k\in K} (\lambda_k + \mu_k) = 1 \\
& \lambda_k, \mu_k \geq 0, && k = 1, \ldots, K\}
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
H_N = & \max_{\phi,z_k} \phi \\
& \text{st.} \sum_{k\in K} z_k y_{km} \geq \phi y_k^o, && m = 1, \ldots, M \\
& \sum_{k\in K} z_k b_{kj} = (1/\phi) b_k^o, && j = 1, \ldots, J \\
& \sum_{k\in K} z_k x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k\in K} z_k = 1 \\
& z_k \geq 0, && k = 1, \ldots, K\}
\end{aligned} \tag{10}
$$

The hyperbolic efficiency is calculated under weakly and no disposable technology. It is a relative measure comparing to the best practice frontier. The hyperbolic efficiency estimate is equal to 1 if the firm operates at the frontier, i.e. either the firm is efficient or the firm is unable to increase good outputs while reducing undesirable outputs at the same time. An efficiency estimate greater than 1 indicates that the firm is inefficient in the sense that it is still able to expand good outputs and reduce undesirable outputs simultaneously. We note that increasing good outputs and reducing undesirable outputs are equally effective strategies.

Moreover, to observe the difference of the two weakly disposable technologies proposed by Fare and Kuosmanen, we compare hyperbolic efficiency estimates obtained from model (9) to the efficiency estimates from the following non-linear program:

$$
\begin{aligned}
H_N = & \max_{\phi,z_k} \phi \\
& \text{st.}\, \theta \sum_{k\in K} z_k y_{km} \geq \phi y_k^o, && m = 1, \ldots, M \\
& \theta \sum_{k\in K} z_k b_{kj} = (1/\phi) b_k^o, && j = 1, \ldots, J \\
& \sum_{k\in K} z_k x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k\in K} z_k = 1 \\
& z_k \geq 0, && k = 1, \ldots, K \\
& 0 \leq \theta \leq 1 && \}
\end{aligned} \tag{11}
$$

The hyperbolic efficiency measure based on strong disposability between good and undesirable outputs can be calculated and compared with the weak disposability hyperbolic efficiency measure to estimate the output loss due to pollution abatement. The efficiency measure, when strong disposability of undesirable outputs is assumed, is computed by solving the following non-linear programming:

$$
\begin{aligned}
H_s = & \max_{\phi,\lambda_k,\mu_k} \phi \\
& \text{st.} \sum_{k \in K} \lambda_k y_{km} \geq \phi y_k^o, && m = 1, \ldots, M \\
& \sum_{k \in K} \lambda_k b_{kj} \geq (1/\phi) b_k^o, && j = 1, \ldots, J \\
& \sum_{k \in K} \lambda_k x_{kn} \leq x_k^o, && n = 1, \ldots, N \\
& \sum_{k \in K} \lambda_k = 1 \\
& \lambda_k, \mu_k \geq 0, && k = 1, \ldots, K\}
\end{aligned}
\tag{12}
$$

The above measure imposes inequality constraints on undesirable outputs to estimate the technology assuming strong disposability of undesirable outputs. The ratio H_s/H_w indicates the output loss due to the abatement of undesirable outputs (Fare *et al.*, 1989). If H_s/H_w is equal to 1, then abatement has no effect on evaluating efficiency. On the other hand, if the ratio is greater than 1, the pollution abatement contributes to the lost opportunity to produce more good outputs.

4. Data description

Table I gives a summary of the variables selected. Three inputs consist of equivalent distillation as a proxy of capital, energy and crude oil. Two desirable outputs are gasoline and distillate and an undesirable output is toxic release. Plant-level data of US petroleum refineries derives from the EIA Refinery Capacity 2006 and 2007 reports (beginning in 2006, information such as atmospheric crude oil distillation capacity, downstream charge capacity and production yearly data are publicly reported by EIA (2006) and EIA (2007)). The data allow us to calculate the Nelson complexity index and equivalent distillation capacity (EDC) in mega-barrels per calendar day (MB/CD). The latter is used as the proxy variable for capital. Since petroleum refining is one of the most energy-intensive manufacturing industries in the USA, we include energy as an input. Refining uses a diverse set of fuel sources to convert crude oil to finished products. A document published by the US DOE Office of Industrial Technologies (OIT), USDOE-OIT (1998), identifies still gas, natural gas, electricity and petroleum coke as the primary fuel sources used in the refining process. We combine these into a single variable energy measured in GBtu. Actual fuel consumed in each Petroleum Administration for Defense Districts (PADD) area is reported by the EIA (various, 2006, 2007). We calculate the energy consumption for each refining process by using the fuel information required by each refining process reported in USDOE-OIT (1998) and Maple (1993). The energy variable for each refinery is then constructed by the ratio

Table I. Summary statistics for 113 US oil refineries in 2006 and 2007

	PADD1 (Ten refineries)				PADD2 (24 refineries)				PADD3 (43 refineries)				PADD4 (15 refineries)				PADD5 (21 refineries)			
	2006		2007		2006		2007		2006		2007		2006		2007		2006		2007	
EDC	1326.71	(799.71)	1344.90	(804.75)	1277.61	(918.89)	1312.01	(917.33)	1801.86	(1493.29)	1819.96	(1487.03)	298.08	(188.51)	313.40	(199.05)	1227.54	(982.64)	1243.59	(1003.61)
Crude oil	130.07	(78.88)	130.84	(79.12)	126.28	(83.64)	123.64	(82.76)	162.78	(125.07)	164.03	(125.48)	34.89	(20.8)	34.20	(20.08)	103.77	(60.93)	101.16	(59.66)
Energy (10^9 Btu/day)	63.24	(37.8)	65.64	(38.93)	58.79	(40.84)	58.75	(39.76)	93.55	(76.67)	88.23	(71.65)	17.76	(11.28)	17.42	(11.12)	60.49	(44.47)	62.24	(46.05)
Gasoline	43.57	(26.63)	37.41	(22.8)	49.31	(32.68)	46.91	(30.66)	67.06	(52.97)	64.94	(51.88)	17.06	(10.63)	16.53	(10.34)	15.92	(9.98)	14.18	(8.98)
Distillate	49.96	(30.7)	51.34	(31.48)	42.48	(29.29)	43.08	(30.04)	60.34	(48.65)	61.72	(50.59)	12.66	(8.32)	12.05	(7.98)	40.35	(26.68)	39.71	(26.08)
Toxic release (10^3 lb/day)	22.60	(27.15)	23.13	(33.53)	13.29	(16.94)	18.60	(20.06)	28.55	(36.62)	42.13	(80.20)	3.56	(39.37)	3.79	(41.17)	14.33	(22.33)	13.56	(20.13)

Notes: SDs are in parentheses; MB/CD, except where noted

Sources: EIA (2006, 2007, various); RTK-NET (2006, 2007); USDOE-OIT (1998) of the calculated energy consumption per refinery as a ratio to total calculate energy consumption for the PADD multiplied by the actual fuel consumed in each PADD. The amount of crude oil consumption is assumed to vary by the atmospheric crude oil distillation capacity. The crude oil variable is constructed as the ratio of individual atmospheric crude oil distillation capacity to the sum of all refineries' atmospheric crude oil distillation capacity in that PADD area. The amount of crude oil in MB/CD is then approximated by multiplying these weights with the actual amount of crude oil consumption in the PADD area. As large capital-intensive operations with relatively few employees, refinery labor data are not significant and we exclude it from this analysis.

About 90 per cent of the refined oil is converted to fuel products, most of which are gasoline and distillate-type fuel (diesel fuel and jet fuel). EIA reports the amount of finished motor gasoline and distillate in 12 different sub-PADD areas. EIA also reports the capacity of each process such as thermal cracking, catalytic cracking, hydro cracking, desulfurization and production capacity by year (2006 and 2007). The weight of each refinery yield gasoline is then constructed by the sum of capacity of the process yielding gasoline divided by the sum of this capacity from all refineries in the sub-PADD areas. The weight of yield distillate is constructed in the same manner. Assuming that gasoline and distillate are proportional to these weights, the approximated amount of gasoline and distillate produced in MB/CD from each refinery is estimated by multiplying the actual amount of gasoline and distillate by these weights. Undesirable outputs considered are the byproduct toxins released during the refining process. Beginning in 1986, the federal EPCRA requires firms to report toxic emission information to the EPA for public disclosure. The data are available in the Right-to-Know Network's databases (RTKNET, 2006, 2007). The Toxics Release Inventory (TRI) is a database of information about releases and transfers of toxic chemicals from facilities in particular industrial sectors, including petroleum refining. While many toxins are reported, the two main types in the TRI data are release and waste. Waste-generated data used in the analysis are the production-related waste. This waste may end up being recycled, destroyed in treatment or released. According to RTK Network, release is defined as any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping or disposing into the environment. Release can be emitted to air, water and land on-site and off-site. Only the total amount of waste in pounds is used as an undesirable output. Bui (2005) finds that refineries have lower toxic emission levels when they face more stringent environmental regulations. Thus, the TRI data are a good proxy for undesirable outputs when one wants to study the impact of environmental regulation on a firm's efficiency.

