THREE ESSAYS ON TECHNICAL INEFFICIENCY, PRODUCTIVITY CHANGE, PRICE EFFICIENCY, AND COLLUSIVE PRICING

by

CHON VAN LE

(Under the direction of Scott E. Atkinson)

ABSTRACT

My dissertation consists of three empirical studies on technical inefficiency, productivity change, price efficiency, and collusive pricing. In the first essay, I measure technical and allocative efficiency of Vietnam's fisheries processing firms, which are a key factor underlying the impressive achievements of the fisheries sector over the last two decades. I estimate a shadow cost system using a Bayesian Markov Chain Monte Carlo procedure. I find that firms have not fully exploited economies of scale. They are likely to over-utilize labor relative to capital. Small firms tend to have higher allocative efficiency than larger ones. Interestingly, based on this measure, while in other regions state-owned enterprises do worse than private enterprises, the pattern seems to be reversed in the Mekong delta. In addition, large fluctuations in efficiency change and productivity change across several firms may indicate the vulnerability of weaker firms to competition from international trade.

In the second essay, I estimate a multiple-input, multiple-output directional distance function for 78 electric utilities spanning from 1988 to 2005. During this period, the U.S. electric power industry underwent remarkable changes in environmental regulations and a wave of restructuring. I find that restructuring in electricity markets tends to improve technical efficiency of deregulated utilities. Deregulated utilities that have NO_X control equipment below average are likely to invest less on these devices, but utilities with above average NO_X control equipment do the opposite. The reverse applies to particulate removal devices. However, the whole sample spends more on these two as well as SO_2 control systems and reduce their electricity sales slightly. In addition, increased capital investments in SO_2 and NO_X control equipment do not reduce SO_2 and NO_X emissions, respectively. But expansions of particulate control systems cut down SO_2 emissions greatly. Moreover, the utilities have been shifted increasingly farther from the frontier over time. Inward shifting of the production frontier, as well as declining technical efficiency and productivity growth, probably results from the implementation of stricter environmental regulations.

In the last essay, I investigate the extent of collusive pricing in the U.S. tobacco industry. In November 1998, the four largest tobacco companies and the attorneys general of more than 40 states reached the Master Settlement Agreement under which the companies would pay $206 billion to the states for recovery of their smoking-related health care costs. However, the allocation of annual payments among the tobacco companies based on their relative market shares and stringent marketing restrictions raised concern over the possibility that the industry would become more collusive. Using the nonparametric tests developed by Ashenfelter and Sullivan (1987), I find strong evidence supporting this argument. Specifically, when the real tax rates increased, the tobacco companies raised their prices after 1998 much more frequently than before the adoption of the settlement. Strikingly, even when the nominal tax rates remained constant, they pushed up prices faster than the consumer price index for majority of the time.

Index words: Technical Inefficiency, Productivity Change, Price Efficiency, Collusive Pricing

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by

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Chapter 1

Production Inefficiency of Vietnam's Fisheries Processing Firms

1.1 Introduction

Since the early 1990s, the fisheries[1] sector has been one of the most dynamic and fastest growing sectors in Vietnam. In 1990-2007, total production increased 4.6 times from 941 thousand tons to over 4.3 million tons. Although the sector contributes roughly 4 percent of GDP, its value added in fish processing, distribution, and marketing is significant. The sector has quickly surpassed other traditional Vietnamese agricultural products such as rice and rubber in terms of export values. Its foreign exchange earnings are now the third largest, after the crude oil and garment industries. According to Vietnam's Ministry of Fisheries (MOFI, 2005), the sector supplies about 40 percent of animal protein in the national human diet and has generated approximately four million jobs.

The rapid expansion of the fisheries sector over the past few decades, however, has led to a high risk of environmental pollution and overfishing, causing hardship for many coastal and

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[1] In this chapter, fisheries include capture/fishing and aquaculture.

downriver communities. In addition, stringent requirements of export markets have raised growing concerns about traceability and quality control of inputs, processing, and relevant services. These issues, among others, will probably hinder the sector's long-term sustainable development.

Despite the important role of the fisheries sector in the Vietnamese economy, there are few studies on this sector. Pomeroy et al. (2008) critically review changes in government policy towards small-scaled fisheries in Vietnam, of which the subsidized-interest scheme to expand the off-shore fleet, according to Nguyen and Symington (2008), is claimed to have contributed to greater fishing of in-shore waters and a greater reduction of in-shore resources. Lem et al. (2004) evaluate measures to improve domestic marketing arrangements to satisfy the increasing local consumption of fish stimulated by strong economic growth. Following the anti-dumping case brought against the Vietnamese catfish industry by the Catfish Farmers of America (CFA), Nguyen (2003) examines intensively the low production cost of catfish in the Mekong delta. But there are no studies so far on the production efficiency of fisheries processing firms in Vietnam.

This chapter investigates whether these firms have attained allocative and technical efficiency. To that end, a shadow cost system is estimated with the data from the 2003 and 2005 Enterprise Censuses surveyed by Vietnam's General Statistics Office (GSO). Since the data are limited, I employ a Bayesian Markov Chain Monte Carlo (MCMC) parametric approach developed by Atkinson and Dorfman (2005). I find that firms have not fully exploited economies of scale. Nearly all of the firms over-utilize labor relative to capital, but those located in the Mekong delta generally perform better than those located in other regions. Small firms, having less than 300 employees, tend to have higher allocative efficiency than larger ones. Interestingly, while in other regions state-owned enterprises (SOEs) do worse than private enterprises in this measure, the pattern seems to be reversed in the Mekong delta. In addition, large fluctuations in efficiency change and productivity change across several firms may indicate the vulnerability of weaker firms to competition from international trade.

The chapter is structured as follows. In section 1.2, I give a brief overview of Vietnam's fisheries sector's performance in recent years. Section 1.3 reviews the shadow cost system. In section 1.4, I present the econometric model. Section 1.5 discusses the empirical results. Conclusions follow in section 1.6.

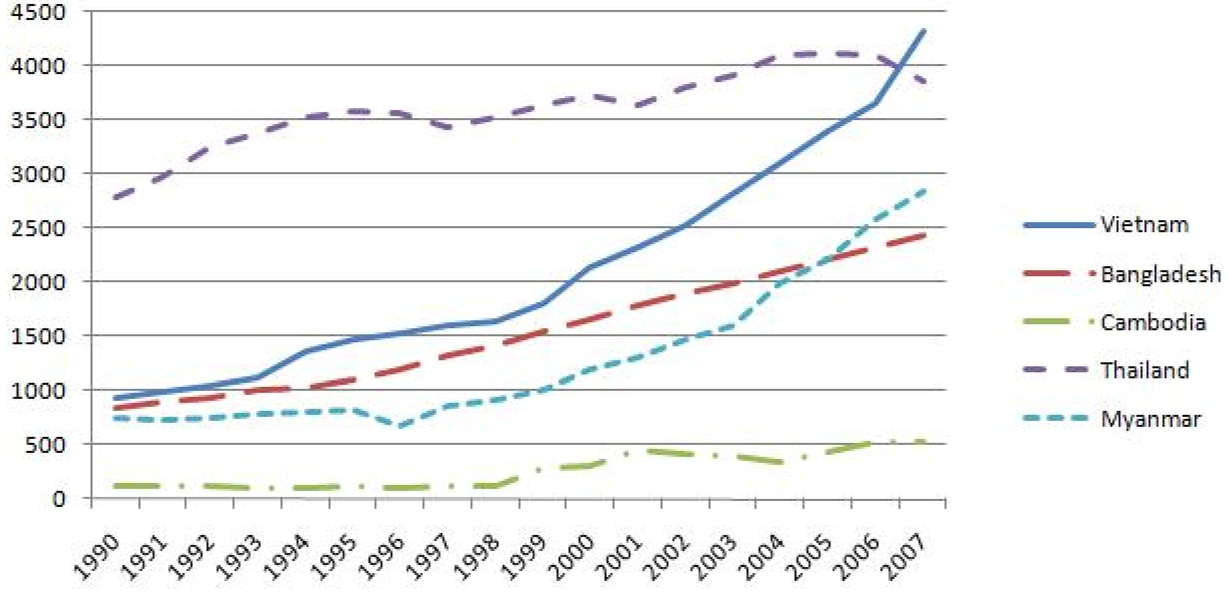
1.2 Vietnam's Fisheries Sector

Fishing and aquaculture are ancient traditions in Vietnam. But it was not until the late 1980s, when the comprehensive economic reform was introduced, that the fisheries sector started growing remarkably. Vietnam has outperformed other neighboring countries in terms of production. Its annual growth rate from 1990 to 2007 is on average 9.37 percent, higher than that of Bangladesh, Thailand, and Myanmar. (The exception is Cambodia, which had a rather low base). Figure 1.1 shows that, while in 1990 Vietnam, Bangladesh, and Myanmar had approximately the same output levels, in 2007 Vietnam left Bangladesh and Myanmar far behind and even overtook Thailand, whose aquatic production was three times greater than that of Vietnam in 1990.

Export earnings from shrimp, fish and other seafood products increased by 7.26 times between 1995 and 2008, reaching \$4.5 billion and making this sector the third most prominent after the crude oil and the garment industries. In the same period, the export volume of rice, which once symbolized Vietnam's success in its early stages of reform, rose by only 2.4 times. Aquatic products are now exported to over 100 countries and territories. The major markets are the U.S., Japan, China, Korea, Taiwan, and the EU.

The outstanding performance of the fisheries sector is attributed to the abundance of aquatic resources. Vietnam has a coastline of about 3,600 km, with many bays and estuaries,

Figure 1.1: Aquatic Production (thousand tons) of Vietnam, Bangladesh, Cambodia, Thailand and Myanmar in 1990-2007



Source: FAO's Fisheries and Aquaculture Department mangrove forests[2] of more than 1,500 km^2, and an exclusive economic zone[3] of over one million km^2 (MOFI, 2005). In addition, the inland area is netted with a dense river network, including 2,360 rivers of more than 10 km in length. It is estimated that the total water surface potentially available for freshwater capture or aquaculture is 17,000 km^2. The great diversity of resources generates considerable opportunities for the development of not only the fisheries sector, but other industries such as tourism and transportation.

Since the majority of fishing vessels are equipped with engines of less than 90 horsepower (hp), capture activities are mostly small-scaled and concentrated in coastal waters. The increase in human population has resulted in heavy pressure on in-shore resources. According to MOFI (2005), catch per unit of effort decreased from 0.7 tons/hp/year in 1993 to 0.4 tons/hp/year in 2003, implying a rapid decline in productivity. In response, the government has strongly promoted off-shore capture since 1997 through a subsidized-interest scheme that has financed construction of 1,300 off-shore vessels[4]. However, due to the lack of off-shore technology, the inexperience by skippers and crew, meager supporting services, and inappropriate specifications of vessels, the subsidized vessels have suffered a high failure rate. In 2003, roughly 90% of them could not meet their repayment schedules, although the interest rate was reduced from 7% to 5.4% (MOFI and World Bank, 2005). Moreover, some of these large vessels fish in-shore, causing faster depletion of coastal resources. As a result, the capture-production in Vietnam increased by only 2.7 times in 1990-2007 (see Figure 1.2).

The driving force underlying the impressive achievements of the fisheries sector is aquaculture. Its output has grown on average at 16.6% annually since 1990, from 162,076 tons to 2,194,500 tons, contributing more than 50% by weight to total fishery production (FAO). Dramatic expansion over the last two decades is the result of a sharp increase in aquaculture

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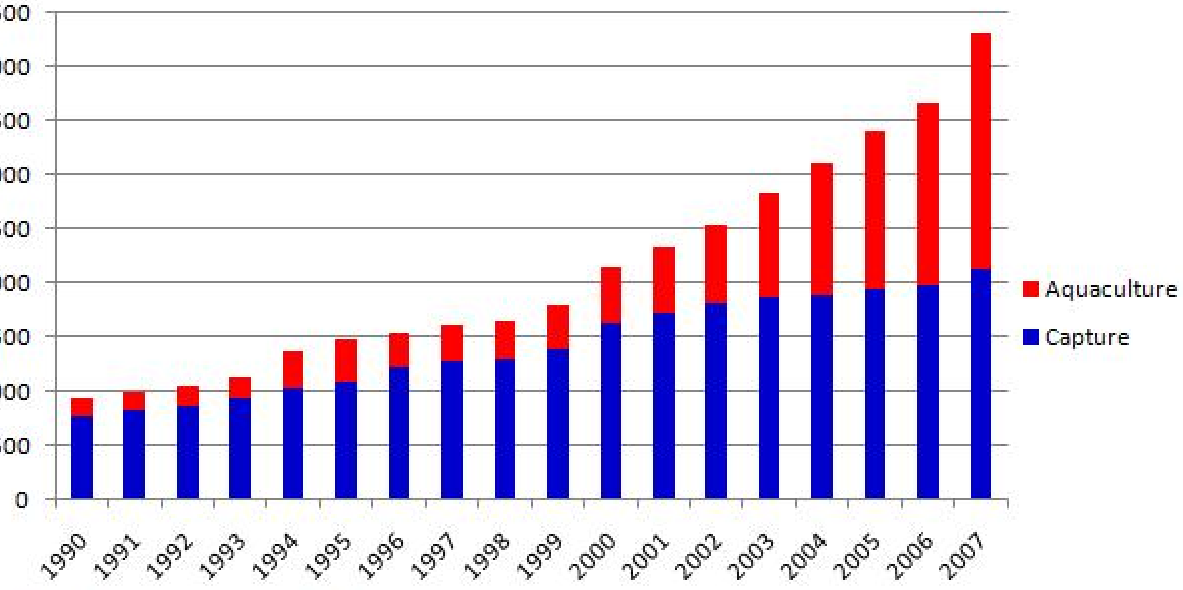
[2] Mangroves are crucial to the sustainability of Vietnam's fisheries since they provide habitat for coastal and marine fish and crustacea.

[3] An exclusive economic zone is the sea zone within which a coastal state has sovereign rights for exploration and exploitation of marine resources. This area extends seaward 200 nautical miles from the coast.

[4] Vessels are classified as off-shore if their engines are over 90 hp.

Figure 1.2: Vietnam's Capture and Aquaculture Production (thousand tons) in 1990-2007



Source: FAO's Fisheries and Aquaculture Department exports. Aquaculture farmers have adapted shrimp and catfish species suitable for export. Cultural practices have been diversified, including mono- and poly-aquaculture in fresh, brackish, and marine waters as well as integrated aquaculture with paddy rice production.

The total aquaculture area has enlarged significantly to 1,019 thousand hectares (ha)[5] by 2007, averaging 7% annual growth since 1995. Figures 1.3 and 1.4 indicate that aquaculture is expanding in all regions, but the Mekong delta dominates in terms of both area and production, representing 71% and 72%, respectively, of Vietnamese totals. With capture taken into account, the Mekong delta is the largest contributor, with two-thirds of Vietnam's fisheries production (GSO, 2009).

Another key factor that has helped boost the fisheries sector is the development of processing firms. This sub-sector has expanded rapidly, particularly with the construction of large modern facilities. In 2003, Vietnam had about 400 registered processing plants with approximately 0.8 million tons of input capacity (Ruckes and Nguyen, 2004). Around half of them were located in the Mekong delta. Seventy four percent of processors had Hazard Analysis at Critical Control Points (HACCP) certification and 100 enterprises were certified for the EU market. By 2006, the number of plants having EU certification increased to 209. In addition, 300 plants were eligible to export their products to the U.S. (Ta, 2006). According to the MOFI and World Bank (2005), processors employ an average of nearly 300 people, of whom 80-85% are female. These jobs are valuable to poor communities (e.g., the Khmer community in Soc Trang province). Often workers are exposed to several potential long-term health risks, although improvements are being made.

Apart from these companies, there are many thousands of small enterprises processing fish products for domestic markets, with a total input capacity of roughly 330,000 tons/year (MOFI, 2004). Their outputs include dried products, fishmeal, fish sauce, as well as frozen and chilled products. Dried products such as dried fish, shrimp, squid, and seaweed are