Table I reports the sample means and standard deviations for the data. The EDC has slightly increased; meanwhile, the amount of crude oil and energy consumption is quite stable over the two time periods. From 2006 to 2007, refineries produced slightly less gasoline but more distillate except refineries in PADD5. Toxic release has increased in every PADD area except in PADD5.

5. Results

The technical efficiency estimates for each refinery using the linear transformation, the directional distance function and the hyperbolic efficiency measure under both weak disposability and no disposability for 2006 and 2007 appear in Tables AI and AII in Appendix. Using a technology constructed under the assumption of weak disposability of undesirable outputs results in 39 efficient refineries when the directional distance function or the hyperbolic efficiency measure is employed. However, 47 refineries are estimated to be efficient when employing a linear transformation of undesirable outputs method. These results are consistent with Fare and Grosskopf (2004) who state that the linear transformation underestimates the size of the production possibility set. Another drawback of a linear transformation method is that the selection of a translation vector w is arbitrary. As w becomes larger, the efficiency estimates are higher and it becomes more difficult to distinguish efficient observations.

Using either the directional distance function or the hyperbolic efficiency measure gives similar results. This is consistent with our expectations since both methods are distance functions which estimate each firm's efficiency. However, one advantage of the hyperbolic efficiency measure method is that it does not require the user to choose the direction of improvement. Figures 1 and 2 show the distribution of the hyperbolic efficiency measure under weak disposability for 2006 and 2007. Table II summarizes the hyperbolic efficiency estimates.

Another conclusion that can be drawn from Tables AI and AII is that under different technologies, almost all efficiency estimates for the US refineries using a directional distance function or a hyperbolic efficiency measure are identical; only refinery 102 in the 2006 data set gives a different result. This refinery is efficient in a no disposable technology, but inefficient in weak disposability technology. This can be explained by considering that a weak disposability technology is a larger set of production possibilities than a no disposable technology. In 2007, the two efficiency measures are the same for both technologies.

Table III shows the hyperbolic efficiency estimates of refineries when using two different weakly disposable technologies. The hyperbolic efficiency estimates from

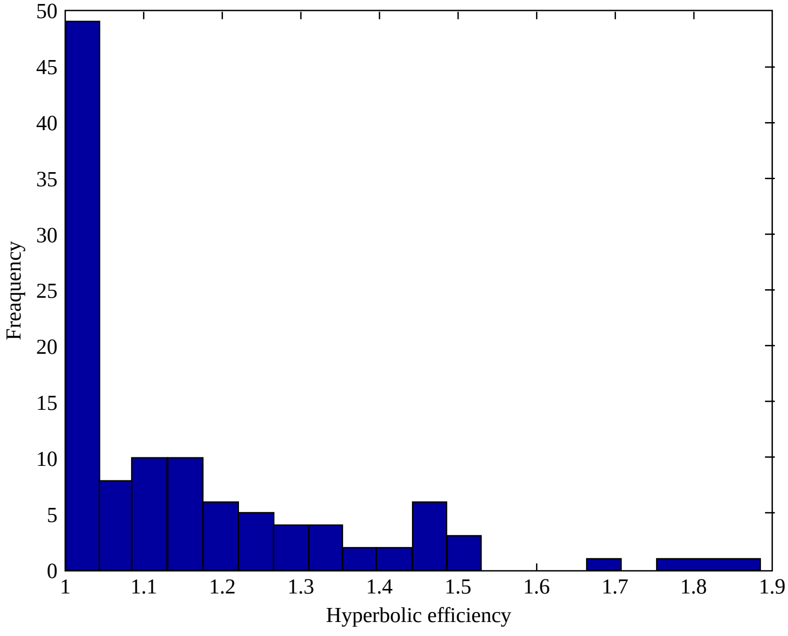

Figure 1.
Distribution of hyperbolic efficiency of refineries in 2006

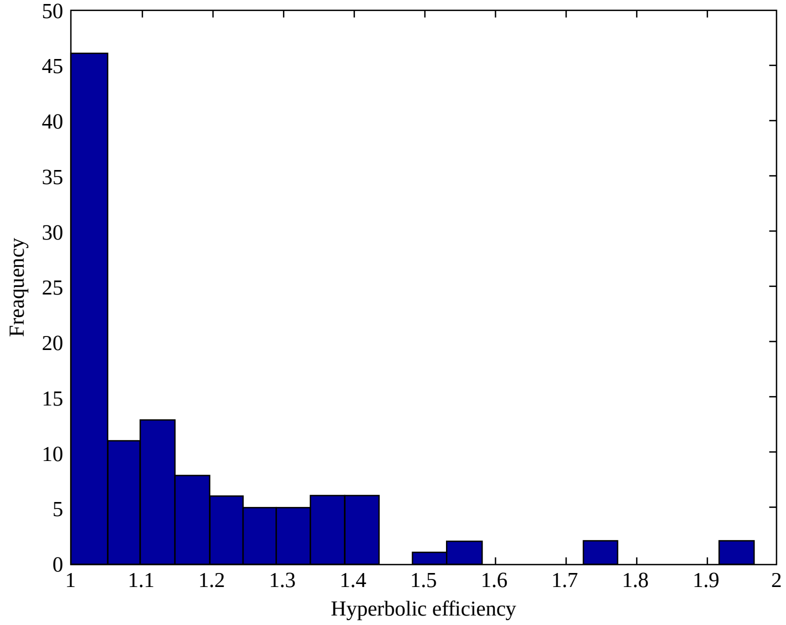

Figure 2.
Distribution of hyperbolic efficiency of refineries in 2007

Table II.
Summary of the hyperbolic efficiency estimates

Year	Mean	SD	Min	Max	Number of frontier refineries
2006	1.155	0.197	1	1.884	36
2007	1.157	0.199	1	1.966	41

Table III.

Year	Number of efficiency refineries having different shadow prices	Number of efficiency refineries having different shadow prices	Total
2006	13	1	14
2007	25	0	25

Note: Number of refineries having different shadow prices of outputs obtained from the Kuosmanen and the Fare weak disposable technology

model (11) equal the efficiency estimates from model (10). Thus, for the refinery data, the efficiency estimates are equal when using a non-disposable technology (1) and a Fare's weakly disposable technology (2). The efficiency estimates when using Kuosmanen's weak disposable technology are different for only one observation, because almost all refineries operate above most productive scale size and when using the hyperbolic distance, most inefficient refineries are projected to the frontiers constructed by convexity assumption. Thus, the assumption of weak disposability or no disposability makes little practical difference for the data set. Although the efficiency estimates from different technologies are almost identical in our analysis, this result may vary in other cases. Kuosmanen (2005) and Kuosmanen and Podinovski (2008) give good examples of the differences of Kuosmanen's and Fare's technologies.

Tables AIV and AV in Appendix show the shadow prices of desirable and undesirable outputs in 2006 and 2007. The shadow prices of desirable and undesirable outputs are the dual variables of the first and second constraints obtained from model (9) and model (11). Graphically, the shadow prices are described by the slope of the tangent line to the production frontier. Table III summarizes the number of refineries with different shadow prices. The shadow prices of both desirable and undesirable outputs are the same for all inefficiency refineries except for refinery 102 in the 2006 data. Note that for some efficient refineries, the shadow prices can differ because they are at the kinks of the production frontier; the shadow prices are not unique. However, the shadow price information confirms that in this data set, almost all inefficient refineries are projected to the same frontier when using either the Kuosmanen or the Fare technology. To conclude, the Kuosmanen and the Fare weak disposable technology can give different results, but the degree of difference depends on the data set and the choice of direction for measuring efficiency.

As shown in Tables AIV and AV, some shadow prices of undesirable outputs appear to be positive. In fact, the positive shadow prices of undesirable indicate the possibility for firms to increase desirable outputs by reducing undesirable outputs. We interpret this as a material balance condition. There are some limitations to a fixed input level that more bad output can only be generated by sacrificing good output. In this paper, about 20 and 15 per cent of refineries in 2006 and 2007, respectively, have benchmarks on the frontier with positive shadow prices for toxic releases (Table IV).

An important reason to estimate technical efficiency is that it serves as an upper bound on economic efficiency. When a firm is allocatively efficient, technical efficiency is equal to allocative efficiency. A common assumption in the externalities or bad output literature is that bad outputs are undesirable and are costly (or at least there is no revenue gained by disposing of them); thus, the weak disposability frontier is used to estimate technical efficiency. However, given any possible cost vector for bad outputs, the observations on the portion of the frontier with non-negative shadow prices for bad outputs are clearly allocatively inefficient. We propose that an upper bound on allocative efficiency can be estimated for these portions of the frontier. This concept is illustrated with a small example and is shown in Figure 3. The upper bound on allocative efficiency is estimated by projecting on the frontier BC.

This interpretation of technical efficiency is very strict and perhaps counter-intuitive. A technical efficiency measure of 1 referencing a portion of the frontier with a non-negative shadow price for undesirable output indicates that it is not possible to produce any more good or bad output. In other words, all inputs are being used efficiently to produce some type of output. An allocative efficiency captures the amount of output desirability or undesirability. Table AVI in Appendix reports the upper bound

Table IV. Number of refineries with positive shadow prices of toxic releases

Year	Number of refineries with positive shadow prices			
	Hyperbolic efficiency $=1$	Hyperbolic efficiency >1	Total	%
2006	5	18	23	20.35
2007	5	12	17	15.04

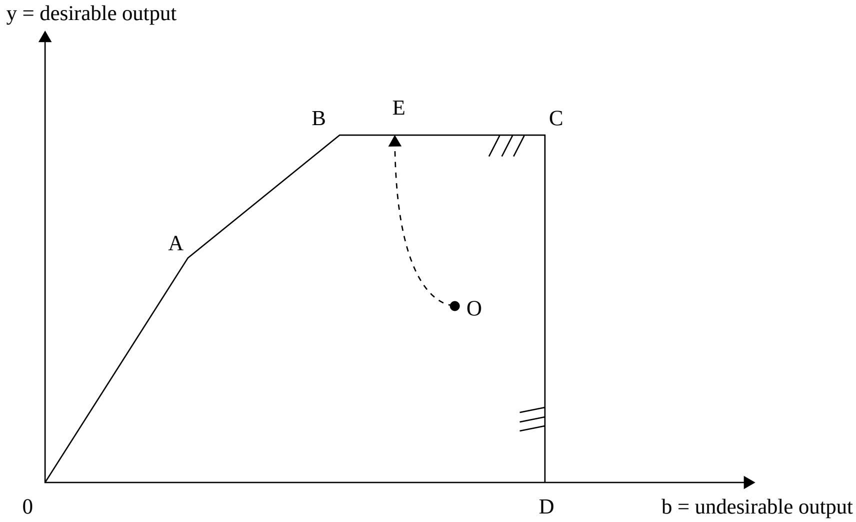

Figure 3.
The upper bound on allocative efficiency estimate using output set 0ABCD

estimates for both allocative and economic efficiency for observations projecting to a portion of the frontier with positive shadow prices for undesirable outputs. For all other observations technical efficiency directly serves as an upper bound on economic efficiency, and the upper bound for allocative efficiency is 1 because it is only assumed that undesirable outputs cannot be used to generate revenues, but that the actual cost is unknown.

Table V shows the average hyperbolic efficiency in a weakly disposable technology and the percentage of efficient refineries in each geographical area (PADD). The average hyperbolic efficiency estimates within each region range between 1.057 and 1.218 in 2006 and between 1.048 and 1.203 in 2007. The percentage of efficient refineries in each region is computed. For example, in 2006, there is 30 per cent efficiency in PADD1, or three out of a total of ten refineries are efficient. Refineries in PADD3 (Gulf Coast region) and PADD4 (Rocky Mountain region) are most efficient with the highest average efficiency estimate and the highest percentage of efficient refineries. Moreover, following Banker (1993) and Banker and Chang (1995), the hypothesis tests involve a comparison of refineries' efficiencies in two groups which are constructed to determine if the regional efficiency is statistically significantly different. Table V also reports the F-statistics used to test the null hypothesis that the refineries in both groups have the same inefficiency distributions against the alternative hypothesis that the refineries in the first group are less efficient. The test shows that on average, refineries in PADD4 are statistically more efficient than refineries in other regions.

Table VI reports the average output loss and the percentage of refineries with an output loss greater than 1. The output loss normally provides a measure of the impact of environmental regulation on regulated firms. The average output loss within each region ranges between 1.010 and 1.042 in 2006 and between 1.012 and 1.057 in 2007. This implies that, on average, regulations affect refineries by reducing potential outputs by 1-4.2 per cent in 2006 and 1.2-5.7 per cent in 2007. These results indicate that the cost of abatement is significantly less than the 40 per cent DOE reported

Table V. Summary of technical efficiency estimate in each PADD area

PADD	Mean efficiency	Percentage of efficiency refineries	*F*-statistic when comparing to PADD 1	2	3	4	5
2006							
1	1.195	0.300	–	0.785 (0.701)	1.356 (0.233)	12.540 (0.000)	2.180 (0.064)
2	1.218	0.208	–	–	1.064 (0.419)	9.839 (0.000)	1.710 (0.109)
3	1.146	0.465	–	–	–	9.250 (0.000)	0.622 (0.879)
4	1.057	0.467	–	–	–	–	5.752 (0.001)
5	1.152	0.190	–	–	–	–	–
2007							
6	1.195	0.200	–	0.855 (0.643)	1.008 (0.452)	13.063 (0.000)	1.629 (0.166)
7	1.203	0.292	–	–	0.862 (0.645)	11.174 (0.000)	1.393 (0.233)
8	1.156	0.465	–	–	–	12.959 (0.000)	0.619 (0.881)
9	1.048	0.533	–	–	–	–	8.021 (0.000)
10	1.166	0.238	–	–	–	–	–

Note: *p*-values are in parentheses

Table VI.
Average of hyperbolic efficiency estimate and the percentage of efficient refineries by PADD area

PADD	Average output loss	Percentage of refineries that output loss >1
2006		
1	1.010	0.300
2	1.010	0.375
3	1.022	0.442
4	1.012	0.400
5	1.042	0.619
2007		
6	1.055	0.600
7	1.023	0.500
8	1.033	0.372
9	1.012	0.267
10	1.057	0.810

in 1997. This could be due to the large initial investment required to abate pollution which may have taken place when the regulations were initially put into effect. Furthermore, the result shows that efficiency estimates of refineries in PADD5 (West Coast region) are most affected by environmental regulations. About 62 per cent in 2006 and about 81 per cent in 2007 in PADD5 are influenced by environmental constraints. This implies that the regulations have the most impact on the refineries in PADD5 in the sense that the refineries fail to produce enough output to be efficient, because the cost of disposing of undesirable outputs is significant. In fact, California mandates a higher quality gasoline than other states. Costly reformulating is thus required. “Bad” parts must be extracted (and sold as byproducts) or undergo intense processing to convert the “bad” to good. Either way, refineries end up with less gasoline and distillate and more byproducts and higher emissions.

Another major finding of this paper is that efficient refineries are less affected by pollution abatement costs. From Tables V and VI, on average, refineries in PADD4 are the most efficient refineries but the percentage of refineries that are affected by pollution abatement in these two regions is less than in other regions. Moreover, when the percentage of efficient refineries in one area decreases, the percentage with output losses greater than 1 will increase. For example, from 2006 to 2007, the percentage of efficient refineries drops from 30 to 20 per cent, but the percentage of refineries affected by environmental constraints increases from 30 to 60 per cent. The interpretation is that environmental regulation has a greater impact on the less-efficient refineries.

Refineries in PADD4 are found to be the most efficient, but these refineries are significantly different from the other refineries in the data set in terms of scale. Their capacity ranges between 34.95 and 595.69 MB/CD. PADD4 refineries normally are less complex and the technology can be somewhat outdated when compared to the technology in other PADD areas. They specialize in handling only sweet crude from Alaska and the Rocky Mountain region. This allows them to be small and efficient at a very specialized task, but it also makes them vulnerable to fluctuations in the availability of sweet crude. Table AVII in Appendix shows the hyperbolic efficiency estimates when excluding the PADD4 refineries from the analysis. Figures 4 and 5 show the distributions of the hyperbolic efficiency when including and excluding the PADD4 refineries in 2006 and 2007, respectively, and Table VII summarizes the hyperbolic efficiency estimates in this comparison.

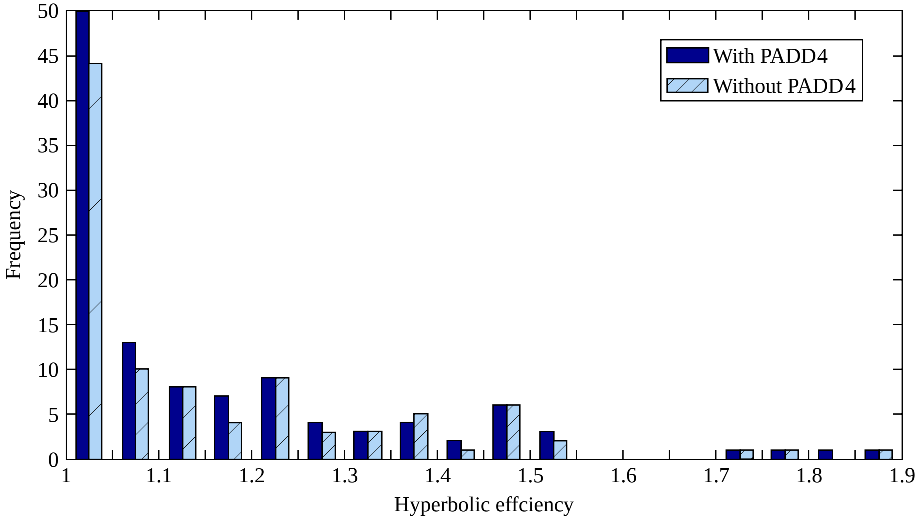

Figure 4.
Distribution of hyperbolic efficiency estimates with/without PADD4 refineries in 2006