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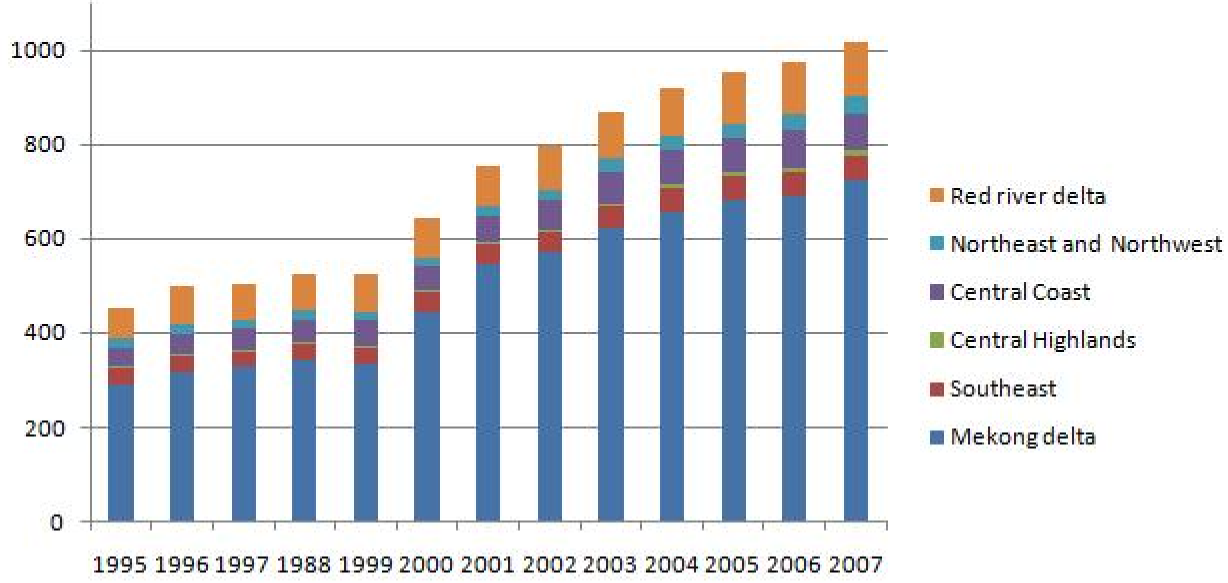
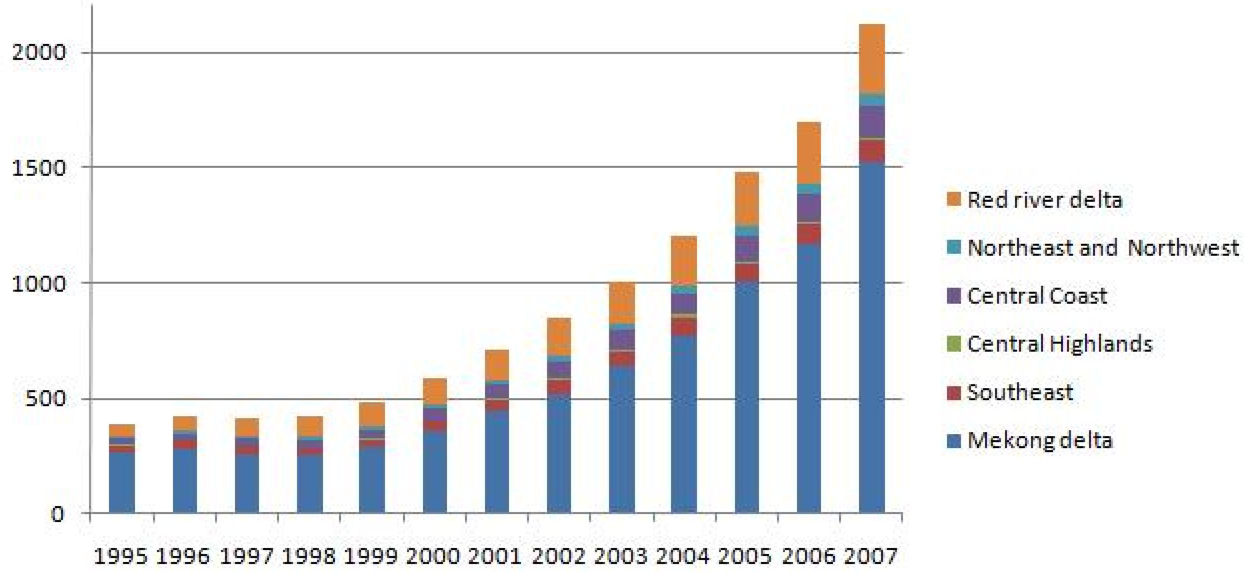
[5] A hectare is equal to 10,000 m^2, and equivalent to 2.471 acres.

Figure 1.3: Aquaculture Area (thousand hectares) by Region in 1995-2007



Source: GSO (2009)

Figure 1.4: Aquaculture Production (thousand tons) by Region in 1995-2007



Source: GSO (2009)

popular with small businesses since the production method is simple and does not require complicated facilities and technology.

Capture and aquaculture generally provide a wide diversity of livelihood activities and have helped to reduce poverty among rural households. However, there are many concerns over sustainable development. Although Vietnam has upgraded its internal sanitary legislation in line with international standards, food safety is still a big challenge. In major export markets such as the U.S., the EU, and Japan, there is an increasing trend towards traceability and application of HACCP at the farm level in order to lower risks of contamination. This demands knowledge, skills, and investment in infrastructure that poorer households are likely to find very difficult to meet, since they usually do not have business connections or property that can be used as collateral to allow them easier access to formal credit. In addition, there are insufficient fishery supporting services, such as high quality seed, feed and fingerlings supply, disease control, environmental management, wide-spread extension of better fishing and farming practices, quality control systems, and market information.

1.3 Shadow Cost System

In this chapter, I use a shadow cost system based on duality theory in which systems of input demand equations can be derived by simple differentiation and estimated with flexible functional forms. Firms are assumed to choose input quantities to minimize the total shadow costs of the chosen levels of output.

The theory below follows Atkinson and Primont (2002). Let $\mathbf{x} = (x_1, ..., x_N)' \in R_+^N$ denote an $(N \times 1)$ vector of N nonnegative inputs and let $\mathbf{y} = (y_1, ..., y_M)' \in R_+^M$ denote an $(M \times 1)$ vector of M nonnegative outputs. The input requirement set is given by

$$L(\mathbf{y}) = \{\mathbf{x} : \mathbf{x}\,\text{can produce}\,\mathbf{y}\}. \tag{1.1}$$

Under the assumption of shadow cost minimization, the shadow cost function is

$$C(\mathbf{y}, \mathbf{p}^*) = \min_{\mathbf{x}}\{\mathbf{p}^*\mathbf{x} : \mathbf{x} \in L(\mathbf{y})\}, \tag{1.2}$$

where $\mathbf{p}^* = (p_1^*, ..., p_N^*) = (k_1p_1, ..., k_Np_N) \in R_+^N$ is a $(1 \times N)$ vector of N shadow input prices. $\mathbf{p}^*$ is the price that makes the optimal input vector, $\mathbf{h}(\mathbf{y}, \mathbf{p}^*)$, equal to the actual input vector, $\mathbf{x}$. The k_n parameters, $n = 1, ..., N$, measure the divergence of actual prices from shadow prices.

Applying Shephard's lemma, I obtain

$$\frac{\partial C(\mathbf{y}, \mathbf{p}^*)}{\partial p_n} = h_n(\mathbf{y}, \mathbf{p}^*), \qquad n = 1, ..., N, \tag{1.3}$$

where $\frac{\partial C(\mathbf{y}, \mathbf{p}^*)}{\partial p_n}$ is the partial derivative of $C(\mathbf{y}, \mathbf{p})$ with respect to p_n, evaluated at $\mathbf{p}^*$.

Let S_n denote the shadow cost share of input n

$$S_n \equiv \frac{p_n^* x_n}{C(\mathbf{y}, \mathbf{p}^*)}, \qquad n = 1, ..., N. \tag{1.4}$$

Rearranging (1.4), I have

$$x_n = S_n C(\mathbf{y}, \mathbf{p}^*)(p_n^*)^{-1}, \qquad n = 1, ..., N. \tag{1.5}$$

The firm's total actual cost is

$$C^A = \sum_{n=1}^{N} p_n x_n. \tag{1.6}$$

Substituting (1.5) into (1.6), the total actual cost function becomes

$$C^A = C(\mathbf{y}, \mathbf{p}^*) \sum_{n=1}^{N} (k_n)^{-1} S_n. \tag{1.7}$$

Taking logarithms, I get

$$\ln C^A = \ln C(\mathbf{y}, \mathbf{p}^*) + \ln \left[\sum_{n=1}^{N} (k_n)^{-1} S_n \right]. \tag{1.8}$$

Given a flexible functional form approximation to the unobserved shadow cost function $C(\mathbf{y}, \mathbf{p}^*)$, I can estimate allocative and technical inefficiency by joint estimation of equation (1.8) and the N - 1 actual cost share equations (which are derived later) with error terms appended to each equation. Let us now move to econometric estimation of this stochastic shadow cost system.

1.4 Econometric Estimation

a. A Stochastic Translog Shadow Cost System

Again, following Atkinson and Primont (2002), I use the translog cost function to approximate the unobserved shadow cost function. Let f denote an individual firm, $f = 1, ..., F$, and t a time trend, $t = 1, ..., T$. The stochastic translog shadow cost function is

$$\begin{aligned} \ln [C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) h(\epsilon_{ft})] &= \ln C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) + \ln h(\epsilon_{ft}) \\ &= \gamma_{0f} d_f + \sum_m \gamma_m \ln y_{mft} + \frac{1}{2} \sum_m \sum_w \gamma_{mw} \ln y_{mft} \ln y_{wft} \\ &\quad + \sum_m \sum_n \gamma_{mn} \ln y_{mft} \ln p^*_{nft} + \sum_n \gamma_n \ln p^*_{nft} \\ &\quad + \frac{1}{2} \sum_n \sum_l \gamma_{nl} \ln p^*_{nft} \ln p^*_{lft} + \sum_m \gamma_{mt} \ln y_{mft} t \\ &\quad + \gamma_{t1} t + \ln h(\epsilon_{ft}), \end{aligned} \tag{1.9}$$

where d_f is a dummy variable for firm f and

$$h(\epsilon_{ft}) = \exp(v_{ft} + u_{ft}). \tag{1.10}$$

The composite error $\ln h(\epsilon_{ft})$ is an additive error with a one-sided component, $u_{ft} \geq 0$, and a statistical noise, v_{ft}, assumed to be iid with zero mean.