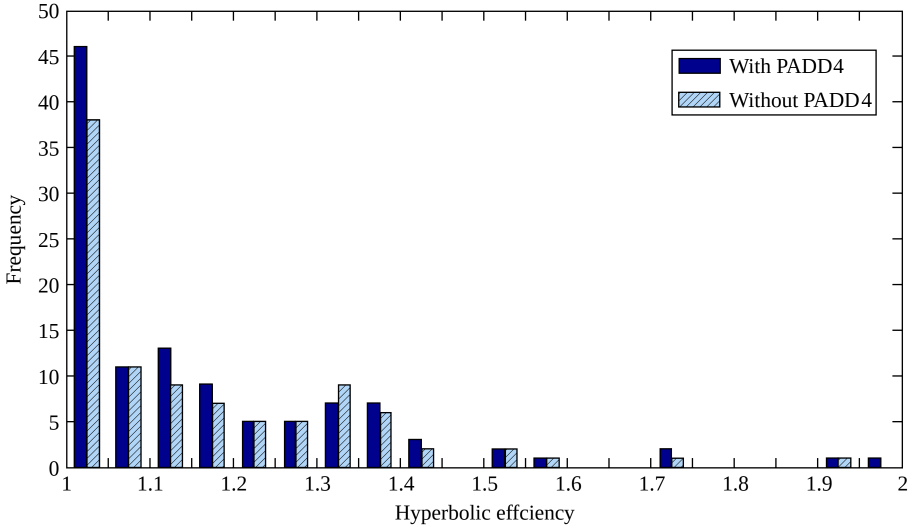

Figure 5.
Distribution of hyperbolic efficiency estimates with/without PADD4 refineries in 2007

Year	With or without PADD4	Mean	SD	Min	Max	Number of frontier refineries
2006	With PADD4	1.155	0.197	1	1.884	36
	Without PADD4	1.153	0.192	1	1.884	36
2007	With PADD4	1.157	0.199	1	1.966	41
	Without PADD4	1.163	0.198	1	1.966	35

Table VII.
Summary of the hyperbolic efficiency with/without PADD4 refineries

In 2006, 33 of the 98 refineries change their efficiency estimates; however, most of the efficiency estimates slightly improve with an average 0.05. Only five small refineries (EDC equals 53.52, 75.90, 93.59, 210.16 and 243.54 MB/CD) become efficient. In 2007, only 16 refineries slightly improve their efficiency estimates with an average change of 0.06. Only one small refinery, with an EDC of 53.52 MB/CD, becomes efficient. This result indicates that PADD4 refineries are efficient due to specialization and size. When estimating efficiency using the VRS assumption, PADD4 refineries tend to benchmark within a group of small refineries. They are not compared with large refineries in PADD3 and PADD5 areas which are considered more complex and more advanced refineries.

7. Conclusion

This paper evaluates the relative efficiency of US refineries while considering undesirable outputs generated in the production process. Unlike other previous studies, this paper constructs the weak disposability technology by using non-uniform abatement factors. To observe the impact when using non-uniform abatement factors, three DEA-based measures are implemented and compared under two different technology assumptions. The output oriented hyperbolic efficiency is used to evaluate the relative efficiency of an original data set of 113 domestic refineries in five PADD areas and to study the output loss due to environmental regulations.

When needing to evaluate a firm's relative efficiency considering undesirable outputs, the hyperbolic efficiency measure in a DEA framework is attractive because of its ability to simultaneously expand desirable outputs and reduce undesirable outputs at the same rate. The measure is also advantageous because:

- a linear transformation method underestimates the size of the production possibility set and the selection of a proper translation vector w is arbitrary; and
- a direction distance function method requires the user to choose the direction of improvement.

By implementing the three methods on two different technologies, the efficiency estimates show similar results for our refinery data set.

This paper's other contributions are as follows. First, refineries in the PADD4 (Rocky Mountain) region performed best in our benchmarking analysis; however, this may be strongly related to their specialization and small size. Second, the hyperbolic efficiency measure shows that it is possible for about 60 percent of oil refineries in the data set to improve their efficiencies by increasing an amount of gasoline and distillate while reducing overall emission. Third, some refineries are affected by environmental regulation in the sense that desirable outputs are reduced due to pollution abatement, particularly refineries in the PADD5 region. Fourth, environmental regulations are likely to have less effect on efficient refineries.

Further research in estimating refineries' efficiency with undesirable outputs could be improved by including more premium products, such as lubricants, as desirable outputs. Doing so would benefit the more complex refineries and provide a more complete efficiency indicator. Additionally, even though toxic release is a good proxy variable for undesirable outputs since it is correlated with environmental regulation, most of the "bad" outputs are not generated by crude oil. Clearly, toxic release can derive from other materials such as catalyst. Only the fugitive hydrocarbon is directly generated from crude oil and in typically small amounts relative to the other classes of emissions.

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(Appendices follow overleaf.)

Appendix

Table AI. Comparison of the technical efficiency estimate of 113 US oil refineries in 2006 obtained from several methods

Area	Refinery	No disposability: Linear transformation	No disposability: Directional distance function	No disposability: Hyperbolic efficiency	Weak disposability: Linear trans-formation	Weak disposability: Directional distance function	Weak disposability: Hyperbolic efficiency
PADD1	1	1	0	1	1	0	1
	2	1	0	1	1	0	1
	3	1.056	0.413	1.419	1.056	0.413	1.419
	4	1.027	0.049	1.049	1.027	0.049	1.049
	5	1.006	0.757	1.824	1.006	0.757	1.824
	6	1.232	0.223	1.221	1.232	0.223	1.221
	7	1.086	0.243	1.242	1.086	0.243	1.242
	8	1.010	0.040	1.040	1.010	0.040	1.040
	9	1.008	0.155	1.156	1.008	0.155	1.156
	10	1	0	1	1	0	1
PADD2	11	1.147	0.144	1.143	1.147	0.144	1.143
	12	1.112	0.142	1.143	1.112	0.142	1.143
	13	1.165	0.344	1.351	1.165	0.344	1.351
	14	1.122	0.244	1.243	1.122	0.244	1.243
	15	1.054	0.051	1.051	1.054	0.051	1.051
	16	1.003	0.290	1.296	1.003	0.290	1.296
	17	1.019	0.249	1.279	1.019	0.249	1.279
	18	1.030	0.353	1.352	1.030	0.353	1.352
	19	1.018	0.204	1.205	1.018	0.204	1.205
	20	1.007	0.467	1.470	1.007	0.467	1.470
	21	1.049	0.357	1.379	1.049	0.357	1.379
	22	1.050	0.472	1.484	1.050	0.472	1.484
	23	1.038	0.332	1.331	1.038	0.332	1.331
	24	1.051	0.497	1.502	1.051	0.497	1.502
	25	1.077	0.404	1.396	1.077	0.404	1.396
	26	1.002	0.359	1.414	1.002	0.390	1.414
	27	1	0	1	1	0	1
	28	1.011	0.023	1.023	1.011	0.023	1.023
	29	1	0	1	1	0	1
	30	1	0	1	1	0	1
	31	1	0	1	1	0	1
	32	1	0	1	1	0	1
	33	1.087	0.097	1.098	1.087	0.097	1.098
	34	1.020	0.094	1.094	1.020	0.094	1.094
PADD3	35	1	0	1	1	0	1
	36	1.013	0.088	1.089	1.013	0.088	1.089
	37	1	0	1	1	0	1

(continued)

Table AI.

Area	Refinery	No disposability: Linear transformation	No disposability: Directional distance function	No disposability: Hyperbolic efficiency	Weak disposability: Linear trans-formation	Weak disposability: Directional distance function	Weak disposability: Hyperbolic efficiency
	38	1	0	1	1	0	1
	39	1.062	0.059	1.059	1.062	0.059	1.059
	40	1	0	1	1	0	1
	41	1.065	0.061	1.061	1.065	0.061	1.061
	42	1	0.005	1.005	1	0.005	1.005
	43	1.024	0.223	1.223	1.024	0.223	1.223
	44	1	0	1	1	0	1
	45	1	0	1	1	0	1
	46	1.192	0.217	1.217	1.192	0.217	1.217
	47	1.192	0.469	1.465	1.192	0.469	1.465
	48	1.075	0.114	1.114	1.075	0.114	1.114
	49	1.124	0.544	1.524	1.124	0.544	1.524
	50	1.223	0.221	1.221	1.223	0.221	1.221
	51	1	0	1	1.292	0	1
	52	1	0	1	1	0	1
	53	1.045	0.462	1.473	1.045	0.462	1.473
	54	1	0	1	1	0	1
	55	1.191	0.307	1.307	1.191	0.307	1.307
	56	1.088	0.091	1.091	1.088	0.091	1.091
	57	1.008	0.087	1.087	1.008	0.087	1.087
	58	1.017	0.021	1.021	1.017	0.021	1.021
	59	1	0	1	1	0	1
	60	1.043	0.060	1.060	1.043	0.060	1.060
	61	1	0	1	1	0	1
	62	1	0	1	1	0	1
	63	1	0	1	1	0	1
	64	1.005	0.005	1.005	1.005	0.005	1.005
	65	1	0	1	1	0	1
	66	1.028	0.163	1.163	1.028	0.163	1.163
	67	1	0	1	1.192	0	1
	68	1.036	0.145	1.145	1.036	0.145	1.145
	69	1	0	1	1	0	1
	70	1	0	1	1	0	1
	71	1.004	0.459	1.480	1.004	0.459	1.480
	72	1.012	0.649	1.704	1.012	0.649	1.704
	73	1	0	1	1	0	1
	74	1.033	0.734	1.753	1.033	0.734	1.753