The fixed effects approach is used here to relax strong distributional assumptions on both v_{ft} and u_{ft}, and the unlikely assumption of no correlation between u_{ft} and the explanatory variables that are required in the random effects approach. The γ_{0f}'s, $f = 1, ..., F$, represent time-invariant, firm-specific differences in technology. In addition, I include continuous time interacted with the logs of output quantities and a first-order term in time to account for the effect of time.

Logarithmic differentiation of the equation (1.9) yields parametric expressions for the shadow cost shares (1.4),

$$\begin{aligned} \frac{\partial \ln C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t)}{\partial \ln p^*_{nft}} &= \frac{\partial C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t)}{\partial p^*_{nft}} \frac{p^*_{nft}}{C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t)} = \frac{x_{nft} p^*_{nft}}{C(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t)} = S_{nft} \\ &= \gamma_n + \sum_l \gamma_{nl} \ln p^*_{lft} + \sum_m \gamma_{mn} \ln y_{mft}. \end{aligned} \tag{1.11}$$

Substituting the stochastic translog shadow cost function and the shadow cost shares into (1.8), I obtain the stochastic actual cost function

$$\begin{aligned} \ln C^A_{ft} = {} & \gamma_{0f} d_f + \sum_m \gamma_m \ln y_{mft} + \frac{1}{2} \sum_m \sum_w \gamma_{mw} \ln y_{mft} \ln y_{wft} \\ & + \sum_m \sum_n \gamma_{mn} \ln y_{mft} \ln p^*_{nft} + \sum_n \gamma_n \ln p^*_{nft} \\ & + \frac{1}{2} \sum_n \sum_l \gamma_{nl} \ln p^*_{nft} \ln p^*_{lft} + \sum_m \gamma_{mt} \ln y_{mft} t + \gamma_{t1} t \\ & + \ln \left[\sum_{n=1}^{N} (k_{nft})^{-1} \left(\gamma_n + \sum_l \gamma_{nl} \ln p^*_{lft} + \sum_m \gamma_{mn} \ln y_{mft} \right) \right] \\ & + v_{ft} + u_{ft}. \end{aligned} \tag{1.12}$$

The actual cost share of input n is

$$S_{nft}^{A} = \frac{p_{nft}x_{nft}}{C_{ft}^{A}}. \tag{1.13}$$

Substituting (1.5) and (1.7) into (1.13) yields

$$S_{nft}^{A} = \frac{(k_{nft})^{-1}S_{nft}}{\sum_{n=1}^{N}(k_{nft})^{-1}S_{nft}}. \tag{1.14}$$

Substituting for S_{nft} from equation (1.11), I obtain

$$S_{nft}^{A} = \frac{(k_{nft})^{-1}(\gamma_n + \sum_l \gamma_{nl}\ln p_{lft}^{*} + \sum_m \gamma_{mn}\ln y_{mft})}{\sum_{n=1}^{N}(k_{nft})^{-1}(\gamma_n + \sum_l \gamma_{nl}\ln p_{lft}^{*} + \sum_m \gamma_{mn}\ln y_{mft})}. \tag{1.15}$$

I need to impose some restrictions before estimating the model. Symmetry requires that

$$\begin{aligned} \gamma_{mw} &= \gamma_{wm}, \quad \forall m, w, m \neq w, \\ \gamma_{nl} &= \gamma_{ln}, \quad \forall n, l, n \neq l. \end{aligned} \tag{1.16}$$

Since $C(\mathbf{y}, \mathbf{p}^{*}, t)$ is homogeneous of degree one in $\mathbf{p}^{*}$, the parameters in (1.9) have the following relationships:

$$\begin{aligned} \sum_n \gamma_n &= 1, \\ \sum_n \gamma_{nl} &= \sum_l \gamma_{nl} = \sum_n \sum_l \gamma_{nl} = 0, \\ \sum_n \gamma_{mn} &= 0, \quad \forall m. \end{aligned} \tag{1.17}$$

The set of equations to be estimated is the actual cost function (1.12) and the N - 1 actual cost share equations (1.15), since one share equation must be dropped due to the linear dependence of the error terms. I cannot estimate the absolute values of the k_{nft}'s because the actual cost equation and the actual cost share equations are homogenous of degree zero in the k_{nft}'s. Therefore, for one input n, I must restrict a k_{nft} to some constant $\forall t$. Here, I restrict k_{nft} for input N[6]. For the remaining inputs, I specify

$$k_{nft} = \exp(\kappa_{nf} + \kappa_n t), \quad n = 1, ..., N - 1, \tag{1.18}$$

which allows for firm-specific, time-invariant parameters κ_{nf} and industry-wide time-varying parameters κ_n that are shared across firms.

Due to limited data (which will be discussed in the next section), I am not able to include the second-order terms in time in (1.18) and (1.12). Moreover, I employ the Bayesian Markov Chain Monte Carlo approach developed by Atkinson and Dorfman (2009) to obtain posterior densities for estimates of allocative inefficiency. I treat the covariance of the errors and the unknown parameters of the shadow cost system as random variables. The parameters are assumed to have a multivariate normal distribution.

In each draw, I first obtain the covariance matrix of the model's stochastic errors (Ω) in the form of the standard inverted Wishart conditional on parameter starting values. Then, I get posterior estimates of three groups of parameters (the firm dummies, the k_{nft}'s, and the other parameters) separately. In each step, I (i) estimate the shadow cost system, holding previously estimated parameters constant, (ii) combine estimated parameters with priors (zero mean, covariance matrix H_0[7]) to obtain posterior means and variances using Bayes' theorem, (iii) draw from a multivariate normal distribution with these posterior means and variances, (iv) impose monotonicity for at least 85% of all observations[8], and (v) proceed to next step conditional on all previous draws. After three steps are done to gain posterior estimates of the three groups of parameters, I regress the shadow cost system, holding Ω

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[6] The choice of the numeraire input does not affect the results.

[7] H_0 is a diagonal matrix with diagonal elements set to 100 for the firm dummies, 0.01 for the allocative parameters, and 100 for the other parameters.

[8] The costs are monotonically increasing in input prices and outputs.

constant, to get new estimates of the error terms for the next draw. A total of 28,000 Gibbs draws are generated from two separate models. Each model contains 14,000 draws of which the first 4,000 are discarded to remove dependence on initial starting values.

b. Measuring Economies of Scale

According to Hanoch (1975), scale economies should be measured by the relationship between total cost and output along the expansion path. Scale economies (SE) equal one minus the elasticity of total cost with respect to output

$$\begin{aligned} SE_{ft} &= 1 - \frac{\partial \ln C^{A}_{ft}}{\partial \ln y_{mft}} \\ &= 1 - \gamma_m - \sum_{w} \gamma_{mw} \ln y_{wft} - \sum_{n} \gamma_{mn} \ln p^{*}_{nft} - \gamma_{mt} t \\ &\quad - \frac{\sum_{n=1}^{N} (k_{nft})^{-1} \gamma_{mn}}{\sum_{n=1}^{N} (k_{nft})^{-1} \left(\gamma_n + \sum_{l} \gamma_{nl} \ln p^{*}_{lft} + \sum_{m} \gamma_{mn} \ln y_{mft} \right)}. \end{aligned} \tag{1.19}$$

Positive scale economies receive positive numbers and scale diseconomies negative numbers.

c. Measuring Allocative Inefficiency

The N - 1 relative values of k_{nft} estimated above indicate relative price inefficiencies. Relative price efficiency is achieved at time t if marginal rates of technical substitution equal the corresponding ratios of market input prices or $k_{nft} = 1$, $n = 1, ..., N - 1$. I then compute ratios of fitted demands using the estimated values of k_{nft} to efficient demands with k_{nft} set equal to 1, $n = 1, ..., N - 1$. These ratios imply relative inefficiencies for input usage.

d. Measuring Technical Inefficiency and Productivity Change

To compute technical efficiency (TE), efficiency change (EC), technical change (TC), and productivity change (PC), I follow Atkinson, Cornwell, and Honerkamp (2003). For a given level of outputs, the technically efficient firm is the one that employs the fewest inputs. I measure EC as the rate of catching up to the frontier from period to period and TC as the movement outward of the frontier over time. Then PC is the sum of EC and TC.