(*continued*)

		No disposability			Weak disposability		
Area	Refinery	Linear transformation	Directional distance function	Hyperbolic efficiency	Linear trans-formation	Directional distance function	Hyperbolic efficiency
	75	1.016	0.853	1.884	1.016	0.853	1.884
	76	1	0.009	1.009	1	0.009	1.009
	77	1.002	0.128	1.128	1.002	0.128	1.128
PADD4	78	1	0	1	1	0	1
	79	1.062	0.151	1.151	1.062	0.151	1.151
	80	1	0	1	1	0	1
	81	1.005	0.006	1.006	1.005	0.006	1.006
	82	1	0	1	1	0	1
	83	1.076	0.192	1.192	1.076	0.192	1.192
	84	1	0.001	1.001	1	0.001	1.001
	85	1.005	0.087	1.087	1.005	0.087	1.087
	86	1	0	1	1	0	1
	87	1.053	0.156	1.157	1.053	0.156	1.157
	88	1	0	1	1	0	1
	89	1.001	0.026	1.026	1.001	0.026	1.026
	90	1	0	1	1	0	1
	91	1.055	0.129	1.129	1.055	0.129	1.129
	92	1.002	0.096	1.096	1.002	0.096	1.096
PADD5	93	1.023	0.529	1.525	1.023	0.529	1.525
	94	1.009	0.224	1.224	1.009	0.224	1.224
	95	1.031	0.171	1.172	1.031	0.171	1.172
	96	1.017	0.140	1.141	1.017	0.140	1.141
	97	1	0	1	1	0	1
	98	1	0	1	1	0	1
	99	1.007	0.026	1.026	1.007	0.026	1.026
	100	1.001	0.015	1.015	1.001	0.015	1.015
	101	1.021	0.041	1.041	1.021	0.041	1.041
	102	1	0	1	1	0.038	1.038
	103	1	0	1	1	0	1
	104	1.080	0.080	1.080	1.080	0.080	1.080
	105	1	0	1	1	0	1
	106	1.096	0.096	1.095	1.096	0.096	1.095
	107	1.160	0.160	1.161	1.160	0.160	1.161
	108	1.010	0.221	1.221	1.010	0.221	1.221
	109	1.113	0.110	1.110	1.113	0.110	1.110
	110	1.031	0.267	1.269	1.031	0.267	1.269
	111	1.192	0.252	1.253	1.192	0.252	1.253
	112	1.067	0.455	1.465	1.067	0.455	1.465
	113	1.003	0.338	1.346	1.003	0.338	1.346

Table AI.

Table AII. Comparison of the technical efficiency estimate of 113 US oil refineries in 2007 obtained from several methods

		No disposability			Weak disposability		
Area	Refinery	Linear transformation	Directional distance function	Hyperbolic efficiency	Linear transformation	Directional distance function	Hyperbolic efficiency
PADD1	1	1	0	1	1	0	1
	2	1.088	0.135	1.135	1.088	0.135	1.135
	3	1.060	0.309	1.324	1.060	0.309	1.324
	4	1.037	0.089	1.090	1.037	0.089	1.090
	5	1.004	0.732	1.748	1.004	0.732	1.748
	6	1.045	0.217	1.222	1.045	0.217	1.222
	7	1.078	0.256	1.267	1.078	0.256	1.267
	8	1.016	0.101	1.101	1.016	0.101	1.101
	9	1.003	0.065	1.065	1.003	0.065	1.065
	10	1	0	1	1	0	1
PADD2	11	1.205	0.226	1.226	1.205	0.226	1.226
	12	1.119	0.228	1.233	1.119	0.228	1.233
	13	1.138	0.386	1.414	1.138	0.386	1.414
	14	1.119	0.291	1.304	1.119	0.291	1.304
	15	1.139	0.138	1.138	1.139	0.138	1.138
	16	1.003	0.102	1.103	1.003	0.102	1.103
	17	1.182	0.362	1.367	1.182	0.362	1.367
	18	1.043	0.181	1.186	1.043	0.181	1.186
	19	1.009	0.156	1.159	1.009	0.156	1.159
	20	1.128	0.394	1.392	1.128	0.394	1.392
	21	1.137	0.398	1.398	1.137	0.398	1.398
	22	1.042	0.399	1.415	1.042	0.399	1.415
	23	1.100	0.295	1.311	1.100	0.295	1.311
	24	1.050	0.523	1.572	1.050	0.523	1.572
	25	1.076	0.385	1.383	1.076	0.385	1.383
	26	1.002	0.185	1.191	1.002	0.185	1.191
	27	1	0	1	1	0	1
	28	1	0	1	1	0	1
	29	1	0	1	1	0	1
	30	1	0	1	1	0	1

(continued)

Table AII.

Area	Refinery	No disposability Linear transformation	No disposability Directional distance function	No disposability Hyperbolic efficiency	Weak disposability Linear transformation	Weak disposability Directional distance function	Weak disposability Hyperbolic efficiency
	31	1	0	1	1	0	1
	32	1	0	1	1	0	1
	33	1.108	0.103	1.103	1.109	0.103	1.103
	34	1	0	1	1.109	0	1
PADD3	35	1	0	1	1	0	1
	36	1.013	0.095	1.096	1.013	0.095	1.096
	37	1	0	1	1	0	1
	38	1	0	1	1	0	1
	39	1.134	0.130	1.130	1.134	0.130	1.130
	40	1	0	1	1	0	1
	41	1.081	0.084	1.084	1.081	0.084	1.084
	42	1	0	1	1	0	1
	43	1.086	0.163	1.164	1.086	0.163	1.164
	44	1.009	0.110	1.115	1.009	0.110	1.115
	45	1	0	1	1	0	1
	46	1.283	0.283	1.283	1.283	0.283	1.283
	47	1.208	0.515	1.514	1.208	0.515	1.514
	48	1.056	0.129	1.130	1.056	0.129	1.130
	49	1.133	0.355	1.352	1.133	0.355	1.352
	50	1.323	0.342	1.337	1.323	0.342	1.337
	51	1.309	0.319	1.311	1.361	0.319	1.311
	52	1.107	0.116	1.115	1.107	0.116	1.115
	53	1.004	0.075	1.077	1.004	0.075	1.077
	54	1	0	1	1	0	1
	55	1.148	0.352	1.350	1.148	0.352	1.350
	56	1.266	0.280	1.279	1.266	0.280	1.279
	57	1.015	0.090	1.090	1.015	0.090	1.090
	58	1	0	1	1	0	1
	59	1	0	1	1	0	1

(continued)

Area	Refinery	No disposability Linear transformation	Directional distance function	Hyperbolic efficiency	Weak disposability Linear transformation	Directional distance function	Hyperbolic efficiency
	60	1.055	0.055	1.055	1.055	0.055	1.055
	61	1	0	1	1	0	1
	62	1	0	1	1	0	1
	63	1	0	1	1	0	1
	64	1.047	0.046	1.046	1.047	0.046	1.046
	65	1	0	1	1	0	1
	66	1.032	0.108	1.110	1.032	0.108	1.110
	67	1	0	1	1.050	0	1
	68	1	0	1	1	0	1
	69	1	0	1	1	0	1
	70	1	0	1	1	0	1
	71	1.003	0.388	1.409	1.003	0.388	1.409
	72	1.013	0.673	1.726	1.013	0.673	1.726
	73	1	0	1	1	0	1
	74	1.059	0.894	1.966	1.059	0.894	1.966
	75	1.020	0.879	1.939	1.020	0.879	1.939
	76	1	0	1	1	0	1
	77	1	0	1	1	0	1
PADD4	78	1.001	0.023	1.023	1.001	0.023	1.023
	79	1.047	0.104	1.104	1.047	0.104	1.104
	80	1	0	1	1	0	1
	81	1	0	1	1.003	0	1
	82	1.003	0.001	1.001	1.003	0.001	1.001
	83	1.074	0.134	1.134	1.074	0.134	1.134
	84	1	0	1	1	0	1
	85	1.008	0.175	1.175	1.008	0.175	1.175
	86	1	0	1	1	0	1
	87	1.068	0.067	1.067	1.068	0.067	1.067
	88	1	0	1	1	0	1
	89	1	0	1	1	0	1

(continued)

Table AII.

Table AII.