I first calculate the residuals from (1.12) as $\hat{v}_{ft} + \hat{u}_{ft}$. Since u_{ft} needs to be non-negative, I transform $\hat{u}_{ft}$ by subtracting $\hat{u}_t = min_f(\hat{u}_{ft})$, which is the estimated frontier intercept and obtain $\hat{u}^F_{ft} = \hat{u}_{ft} - \hat{u}_t \geq 0$. Adding and subtracting $\hat{u}_t$ from the estimated (1.9) yields

$$\begin{aligned}
\ln[\hat{C}(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t)h(\hat{\epsilon}_{ft})] &= \ln\hat{C}(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) + \hat{v}_{ft} + \hat{u}_{ft} + \hat{u}_t - \hat{u}_t \\
&= \ln\hat{C}(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) + \hat{u}_t + \hat{v}_{ft} + \hat{u}^F_{ft} \\
&= \ln\hat{C}^F(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) + \hat{v}_{ft} + \hat{u}^F_{ft}, \qquad (1.20)
\end{aligned}$$

where $\ln\hat{C}^F(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) = \ln\hat{C}(\mathbf{y}_{ft}, \mathbf{p^*}_{ft}, t) + \hat{u}_t$ is the fitted frontier shadow cost function. Firm f's level of TE in period t is defined as

$$TE_{ft} = \exp(-\hat{u}^F_{ft}). \qquad (1.21)$$

TE should lie between 0 and 1 due to the normalization of $\hat{u}^F_{ft}$. EC_{ft} is the change in TE_{ft} from t to $t+1$

$$EC_{ft} = TE_{f,t+1} - TE_{f,t}. \qquad (1.22)$$

TC_{ft} is estimated as the difference between $\ln\hat{C}^F(\mathbf{y}, \mathbf{p}^*, t+1)$ and $\ln\hat{C}^F(\mathbf{y}, \mathbf{p}^*, t)$, holding input and output quantities constant,

$$\begin{aligned}
TC_{ft} &= \ln\hat{C}(\mathbf{y}, \mathbf{p}^*, t+1) + \hat{u}_{t+1} - \ln\hat{C}(\mathbf{y}, \mathbf{p}^*, t) - \hat{u}_t \\
&= \sum_m \hat{\gamma}_{mt} \ln y_{mft} + \hat{\gamma}_{t1} + \hat{u}_{t+1} - \hat{u}_t. \qquad (1.23)
\end{aligned}$$

Given EC_{ft} and TC_{ft}, I obtain PC_{ft}:

$$PC_{ft} = TC_{ft} + EC_{ft}. \qquad (1.24)$$

1.5 Data and Empirical Results

The data used in this chapter are from the Enterprise Censuses surveyed by Vietnam's General Statistics Office. These surveys have been conducted annually since 2000. They are designed to collect systematically information on quantities of factors of production and the performance of firms that came into operation by January 1^{st} of that year and were still in business. The survey data can be used to evaluate competitiveness in all industries and sectors of the Vietnamese economy.

Those enterprises under survey are either state-owned, 'equitized'[9], domestically private, joint ventures, or 100% foreign-owned and are doing business in farming, aquaculture, mining, processing, electricity, gas and water, construction, trading, manufacturing, hospitality, transportation, finance, health, education, among others. The questionnaires cover revenue, taxes, number of employees and their income, assets, liabilities and equity, investments, on-the-job training, and input costs including fuel, raw materials, services and utilities, etc. The GSO follows a stratified random cluster sampling procedure so that the sample's results are statistically representative of industries and sectors at the national and regional levels.

A cost section is included in questionnaires only in odd-numbered years. Data with costs information included are available for 2001, 2003, and 2005[10]. But a very large percentage of firms did not fully report their costs, especially for 2001 and 2003. Those firms whose data are missing are more likely to be smaller and private. Therefore, inferences should be made with caution. The data situation is better for 2005, though far from perfect. For this year, there are 685 enterprises in the fisheries processing sector, but only 223 firms report revenue and cost data. I have to drop 41 firms, among which 1 firm has negative revenue, 13 have negative equities, 1 has negative liabilities, 2 have zero total costs, 8 have non-positive

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[9] SOEs in Vietnam have undergone a reform in which their equity shares continue to be kept by the State or are sold fully or partly to the private sector. 'Equitized' firms are those owned partly by the State and partly by the private sector.

[10] The survey questionnaire in 2007 does not include a cost section as expected.

capital, 10 have negative values added, 3 have extraordinarily high wages, 2 have negative corporate tax rates, and 1 has an interest rate greater than 100%. That leaves 182 firms. Merging them with the 102 firms from 2003 produces a balanced panel with only 47 firms. I employ this panel that has 94 observations.

In this study, the fisheries processing firms' output or value added is a function of two inputs: capital (K) and labor (L). The price of labor, p_l, is the wage rate, defined as the sum of salaries, wages and other benefits, divided by the average number of employees. The price of capital, p_k, is calculated by the Christensen-Jorgenson (1969) rental price index defined as

$$p_k = (r + \delta)\frac{1 - bds}{1 - bs}, \tag{1.25}$$

where

$r =$ interest rate,

$\delta =$ rate of depreciation,

$b =$ corporate income tax rate,

$d =$ present value of depreciation allowances, and

$s =$ ratio of equity to total capitalization.

Straight-line depreciation is assumed. Because enterprises are likely to depreciate their assets as fast as possible to reduce their tax burden, Vietnam's Ministry of Finance issued decree No. 206, which states that the minimum number of years for assets in the food processing industries to be completely depreciated is 7 years. The present value of depreciation allowances is

$$d = \frac{1}{7r}\left[1 - \left(\frac{1}{1+r}\right)^7\right].$$

Table 1.1: Posterior Medians for k_{lft} (4 groups)

	Out of Mekong	In Mekong
	year 2003	
Small firms	0.897	0.915
	(0.195)	(0.194)
Large firms	0.830	0.882
	(0.185)	(0.200)
	year 2005	
Small firms	0.790	0.804
	(0.345)	(0.345)
Large firms	0.731	0.777
	(0.325)	(0.349)

Note: Standard errors in parentheses.

Since the number of time periods T is just two (i.e., years 2003 and 2005), it is not possible to include the second-order terms in time in (1.12) and (1.18) and to estimate separate values of k_{nft} for individual firms. One possibility for identifying the k_{nft}'s is to divide the sample into groups of firms. The 47 firms are grouped in two ways: (a) 4 groups based on location (in vs. out of the Mekong delta) and firm size (small vs. large), and (b) 6 groups based on location and firm ownership (state-owned, equitized vs. private). The shadow cost system is thus run twice accordingly.

The shadow cost system is comprised of the total actual cost function (1.12) and one actual cost share equation (1.15) and estimated with the restrictions (1.16) and (1.17) imposed. Because I cannot estimate two absolute values k_{lft} and k_{kft}, I normalize $k_{kft} = 1$, for $t = 1, 2$, and $f = 1, ..., 47$. The condition for relative price efficiency then becomes $k_{lft} = 1$. Table 1.1 presents posterior medians for estimates of 4 groups' k_{lft}'s in 2003 and 2005. All of them are less than 1, meaning that the ratio of the shadow price of labor to that of capital is lower than the corresponding ratio of actual prices. This implies widespread over-utilization of labor relative to capital, which is supported by the fact that ratios of fitted to efficient

Table 1.2: Posterior Medians for Relative Inefficiencies for Labor (4 groups)

	Out of Mekong	In Mekong
	year 2003	
Small firms	1.028	1.025
	(0.061)	(0.063)
Large firms	1.046	1.024
	(0.062)	(0.051)
	year 2005	
Small firms	1.057	1.053
	(0.107)	(0.105)
Large firms	1.067	1.043
	(0.097)	(0.081)

Note: Standard errors in parentheses.

demands for labor are all greater than 1 (see Table 1.2).

Moreover, firms located in the Mekong delta have higher values of k_{lft} than those located in other regions in both years. This is probably attributable to more intense competition in the nation's biggest marine food producing basin. Small enterprises also have bigger k_{lft}'s than larger ones. Due to the availability of a large pool of low cost labor in Vietnam that firms seem to have easier access to than to capital, they are likely to use much more labor as their production expands. This fact is strengthened when I compare years 2003 and 2005. Generally, four groups of firms grew in size from 2003 to 2005, and their k_{lft}'s all decline over time.

Relative over-utilization of labor is revealed clearly in Table 1.2. All groups employ labor more than they should. The patterns displayed here correspond to those indicated in Table 1.1. Allocative inefficiencies are worse for out-of-Mekong enterprises in the two time periods. Small firms have more efficient input combinations than larger ones in other regions of the country, but this does not hold for firms in the Mekong delta. Large firms' weighted-average ratios of fitted to efficient demands for labor (where the weights are firms' shares of their

Table 1.3: Posterior Medians for k_{lft} (6 groups)

	Out of Mekong	In Mekong
	year 2003	
State-owned firms	0.840	0.874
	(0.198)	(0.204)
Equitized firms	0.819	0.876
	(0.184)	(0.198)
Private firms	0.897	0.852
	(0.214)	(0.195)
	year 2005	
State-owned firms	0.720	0.749
	(0.357)	(0.366)
Equitized firms	0.701	0.753
	(0.343)	(0.359)
Private firms	0.770	0.729
	(0.388)	(0.356)

Note: Standard errors in parentheses.

group's total output) are smaller, suggesting that several bigger companies in this group may actually use labor more properly than the small-firm group.