Area	Refinery	No disposability Linear transformation	No disposability Directional distance function	No disposability Hyperbolic efficiency	Weak disposability Linear transformation	Weak disposability Directional distance function	Weak disposability Hyperbolic efficiency
	90	1	0	1	1	0	1
	91	1.056	0.163	1.163	1.056	0.163	1.163
	92	1.002	0.062	1.062	1.002	0.062	1.062
PADD5	93	1.024	0.385	1.400	1.024	0.385	1.400
	94	1.011	0.222	1.224	1.011	0.222	1.224
	95	1.035	0.256	1.258	1.035	0.256	1.258
	96	1.032	0.224	1.225	1.032	0.224	1.225
	97	1	0	1	1	0	1
	98	1	0	1	1	0	1
	99	1	0	1	1	0	1
	100	1.001	0.016	1.016	1.001	0.016	1.016
	101	1.021	0.067	1.067	1.021	0.067	1.067
	102	1	0	1	1	0	1
	103	1	0	1	1	0	1
	104	1.097	0.096	1.096	1.097	0.096	1.096
	105	1.007	0.012	1.012	1.007	0.012	1.012
	106	1.122	0.126	1.126	1.122	0.126	1.126
	107	1.183	0.181	1.181	1.183	0.181	1.181
	108	1.010	0.195	1.198	1.010	0.195	1.198
	109	1.083	0.163	1.165	1.083	0.163	1.165
	110	1.049	0.328	1.343	1.049	0.328	1.343
	111	1.227	0.351	1.352	1.227	0.351	1.352
	112	1.080	0.510	1.537	1.080	0.510	1.537
	113	1.003	0.278	1.280	1.003	0.278	1.280

Area	Refinery	Kuosmanen weak disposability 2006	Kuosmanen weak disposability 2007	Fare weak disposability 2006	Fare weak disposability 2007
PADD1	1	1	1	1	1
	2	1	1.135	1	1.135
	3	1.419	1.324	1.419	1.324
	4	1.049	1.090	1.049	1.090
	5	1.824	1.748	1.824	1.748
	6	1.221	1.222	1.221	1.222
	7	1.242	1.267	1.242	1.267
	8	1.040	1.101	1.040	1.101
	9	1.156	1.065	1.156	1.065
	10	1	1	1	1
PADD2	11	1.143	1.226	1.143	1.226
	12	1.143	1.233	1.143	1.233
	13	1.351	1.414	1.351	1.414
	14	1.243	1.304	1.243	1.304
	15	1.051	1.138	1.051	1.138
	16	1.296	1.103	1.296	1.103
	17	1.279	1.367	1.279	1.367
	18	1.352	1.186	1.352	1.186
	19	1.205	1.159	1.205	1.159
	20	1.470	1.392	1.470	1.392
	21	1.379	1.398	1.379	1.398
	22	1.484	1.415	1.484	1.415
	23	1.331	1.311	1.331	1.311
	24	1.502	1.572	1.502	1.572
	25	1.396	1.383	1.396	1.383
	26	1.414	1.191	1.414	1.191
	27	1	1	1	1
	28	1.023	1	1.023	1
	29	1	1	1	1
	30	1	1	1	1
	31	1	1	1	1
	32	1	1	1	1
	33	1.098	1.103	1.098	1.103
	34	1.094	1	1.094	1
PADD3	35	1	1	1	1
	36	1.089	1.096	1.089	1.096
	37	1	1	1	1
	38	1	1	1	1
	39	1.059	1.130	1.059	1.130
	40	1	1	1	1
	41	1.061	1.084	1.061	1.084
	42	1.005	1	1.005	1
	43	1.223	1.164	1.223	1.164
	44	1	1.115	1	1.115
	45	1	1	1	1
	46	1.217	1.283	1.217	1.283
	47	1.465	1.514	1.465	1.514
	48	1.114	1.130	1.114	1.130

(*continued*)

Table AIII. Comparison of the hyperbolic efficiency estimate of 113 US oil refineries in 2006 and 2007 obtained from two different weak disposable technologies

Area	Refinery	Kuosmanen weak disposability 2006	Kuosmanen weak disposability 2007	Fare weak disposability 2006	Fare weak disposability 2007
	49	1.524	1.352	1.524	1.352
	50	1.221	1.337	1.221	1.337
	51	1	1.311	1	1.311
	52	1	1.115	1	1.115
	53	1.473	1.077	1.473	1.077
	54	1	1	1	1
	55	1.307	1.350	1.307	1.350
	56	1.091	1.279	1.091	1.279
	57	1.087	1.090	1.087	1.090
	58	1.021	1	1.021	1
	59	1	1	1	1
	60	1.060	1.055	1.060	1.055
	61	1	1	1	1
	62	1	1	1	1
	63	1	1	1	1
	64	1.005	1.046	1.005	1.046
	65	1	1	1	1
	66	1.163	1.110	1.163	1.110
	67	1	1	1	1
	68	1.145	1	1.145	1
	69	1	1	1	1
	70	1	1	1	1
	71	1.480	1.409	1.480	1.409
	72	1.704	1.726	1.704	1.726
	73	1	1	1	1
	74	1.753	1.966	1.753	1.966
	75	1.884	1.939	1.884	1.939
	76	1.009	1	1.009	1
	77	1.128	1	1.128	1
PADD4	78	1	1.023	1	1.023
	79	1.151	1.104	1.151	1.104
	80	1	1	1	1
	81	1.006	1	1.006	1
	82	1	1.001	1	1.001
	83	1.192	1.134	1.192	1.134
	84	1.001	1	1.001	1
	85	1.087	1.175	1.087	1.175
	86	1	1	1	1
	87	1.157	1.067	1.157	1.067
	88	1	1	1	1
	89	1.026	1	1.026	1
	90	1	1	1	1
	91	1.129	1.163	1.129	1.163
	92	1.096	1.062	1.096	1.062
PADD5	93	1.525	1.400	1.525	1.400
	94	1.224	1.224	1.224	1.224
	95	1.172	1.258	1.172	1.258
	96	1.141	1.225	1.141	1.225

Table AIII.

(*continued*)

Area	Refinery	Kuosmanen weak disposability 2006	Kuosmanen weak disposability 2007	Fare weak disposability 2006	Fare weak disposability 2007
	97	1	1	1	1
	98	1	1	1	1
	99	1.026	1	1.026	1
	100	1.015	1.016	1.015	1.016
	101	1.041	1.067	1.041	1.067
	102	1.038	1	1	1
	103	1	1	1	1
	104	1.080	1.096	1.080	1.096
	105	1	1.012	1	1.012
	106	1.095	1.126	1.095	1.126
	107	1.161	1.181	1.161	1.181
	108	1.221	1.198	1.221	1.198
	109	1.110	1.165	1.110	1.165
	110	1.269	1.343	1.269	1.343
	111	1.253	1.352	1.253	1.352
	112	1.465	1.537	1.465	1.537
	113	1.346	1.280	1.346	1.280

Table AIII.

Area	Refinery	Kuosmanen weak disposability Gasoline	Distillate	Toxic release	Fare weak disposability Gasoline	Distillate	Toxic release
PADD1	1	0	0.014	0	0.005	0.012	0.002
	2	0	0.012	0	0	0.012	0
	3	0	0.025	−0.006	0	0.025	−0.006
	4	0	0.017	−0.003	0	0.017	−0.003
	5	0	0.667	0.022	0	0.667	0.022
	6	0	0.019	0.001	0	0.019	0.001
	7	0.001	0.021	0.001	0.001	0.021	0.001
	8	0	0.010	−0.002	0	0.010	−0.002
	9	0	0.048	−0.018	0	0.048	−0.018
	10	0	0.040	−0.002	0	0.040	−0.002
PADD2	11	0.002	0.009	0.001	0.002	0.009	0.001
	12	0	0.012	−0.003	0	0.012	−0.003
	13	0.002	0.014	−0.004	0.002	0.014	−0.004
	14	0.006	0.012	0.002	0.006	0.012	0.002
	15	0	0.008	0.002	0	0.008	0.002
	16	0	0.141	−0.169	0	0.141	−0.169
	17	0	0.009	−0.102	0	0.009	−0.102
	18	0	0.035	0.003	0	0.035	0.003
	19	0	0.022	−0.005	0	0.022	−0.005
	20	0.033	0.014	−0.015	0.033	0.014	−0.015
	21	0.018	0	0	0.018	0	0
	22	0.020	0	0.002	0.020	0	0.002
	23	0.008	0.016	0.002	0.008	0.016	0.002
	24	0	0.051	−0.002	0	0.051	−0.002
	25	0	0.082	0.007	0	0.082	0.007
	26	0	0.107	−0.106	0	0.107	−0.106
	27	0	0.013	−0.445	0	0.013	−0.445
	28	0.019	0	0	0.019	0	0
	29	0.024	0	0	0.023	0	0
	30	0.008	0	−0.026	0.008	0	−0.026
	31	0.028	0	−0.012	0.028	0	−0.012
	32	0.016	0	−1.351	0.016	0	−1.351
	33	0.015	0.015	−0.001	0.015	0.015	−0.001
	34	0.034	0.014	0	0.034	0.014	0
PADD3	35	0.013	0.011	−0.515	0.019	0	−0.555
	36	0.014	0	−0.043	0.014	0	−0.043
	37	0.033	0	−0.001	0.033	0	−0.001
	38	0.011	0.004	0	0.013	0	0.002
	39	0.022	0	0.001	0.022	0	0.001
	40	0.011	0	−0.401	0.006	0.007	−0.409
	41	0.002	0.006	0.001	0.002	0.006	0.001
	42	0.006	0.007	−0.184	0.006	0.007	−0.184
	43	0	0.012	−0.003	0	0.012	−0.003
	44	0	0.006	−0.081	0	0.006	−0.081
	45	0	0.004	−0.013	0	0.004	−0.013
	46	0.008	0	0	0.008	0	0
	47	0.008	0.005	0.001	0.008	0.005	0.001
	48	0	0.010	−0.001	0	0.010	−0.001
	49	0.015	0.051	0.006	0.015	0.051	0.006