Tables 1.3 and 1.4 give posterior medians for estimates of k_{lft}'s and relative inefficiencies for 6 groups, which are categorized based on location and ownership. The range of their values is similar to that in Tables 1.1 and 1.2. Firms in the Mekong delta are more allocatively efficient than those located elsewhere, except for private firms. While private firms in other regions have the highest values of k_{lft} for both years, their counterparts in the Mekong delta have the lowest.

This may be caused by two reasons. First, the composition of the private firm group may not be well representative for the Mekong delta where small private firms tend to be less transparent financially and, hence, are dropped from the sample. For the 17 private firms in the sample that are based in the Delta, more than half (9) are classified as large. It is more acceptable for 13 private firms located elsewhere when 5 of them are large. Second,

Table 1.4: Posterior Medians for Relative Inefficiencies for Labor (6 groups)

	Out of Mekong	In Mekong
	year 2003	
State-owned firms	1.039	1.024
	(0.059)	(0.049)
Equitized firms	1.043	1.031
	(0.056)	(0.057)
Private firms	1.027	1.027
	(0.062)	(0.047)
	year 2005	
State-owned firms	1.061	1.043
	(0.092)	(0.077)
Equitized firms	1.076	1.051
	(0.099)	(0.084)
Private firms	1.049	1.051
	(0.090)	(0.080)

Note: Standard errors in parentheses.

the State has actively chosen to keep large and well-performing SOEs and gradually sold the unsound ones. Although the retained SOEs may or may not sustain their competitiveness in the long term, they are likely to perform better than private firms, at least in the short term.

I also estimate the k_{lft}'s with a cross-section sample that pools 102 firms in 2003 and 182 firms in 2005. Tables 1.5 and 1.6 show posterior medians for estimates of the 4 and 6 groups' k_{lft}'s, respectively. An interesting point is that, while out-of-Mekong enterprises tend to over-utilize capital in 2003 and then under-utilize this input in 2005, those enterprises in the Mekong delta do the opposite. The abrupt changes in the k_{lft}'s over time are probably due to the unobserved heterogeneity that is not dealt with in the cross-section sample.

With the estimated parameters in the shadow cost system for the panel data, I am able to compute scale economies for each firm. Median estimates of scale economies for the firm with the median output in each group are presented in Tables 1.7 and 1.8. In each year, large

Table 1.5: Posterior Medians for k_{lft} (4 groups) in a Cross-section Sample

	Out of Mekong	In Mekong
	year 2003	
Small firms	1.026	0.964
	(0.094)	(0.089)
Large firms	1.020	0.969
	(0.119)	(0.092)
	year 2005	
Small firms	0.939	1.125
	(0.084)	(0.098)
Large firms	0.939	1.050
	(0.087)	(0.099)

Note: Standard errors in parentheses.

Table 1.6: Posterior Medians for k_{lft} (6 groups) in a Cross-section Sample

	Out of Mekong	In Mekong
	year 2003	
State-owned firms	1.063	0.986
	(0.109)	(0.098)
Equitized firms	1.001	1.009
	(0.098)	(0.103)
Private firms	1.006	0.925
	(0.089)	(0.084)
	year 2005	
State-owned firms	0.964	1.048
	(0.093)	(0.143)
Equitized firms	0.894	1.047
	(0.080)	(0.096)
Private firms	1.038	1.139
	(0.092)	(0.099)

Note: Standard errors in parentheses.

Table 1.7: Posterior Medians for Scale Economies of the 4 Groups' Median Firms

	Out of Mekong	In Mekong
	year 2003	
Small firms	0.260	0.276
	(0.075)**	(0.086)**
Large firms	0.346	0.503
	(0.128)**	(0.216)*
	year 2005	
Small firms	0.535	0.573
	(0.104)**	(0.078)**
Large firms	0.676	0.838
	(0.063)**	(0.146)**

Notes: Standard errors in parentheses.

* significant at the 0.05 level, ** significant at the 0.01 level.

Table 1.8: Posterior Medians for Scale Economies of the 6 Groups' Median Firms

	Out of Mekong	In Mekong
	year 2003	
State-owned firms	0.565	0.877
	(0.065)**	(0.122)**
Equitized firms	0.657	0.875
	(0.079)**	(0.115)**
Private firms	0.543	0.560
	(0.064)**	(0.067)**
	year 2005	
State-owned firms	0.716	1.114
	(0.043)**	(0.106)**
Equitized firms	0.614	0.894
	(0.044)**	(0.063)**
Private firms	0.619	0.664
	(0.044)**	(0.041)**

Notes: Standard errors in parentheses.

** significant at the 0.01 level.

firms have higher SEs than smaller ones. As all 4 median firms' sizes increase over time, the estimates of SEs in 2005 are bigger than in 2003. Moreover, despite being classified in the same categories as small or large, the median enterprises in the Mekong delta have larger outputs than their counterparts in other regions. Furthermore, the SE estimates in the right column are higher than those in the left column. The positive correlation between size and scale economies implies that all these firms' production levels are below the efficient scale, so that returns to scale are increasing. In Table 1.8, among the 6 median firms in each year, the state-owned firm in the Mekong delta has the largest size and the biggest SE (even larger than 1 in 2005). Another reason is that SOEs still enjoy privileges in terms of lower input prices.

Tables 1.9 and 1.10 provide posterior medians for TE_{ft}, EC_{ft}, TC_{ft}, and PC_{ft} corresponding to two ways of grouping. Median technical efficiency scores reveal an enormous range of efficiencies. Both tables show that firm 41 achieves the highest EC_{ft}. It is a small SOE located in the North Central Coast. Between 2003 and 2005, it laid off 70% of its staff and increased its wages by 146%. Although its capital stock remained the same, its output almost doubled. The firm also has the second-highest and highest PC_{ft} according to Tables 1.9 and 1.10, respectively.

However, the two tables indicate two different enterprises that have the lowest EC_{ft} and PC_{ft}. In Table 1.9, the firm coded 39 is large, privately-owned, and located in the Mekong delta. It underwent a restructuring in which its capital decreased by 24% while its number of employees rose by 32%. Although wages were cut 8.2%, they were still much higher than the wages of the North Central Coast firm[11]. The restructuring seems to have been unsuccessful, as the firm's value added declined by 5%. In Table 1.10, the most technically efficient firm in 2003 experienced a very disappointing result two years later. This private, small firm located in the Mekong delta had unchanged capital and staff. In spite of its remarkable wage rise,

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[11] The North Central Coast is the poorest region in Vietnam.

Table 1.9: Posterior Medians for TE, EC, TC, and PC (4 groups)

Firm	TE		EC	TC	PC
	year 2003	year 2005			
1	0.41	0.28	-0.13	-0.09	-0.22
2	0.31	0.47	0.15	0.15	0.31
3	0.40	0.39	-0.02	-0.32	-0.34
4	0.42	0.41	-0.01	-0.16	-0.19
5	0.28	0.35	0.06	0.04	0.10
6	0.34	0.58	0.22	-0.35	-0.12
7	0.35	0.66	0.30	0.91	1.23
8	0.27	0.31	0.04	0.20	0.25
9	0.32	0.40	0.08	-0.22	-0.14
10	0.23	0.39	0.16	0.08	0.24
11	0.58	0.31	-0.26	0.60	0.31
12	0.32	0.49	0.16	-0.11	0.06
13	0.71	0.25	-0.45	-0.37	-0.84
14	0.64	0.56	-0.07	0.38	0.31
15	0.38	0.56	0.17	0.47	0.65
16	0.45	0.49	0.04	-0.43	-0.38
17	0.72	0.26	-0.45	-0.76	-1.23
18	0.45	0.30	-0.14	-0.39	-0.54
19	0.57	0.28	-0.28	-0.92	-1.22
20	0.56	0.29	-0.27	-0.84	-1.13
21	0.53	0.28	-0.25	-0.63	-0.90
22	0.65	0.23	-0.41	-0.64	-1.08
23	0.28	0.32	0.04	-0.10	-0.06
24	0.53	0.77	0.20	0.38	0.59
25	0.43	0.39	-0.04	-0.05	-0.10
26	0.27	0.48	0.21	0.39	0.61
27	0.42	0.46	0.03	-0.21	-0.18
28	0.36	0.52	0.15	0.07	0.23
29	0.45	0.31	-0.13	-0.28	-0.42
30	0.19	0.73	0.53	0.18	0.73
31	0.46	0.59	0.13	0.27	0.41
32	0.22	0.39	0.16	0.11	0.28
33	0.34	0.45	0.10	0.10	0.21
34	0.57	0.29	-0.27	-0.68	-0.98
35	0.46	0.36	-0.09	0.03	-0.07
36	0.51	0.27	-0.24	-0.60	-0.86
37	0.62	0.31	-0.30	-0.59	-0.92
38	0.39	0.38	-0.01	-0.14	-0.15
39	0.83	0.25	-0.56	-1.05	-1.63
40	0.24	0.65	0.40	0.46	0.88
41	0.20	0.86	0.64	0.30	0.92
42	0.34	0.44	0.10	-0.02	0.08
43	0.30	0.49	0.18	0.28	0.47
44	0.37	0.33	-0.04	-0.34	-0.39
45	0.27	0.52	0.24	0.04	0.29
46	0.54	0.32	-0.21	-0.66	-0.89
47	0.29	0.45	0.16	0.11	0.28

Table 1.10: Posterior Medians for TE, EC, TC, and PC (6 groups)

Firm	TE		EC	TC	PC
	year 2003	year 2005			
1	0.39	0.32	-0.06	0.12	0.06
2	0.35	0.51	0.15	0.15	0.30
3	0.37	0.52	0.14	0.10	0.25
4	0.43	0.50	0.07	0.12	0.18
5	0.29	0.38	0.09	0.14	0.23
6	0.31	0.85	0.53	0.10	0.63
7	0.57	0.53	-0.04	0.23	0.19
8	0.29	0.32	0.03	0.15	0.18
9	0.32	0.50	0.18	0.11	0.30
10	0.23	0.42	0.18	0.14	0.33
11	1	0.25	-0.69	0.19	-0.48
12	0.37	0.52	0.15	0.12	0.28
13	0.62	0.37	-0.25	0.10	-0.16
14	0.90	0.64	-0.22	0.17	-0.05
15	0.51	0.58	0.06	0.18	0.24
16	0.50	0.59	0.09	0.09	0.19
17	0.57	0.42	-0.15	0.06	-0.09
18	0.49	0.34	-0.15	0.10	-0.06
19	0.41	0.47	0.05	0.05	0.10
20	0.41	0.50	0.08	0.06	0.14
21	0.42	0.44	0.02	0.07	0.09
22	0.51	0.37	-0.14	0.07	-0.07
23	0.26	0.37	0.11	0.12	0.23
24	0.73	0.82	0.07	0.17	0.24
25	0.44	0.46	0.02	0.13	0.15
26	0.32	0.48	0.16	0.17	0.33
27	0.41	0.61	0.20	0.11	0.32
28	0.40	0.63	0.22	0.14	0.37
29	0.41	0.42	0.01	0.11	0.12
30	0.21	0.78	0.57	0.15	0.72
31	0.59	0.70	0.10	0.16	0.26
32	0.24	0.38	0.13	0.14	0.28
33	0.37	0.52	0.14	0.14	0.29
34	0.46	0.46	0	0.07	0.07
35	0.50	0.44	-0.06	0.14	0.07
36	0.41	0.40	-0.01	0.08	0.07
37	0.55	0.45	-0.10	0.08	-0.03
38	0.39	0.46	0.07	0.12	0.20
39	0.54	0.50	-0.04	0.04	0
40	0.30	0.65	0.35	0.18	0.53
41	0.24	0.91	0.65	0.16	0.80
42	0.36	0.50	0.14	0.13	0.28
43	0.36	0.52	0.15	0.16	0.31
44	0.32	0.45	0.12	0.10	0.23
45	0.29	0.60	0.31	0.14	0.45
46	0.46	0.49	0.02	0.07	0.09
47	0.31	0.50	0.18	0.15	0.33

its output fell by more than 80%.

The wide range of the median estimates of TE_{ft}, EC_{ft}, TC_{ft}, and PC_{ft} as well as the large fluctuations in performance of the firms examined above may be attributed to the huge difficulties that the fisheries sector in Vietnam faced in this period. The anti-dumping case brought against the Vietnamese catfish industry by the CFA reversed the commodity export boom into the U.S, which is the Vietnam's biggest marine food market. Many firms were badly hit and had to struggle to survive.

1.6 Conclusions

Vietnam has gone through a dramatic development of its fisheries sector over the last two decades, with an average annual growth rate of 9.37% from 1990 to 2007. Vietnam quickly left Bangladesh and Myanmar far behind in fisheries output and even surpassed Thailand, whose production was three times greater than that of Vietnam in 1990. However, sustainable development has been called into question because of concerns about the risk of environmental pollution, overfishing, quality control, supporting services, the performance of firms in this sector, etc.

Using a shadow cost system and an MCMC parametric approach, I find that firms have not fully exploited economies of scale and there are a lot of opportunities for future expansion. Nearly all of the firms over-utilize labor relative to capital. Firms located in the Mekong delta tend to have higher degrees of allocative efficiency than those located in other regions. Small firms generally perform better than larger ones. However, while in other regions SOEs combine inputs less efficiently than private enterprises, the pattern seems to reverse itself in the Mekong delta. In addition, I have looked at firms that are the best or worst in terms of TE_{ft}, EC_{ft}, TC_{ft}, and PC_{ft}. The performance of private enterprises relative to SOEs is mixed. This may be due to the privileges that SOEs still enjoy. Large fluctuations over time on these rankings may indicate the vulnerability of the weaker firms to competition from international trade.

However, since the data are limited, I am not able to estimate separate values of k_{lft} for individual firms. Grouping them is likely to lead to aggregation bias, as seen in Table 1.2. In addition, two time periods do not allow the specification of the time effect to be more flexible, and prevent me from obtaining firm-specific and time-varying estimates of allocative efficiency. Therefore, richer data are needed to extend this study.

Chapter 2

Production Inefficiency of the U.S. Electricity Industry in the Face of Restructuring and Emission Reduction

2.1 Introduction

Emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_X) from electric generating units (EGUs) and other large combustion sources contribute to the formation of ozone. High concentration of ozone at ground level can exacerbate respiratory diseases and raise susceptibility to respiratory infections. It can also damage sensitive vegetation, causing loss of diversity that may reduce the value of real property (US EPA, 2009). Serious health and ecological hazards of air pollution have brought about remarkable changes in environmental regulations, which began with the Clean Air Act Amendments of 1990. Accordingly, several programs have been established to require power utilities to reduce SO_2 and NO_X emissions through cap-and-trade (CAT) systems. These programs set a cap on regional emissions and provide individual emission sources with flexibility in how they comply with emission limits.

It has long been recognized that this approach could coordinate pollution abatement activities highly effectively. However, Fowlie (2010) indicates that pre-existing distortions in output markets may hinder the CAT programs from operating efficiently. Restructuring in electricity markets could induce deregulated plants to choose less capital-intensive control technology as compared to regulated or publicly-owned plants. Since regulated utilities enjoy a guaranteed rate of return on capital investment, they tend to relatively over-capitalize their control devices. Fowlie assumes that plant managers would choose a compliance strategy that minimizes a weighted sum of expected annual compliance costs and capital costs. There is, though, implied separability of emission control and electricity generation. It is probably more reasonable to expect that power plant managers would decide on an environmental compliance option based on not only its costs but also other indicators relevant to plant operation. This chapter puts those managers' decisions in a broader view by examining production efficiency of U.S. electric utilities in light of multiple inputs and multiple outputs.

To measure the productivity of U.S. electric utilities, Atkinson et al. (2003) use a stochastic distance function that takes into account three inputs (i.e., fuel, labor, and capital), and two good outputs (i.e., residential and industrial-commercial electricity). Then, Atkinson and Dorfman (2005) include one bad output, SO_2 emissions, as a technology shifter. Their results show negative efficiency change over the entire sample period that is largely attributed to firms' efforts to reduce SO_2 emissions. Fu (2009) estimates a directional distance function with a data set comprised of 78 privately-owned electric utilities from 1988 to 2005 with three bad outputs, namely, SO_2, CO_2, and NO_X emissions. She also finds declining efficiency and productivity change over time.

In this chapter, I extend Fu's data set by adding annualized capital costs spent on SO_2, NO_X and particulate removal devices. I employ a multiple-input, multiple-output directional distance function[1]. It allows me to avoid assuming separability, which may eliminate statistically significant interactions among various outputs, and to compute the partial effects between any pair of endogenous variables. I find that restructuring in electricity markets tends to improve technical efficiency of deregulated utilities since they operate under the discipline of competitive markets. The absence of rate-of-return regulation is likely to decrease capital investment in NO_X control equipment only for utilities that have this equipment below average but increase for utilities that have this equipment above average. The reverse applies to particulate removal devices. However, the whole sample spends more on these two as well as SO_2 control systems and reduce their electricity sales slightly.