(*continued*)

Table AIV.
Shadow prices of desirable and undesirable outputs for 2006 data

Area	Refinery	Kuosmanen weak disposability Gasoline	Distillate	Toxic release	Fare weak disposability Gasoline	Distillate	Toxic release
	50	0	0.012	0	0	0.012	0
	51	0.011	0.078	0.015	0.847	0	0.245
	52	0	0.018	0.005	0	0.013	0.002
	53	0.003	0.016	−0.008	0.003	0.016	−0.008
	54	0.016	0	0	0.015	0	0
	55	0.004	0.035	0	0.004	0.035	0
	56	0	0.013	0	0	0.013	0
	57	0.031	0.014	−0.002	0.031	0.014	−0.002
	58	0.049	0.170	0.019	0.049	0.170	0.019
	59	0.005	0	0	0.005	0	0
	60	0	0.012	−0.002	0	0.012	−0.002
	61	0	0.013	0.001	0	0.011	0
	62	0.003	0	−0.012	0.003	0	−0.012
	63	0.009	0	0	0.008	0	0
	64	0	0.011	0	0	0.011	0
	65	0.013	0	0.002	0.013	0	0.002
	66	0	0.022	−0.006	0	0.022	−0.006
	67	0	0.079	0.008	0	0.093	0.013
	68	0.026	0.013	0	0.026	0.013	0
	69	0.004	0.007	−0.004	0.004	0.007	−0.004
	70	0.002	0.002	−0.050	0.002	0.002	−0.050
	71	0	0.194	−0.204	0	0.194	−0.204
	72	0.004	0.104	−0.018	0.004	0.104	−0.018
	73	0.027	0.406	−2.718	0	0.676	0
	74	0.005	0.180	−0.006	0.005	0.180	−0.006
	75	0.001	0.376	−0.014	0.001	0.376	−0.014
	76	0	0.235	−0.332	0	0.235	−0.332
	77	0.092	0.040	−0.043	0.092	0.040	−0.043
PADD4	78	0	0.026	−1.724	0	0.026	−1.724
	79	0.030	0.015	0	0.030	0.015	0
	80	0.010	0.020	−0.104	0.010	0.020	−0.104
	81	0.021	0.015	−0.001	0.021	0.015	−0.001
	82	0	0.290	−0.346	0	0.290	−0.346
	83	0.056	0.033	−0.001	0.056	0.033	−0.001
	84	0.031	0.016	−0.024	0.031	0.016	−0.024
	85	0.084	0	−0.002	0.084	0	−0.002
	86	0.140	0.052	−0.665	0.140	0.052	−0.665
	87	0.041	0.008	−0.002	0.041	0.008	−0.002
	88	0.032	0.013	−0.001	0.030	0.013	−0.022
	89	0.067	0.031	−0.251	0.067	0.031	−0.251
	90	0.291	0	−5.556	0.291	0	−5.556
	91	0.011	0.030	0.001	0.011	0.030	0.001
	92	0.150	0.065	−0.006	0.150	0.065	−0.006
PADD5	93	0	0.075	0.006	0	0.075	0.006
	94	0	0.053	−0.002	0	0.053	−0.002
	95	0	0.012	−0.003	0	0.012	−0.003
	96	0	0.011	−0.004	0	0.011	−0.004
	97	0	0.009	−0.028	0	0.009	−0.028
	98	0	0.044	−1.061	0	0.041	−1.146

(*continued*)

Table AIV.

Area	Refinery	Kuosmanen weak disposability Gasoline	Distillate	Toxic release	Fare weak disposability Gasoline	Distillate	Toxic release
	99	0	0.035	−0.009	0	0.035	−0.009
	100	0	0.018	−0.059	0	0.018	−0.059
	101	0	0.017	−0.007	0	0.017	−0.007
	102	0	0.064	−1.567	0	0.063	−1.546
	103	0	0.119	−5.541	0	0.107	−6.250
	104	0	0.017	0	0	0.017	0
	105	0	0.015	−0.006	0	0.015	−0.006
	106	0	0.035	0	0	0.035	0
	107	0	0.020	0	0	0.020	0
	108	0	0.047	0.004	0	0.047	0.004
	109	0	0.017	0	0	0.017	0
	110	0	0.035	−0.007	0	0.035	−0.007
	111	0	0.022	−0.001	0	0.022	−0.001
	112	0	0.032	−0.007	0	0.032	−0.007
	113	0	0.116	−0.164	0	0.116	−0.164

Table AIV.

Area	Refinery	Kuosmanen weak disposability			Fare weak disposability		
		Gasoline	Distillate	Toxic release	Gasoline	Distillate	Toxic release
PADD1	1	0	0.015	0.001	0	0.014	0
	2	0	0.012	0	0	0.012	0
	3	0	0.022	−0.020	0	0.022	−0.020
	4	0	0.016	−0.007	0	0.016	−0.007
	5	0.030	0.633	−0.010	0.030	0.633	−0.010
	6	0	0.017	−0.015	0	0.017	−0.015
	7	0	0.018	−0.017	0	0.018	−0.017
	8	0	0.009	−0.008	0	0.009	−0.008
	9	0	0.043	−0.145	0	0.043	−0.145
	10	0	0.038	−0.001	0	0.038	−0.001
PADD2	11	0	0.011	0	0	0.011	0
	12	0	0.011	−0.005	0	0.011	−0.005
	13	0.006	0.009	−0.013	0.006	0.009	−0.013
	14	0.011	0.005	−0.006	0.011	0.005	−0.006
	15	0	0.008	0	0	0.008	0
	16	0.001	0.137	−0.108	0.001	0.137	−0.108
	17	0	0.014	0.001	0	0.014	0.001
	18	0.002	0.028	−0.024	0.002	0.028	−0.024
	19	0.001	0.021	−0.017	0.001	0.021	−0.017
	20	0.029	0.022	0.001	0.029	0.022	0.001
	21	0.016	0.004	0	0.016	0.004	0
	22	0.009	0.013	−0.019	0.009	0.013	−0.019
	23	0.001	0.018	−0.016	0.001	0.018	−0.016
	24	0	0.048	−0.037	0	0.048	−0.037
	25	0	0.083	0.002	0	0.083	0.002
	26	0.009	0.087	−0.395	0.009	0.087	−0.395
	27	0.020	0	−0.017	0.020	0	−0.017
	28	0.018	0	−0.050	0.014	0	−0.155
	29	0.007	0.018	−0.001	0.007	0.020	−0.001
	30	0.008	0	−0.031	0.008	0	−0.031
	31	0.027	0	−0.019	0.027	0	−0.019
	32	0.018	0	−0.928	0.017	0	−1.015
	33	0.024	0.007	0.001	0.024	0.007	0.001
	34	0.060	0	0.004	0.013	0.076	0.009
PADD3	35	0.019	0	−0.858	0.011	0.010	−0.896
	36	0.015	0	−0.017	0.015	0	−0.017
	37	0.036	0.005	0	0.041	0	0
	38	0.014	0	−0.003	0.014	0	−0.003
	39	0.021	0.005	0	0.021	0.005	0
	40	0.021	0	−0.003	0.019	0	−0.026
	41	0	0.008	0.001	0	0.008	0.001
	42	0.001	0.016	−0.100	0.006	0.004	−0.455
	43	0	0.011	−0.004	0	0.011	−0.004
	44	0	0.006	−0.091	0	0.006	−0.091
	45	0	0.004	−0.016	0	0.004	−0.016
	46	0.009	0	0	0.009	0	0
	47	0.011	0.002	0	0.011	0.002	0
	48	0	0.010	−0.003	0	0.010	−0.003
	49	0	0.063	0.002	0	0.063	0.002
	50	0	0.012	0	0	0.012	0
	51	0	0.038	0.001	0	0.038	0.001

(*continued*)

Table AV. Shadow prices of desirable and undesirable outputs for 2007 data

Area	Refinery	Kuosmanen weak disposability Gasoline	Kuosmanen weak disposability Distillate	Kuosmanen weak disposability Toxic release	Fare weak disposability Gasoline	Fare weak disposability Distillate	Fare weak disposability Toxic release
	52	0.001	0.011	0.001	0.001	0.011	0.001
	53	0	0.014	−0.144	0	0.014	−0.144
	54	0.012	0.003	0	0.012	0.003	0
	55	0	0.040	0.001	0	0.040	0.001
	56	0	0.014	0.001	0	0.014	0.001
	57	0.031	0.013	−0.009	0.031	0.013	−0.009
	58	0.067	0	−0.038	0	0.078	−0.002
	59	0.005	0	0	0.005	0	0
	60	0.010	0.001	0	0.010	0.001	0
	61	0.011	0	0	0.010	0	−0.001
	62	0.003	0	−0.016	0.003	0	−0.016
	63	0.009	0	0	0.009	0	0
	64	0	0.011	0	0	0.011	0
	65	0.040	0	0.006	0.011	0	0
	66	0	0.020	−0.018	0	0.020	−0.018
	67	0	0.059	0.002	0.002	0.059	0.002
	68	0.019	0.016	−0.010	0.019	0.016	−0.010
	69	0.010	0	−0.002	0	0.010	−0.004
	70	0	0.004	−0.059	0.004	0	−0.057
	71	0	0.183	−0.393	0	0.183	−0.393
	72	0.004	0.108	−0.037	0.004	0.108	−0.037
	73	0	0.438	−6.294	0	0.628	−1.799
	74	0	0.209	−0.004	0	0.209	−0.004
	75	0	0.396	−0.007	0	0.396	−0.007
	76	0.015	0.182	−1.052	0.036	0.072	−3.333
	77	0.114	0	−0.146	0.114	0	−0.146
PADD4	78	0.022	0.020	−0.173	0.022	0.020	−0.173
	79	0.042	0	0	0.042	0	0
	80	0.010	0.029	−0.001	0.026	0	−0.073
	81	0.031	0.004	0.001	0.031	0.004	0.001
	82	0.018	0.326	0.013	0.018	0.326	0.013
	83	0.081	0	−0.001	0.081	0	−0.001
	84	0.015	0.034	−0.033	0.015	0.034	−0.033
	85	0.094	0	−0.004	0.094	0	−0.004
	86	0.147	0.055	−0.653	0.147	0.055	−0.653
	87	0.049	0	0	0.049	0	0
	88	0.039	0	−0.048	0.039	0	−0.048
	89	0.091	0	−0.332	0.090	0	−0.346
	90	0.301	0	−5.556	0.301	0	−5.556
	91	0.033	0.005	0.001	0.033	0.005	0.001
	92	0.146	0.059	−0.055	0.146	0.059	−0.055
PADD5	93	0	0.066	−0.030	0	0.066	−0.030
	94	0	0.052	−0.023	0	0.052	−0.023
	95	0	0.012	−0.005	0	0.012	−0.005
	96	0	0.012	−0.004	0	0.012	−0.004
	97	0	0.011	−0.003	0	0.010	−0.012
	98	0	0.047	−1.019	0	0.045	−1.088
	99	0	0.031	−0.036	0	0.031	−0.036
	100	0	0.017	−0.100	0	0.017	−0.100
	101	0	0.018	−0.006	0	0.018	−0.006
	102	0.048	0.039	−3.274	0	0.054	−3.422

Table AV. (*continued*)

Area	Refinery	Kuosmanen weak disposability			Fare weak disposability		
		Gasoline	Distillate	Toxic release	Gasoline	Distillate	Toxic release
	103	0.193	0.156	−13.203	0	0.219	−13.845
	104	0	0.018	0	0	0.018	0
	105	0	0.015	−0.005	0	0.015	−0.005
	106	0	0.034	−0.001	0	0.034	−0.001
	107	0	0.021	0	0	0.021	0
	108	0	0.047	−0.043	0	0.047	−0.043
	109	0	0.015	−0.006	0	0.015	−0.006
	110	0	0.033	−0.026	0	0.033	−0.026
	111	0	0.023	0	0	0.023	0
	112	0	0.031	−0.014	0	0.031	−0.014
	113	0	0.123	−0.055	0	0.123	−0.055

Table AV.

Area	Refinery	2006	2007
PADD1	1	–	1.023
	5	1.826	–
	6	1.233	–
	7	1.244	–
PADD2	11	1.149	–
	14	1.249	–
	15	1.070	–
	17	–	1.368
	18	1.360	–
	20	–	1.399
	22	1.486	–
	23	1.332	–
	25	1.442	1.391
	33	–	1.113
	34	–	1.139
PADD3	39	1.067	–
	41	1.097	1.136
	47	1.470	–
	49	1.582	1.366
	51	1.401	1.372
	52	1.109	1.173
	55	–	1.357
	56	–	1.286
	58	1.034	–
	61	1.019	–
	65	1.076	1.048
	67	1.212	1.064
PADD4	81	–	1.005
	82	–	1.004
	91	1.132	1.165
PADD5	93	1.535	–
	108	1.224	–

Table AVI. The upper bound estimates for both allocative and economic efficiency for observations projecting to a portion of the frontier with positive shadow prices for bad outputs

Area	Refinery	2006 With PADD4	2006 No PADD4	2007 With PADD4	2007 No PADD4
PADD1	1	1	1	1	1
	2	1	1	1.135	1.135
	3	1.419	1.419	1.324	1.324
	4	1.049	1.047	1.090	1.088
	5	1.824	1	1.748	1
	6	1.221	1.221	1.222	1.222
	7	1.242	1.242	1.267	1.267
	8	1.040	1.040	1.101	1.101
	9	1.156	1.116	1.065	1.065
	10	1	1	1	1
PADD2	11	1.143	1.143	1.226	1.226
	12	1.143	1.143	1.233	1.233
	13	1.351	1.351	1.414	1.414
	14	1.243	1.243	1.304	1.304
	15	1.051	1.051	1.138	1.138
	16	1.296	1.103	1.103	1.079
	17	1.279	1.279	1.367	1.367
	18	1.352	1.351	1.186	1.186
	19	1.205	1.198	1.159	1.159
	20	1.470	1.458	1.392	1.392
	21	1.379	1.356	1.398	1.380
	22	1.484	1.484	1.415	1.415
	23	1.331	1.331	1.311	1.311
	24	1.502	1.460	1.572	1.571
	25	1.396	1.382	1.383	1.377
	26	1.414	1.343	1.191	1.191
	27	1	1	1	1
	28	1.023	1	1	1
	29	1	1	1	1
	30	1	1	1	1
	31	1	1	1	1
	32	1	1	1	1
	33	1.098	1.090	1.103	1.103
	34	1.094	1.086	1	1
PADD3	35	1	1	1	1
	36	1.089	1.089	1.096	1.096
	37	1	1	1	1
	38	1	1	1	1
	39	1.059	1.029	1.130	1.095
	40	1	1	1	1
	41	1.061	1.061	1.084	1.084
	42	1.005	1.005	1	1
	43	1.223	1.223	1.164	1.164
	44	1	1	1.115	1.115
	45	1	1	1	1
	46	1.217	1.217	1.283	1.283
	47	1.465	1.465	1.514	1.514
	48	1.114	1.114	1.130	1.130
	49	1.524	1.517	1.352	1.349

(*continued*)

Table AVII. Comparison of the hyperbolic efficiency estimate from Kuosmanen weak disposability technology of 113 US oil refineries in 2006 and 2007 with/withoutPADD4 refineries from the analysis

Area	Refinery	2006 With PADD4	2006 No PADD4	2007 With PADD4	2007 No PADD4
	50	1.221	1.221	1.337	1.337
	51	1	1	1.311	1.308
	52	1	1	1.115	1.115
	53	1.473	1.473	1.077	1.077
	54	1	1	1	1
	55	1.307	1.287	1.350	1.334
	56	1.091	1.091	1.279	1.279
	57	1.087	1.087	1.090	1.075
	58	1.021	1	1	1
	59	1	1	1	1
	60	1.060	1.060	1.055	1.055
	61	1	1	1	1
	62	1	1	1	1
	63	1	1	1	1
	64	1.005	1.005	1.046	1.046
	65	1	1	1	1
	66	1.163	1.160	1.110	1.110
	67	1	1	1	1
	68	1.145	1.144	1	1
	69	1	1	1	1
	70	1	1	1	1
	71	1.480	1.383	1.409	1.301
	72	1.704	1.702	1.726	1.726
	73	1	1	1	1
	74	1.753	1.753	1.966	1.966
	75	1.884	1.884	1.939	1.939
	76	1.009	1	1	1
	77	1.128	1	1	1
PADD4	78	1	–	1.023	–
	79	1.151	–	1.104	–
	80	1	–	1	–
	81	1.006	–	1	–
	82	1	–	1.001	–
	83	1.192	–	1.134	–
	84	1.001	–	1	–
	85	1.087	–	1.175	–
	86	1	–	1	–
	87	1.157	–	1.067	–
	88	1	–	1	–
	89	1.026	–	1	–
	90	1	–	1	–
	91	1.129	–	1.163	–
	92	1.096	–	1.062	–
PADD5	93	1.525	1.520	1.400	1.400
	94	1.224	1.207	1.224	1.218
	95	1.172	1.172	1.258	1.257
	96	1.141	1.140	1.225	1.225
	97	1	1	1	1
	98	1	1	1	1

(*continued*)

Table AVII.

Area	Refinery	2006 With PADD4	2006 No PADD4	2007 With PADD4	2007 No PADD4
	99	1.026	1.017	1	1
	100	1.015	1.015	1.016	1.016
	101	1.041	1.039	1.067	1.067
	102	1.038	1	1	1
	103	1	1	1	1
	104	1.080	1.080	1.096	1.096
	105	1	1	1.012	1.012
	106	1.095	1.095	1.126	1.126
	107	1.161	1.161	1.181	1.181
	108	1.221	1.221	1.198	1.198
	109	1.110	1.110	1.165	1.165
	110	1.269	1.249	1.343	1.339
	111	1.253	1.253	1.352	1.352
	112	1.465	1.454	1.537	1.532
	113	1.346	1.324	1.280	1.280

Table AVII.

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