There are several important interactions among inputs and outputs. Increased capital investments on SO_2 and NO_X control equipment do not reduce SO_2 and NO_X emissions, respectively. However, expansions in particulate control systems cut down SO_2 emissions greatly. Moreover, larger installations of NO_X and particulate removal devices help curb CO2 emissions marginally. While residential and industrial-commercial electricity sales are substitutable, and SO_2, CO_2 and NO_X emissions are generally complementary. Additionally, the utilities have been shifted increasingly farther from the frontier over time. Inward shifting of the production frontier, as well as declining technical efficiency and productivity growth, appears to follow the implementation of stricter environmental regulations.

The remainder of the chapter is organized as follows. The next section gives a brief overview of the U.S. electric power industry. Section 2.3 presents properties of the directional distance function and computation of productivity change. Section 2.4 reports empirical results and conclusions follow in section 2.5.

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[1] Refer to Chambers et al. (1996) for a theoretical derivation of this function.

2.2 The U.S. Electric Power Industry

Net generation of electric power in the United States grew steadily over the last two decades from 3,197 million megawatt hours (MWh) in 1993 to 4,157 million MWh in 2007 (Table 2.1). The average growth rate in this period was 1.89 percent per year. However, the trend reversed in 2001 when California experienced severe electricity shortages and Houston-based Enron got into trouble for fraudulent accounting practices. Electricity generation again dropped 0.9 percent in 2008. The U.S. Energy Information Administration (EIA) attributed the decrease to the weakening economy, with total industrial production falling 2.2 percent, and reduced summer electricity demand for cooling because 2008 produced the coolest temperature in more than a decade.

The primary energy source for generating electric power over this period was coal, which provided about half of total net generation. However, its share of total net generation trended downward, accounting for 48.2 percent in 2008 as compared to 52.9 percent in 1993. The same holds for petroleum and conventional hydroelectric generation. In contrast, natural gas-fired generation sustained solid growth and in 2006 surpassed nuclear generation, whose relative share rose marginally in this period, to become the second largest contributor to total net generation. Renewable energy sources' share of electricity generation (not including conventional hydroelectric) first fell between 1993 and 2001 and then increased consecutively in the last five years, contributing 3.1 percent in 2008. This growth came mainly from wind generation, which was up almost fivefold, from 11.2 million MWh in 2003 to 55.4 million MWh in 2008.

U.S. electric power generation has been shifting gradually from coal and petroleum to natural gas and renewable sources. The change towards 'greener' sources follows significant requirements to reduce SO_2 and NO_X emissions from large stationary sources, primarily EGUs. These emissions contribute to the formation of ozone. High concentration of ozone

Table 2.1: Net Generation (million megawatt hours)

Energy Source	1993	1994	1995	1996	1997	1998	1999	2000
Coal[a]	1690.1	1690.7	1709.4	1795.2	1845.0	1873.5	1881.1	1966.3
Petroleum[b]	112.8	105.9	74.6	81.4	92.6	128.8	118.1	111.2
Natural Gas[c]	414.9	460.2	496.1	455.1	479.4	531.3	556.4	601.0
Nuclear	610.3	640.4	673.4	674.7	628.6	673.7	728.3	753.9
Hydroelectric Conventional[d]	280.5	260.1	310.8	347.2	356.5	323.3	319.5	275.6
Other Renewables[e]	76.2	76.5	74.0	75.8	77.2	77.1	79.4	80.9
Wind					3.3	3.0	4.5	5.6
All Energy Sources	3197.2	3247.5	3353.5	3444.2	3492.2	3620.3	3694.8	3802.1

Energy Source	2001	2002	2003	2004	2005	2006	2007	2008
Coal[a]	1904.0	1933.1	1973.7	1978.3	2012.9	1990.5	2016.5	1985.8
Petroleum[b]	124.9	94.6	119.4	121.1	122.2	64.2	65.7	46.2
Natural Gas[c]	639.1	691.0	649.9	710.1	761.0	816.4	896.6	883.0
Nuclear	768.8	780.1	763.7	788.5	782.0	787.2	806.4	806.2
Hydroelectric Conventional[d]	217.0	264.3	275.8	268.4	270.3	289.2	247.5	254.8
Other Renewables[e]	70.8	79.1	79.5	83.1	87.3	96.5	105.2	126.2
Wind	6.7	10.4	11.2	14.1	17.8	26.6	34.5	55.4
All Energy Sources	3736.6	3858.5	3883.2	3970.6	4055.4	4064.7	4156.7	4119.4

Notes: [a] Includes anthracite, bituminous, sub-bituminous, and lignite coal.

[b] Includes distillate fuel oil, residual fuel oil, jet fuel, kerosene, petroleum coke, and waste oil.

[c] Includes a small number of generating units for which waste heat is the main energy source.

[d] Excludes pumped storage facilities.

[e] Includes wind, solar thermal and photovoltaic, wood and wood derived fuels, geothermal, and other biomass.

Source: US EIA (2010).

at ground level can severely exacerbate respiratory diseases and raise the level of susceptibility to respiratory infections, leading to increased medication use, hospital visits and premature mortality. High levels of ozone can also damage sensitive vegetation, causing loss of biodiversity that may reduce the value of real property (US EPA, 2009). Serious health and ecological impacts of air pollution have led to remarkable changes in environmental regulations, beginning with Congress's enacting the Clean Air Act Amendments of 1990.

The Act set a goal of reducing annual SO_2 emissions by 10 million tons below 1980 levels of about 18.9 million tons. The Acid Rain Program (ARP) was established to implement a two-phase tightening of the restrictions. In Phase I of the ARP starting in 1995, 263 units at 110 mostly coal-burning power plants located in 21 eastern and midwestern states were required to cut SO_2 emission rates to 2.5 lbs/million British thermal units (mmBtu). In Phase II, starting in 2000, all fossil-fired units over 75 megawatts had to limit SO_2 emissions to 1.2 lbs/mmBtu. The Act also called for reductions of NO_X emissions by 2 million tons from 1980 levels. The ARP marked a switch from traditional command and control regulatory methods to market-based cap-and-trade systems. It sets a cap on overall emissions (e.g., 8.95 million tons of SO_2 in phase II) and allocates allowances to emit a specified number of tons of emissions. Since allowances are tradable, each utility is flexible in observing emission limits by adopting the cheapest compliance strategy. Therefore, the electricity industry as a whole can reduce emissions cost-effectively.

In 1997, a new, stricter 8-hour ozone standard of 0.08 parts per million was set to replace the 1979 standard, which was 0.12 parts per million. The U.S. Environmental Protection Agency (EPA) developed the NO_X State Implementation Plan (SIP) Call rule in 1998 to reduce ozone season NO_X emissions. The rule was designed to address the problem of ozone transport across the eastern United States (US EPA, 2009). By 2007, all 20 of the affected states and the District of Columbia decided to meet NO_X SIP Call reductions and to join the NO_X Budget Trading Program. This market-based CAT program was displaced by the

Table 2.2: Emissions (million metric tons)

	1993	1994	1995	1996	1997	1998	1999	2000
CO_2	2034.2	2063.8	2079.8	2155.5	2253.8	2346.0	2360.4	2464.6
SO_2	15.0	14.5	11.9	12.9	13.5	13.5	12.8	12.0
NO_X	8.0	7.8	7.9	6.3	6.5	6.5	6.0	5.6
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
CO_2	2412.0	2417.3	2438.3	2480.0	2536.7	2481.8	2539.8	2477.2
SO_2	11.2	10.9	10.6	10.3	10.3	9.5	9.0	7.8[a]
NO_X	5.3	5.2	4.5	4.1	4.0	3.8	3.7	3.3[a]

Note: [a] SO_2 and NO_X 2008 values are preliminary.

Source: US EIA (2010).

Clean Air Interstate Rule NO_X ozone season program starting in 2009.

The stringent requirements on SO_2 and NO_X emissions have resulted in dramatic reductions in these air pollutants (Table 2.2). While unregulated CO_2 emissions increased by 21.8 percent along with electricity generation between 1993 and 2008, SO_2 emissions fell by 47.7 percent, from 15 to 7.8 million tons. NO_X emissions saw an even bigger decrease of 58.4 percent, from 8 to 3.3 million tons. The largest year-over-year declines in SO_2 and NO_X emissions occurred in 1995 and 1996, respectively, when Phase I of the SO_2 reductions under the ARP took effect one year earlier than that of NO_X. Significant decreases in SO_2 and NO_X emissions also occurred in 2008, mostly due to the installation of flue gas desulfurization units, low-NO_X burners and selective catalytic reduction devices (US EIA, 2010).

In addition, the electric power industry underwent a wave of restructuring beginning in the mid-1990s. Before then, electricity generation in the United States was dominated by vertically integrated investor-owned utilities (IOUs), most of which operated as highly regulated, local monopolies. Since prices were set by state regulators based on a guaranteed rate of return on capital investment, large costs caused by inefficient investments would be passed through to customers. It has long been argued that increased competition brought on by deregulation could improve efficiency and reduce prices. In 1996, states that had relatively high electricity rates began restructuring their electric power industry. Under competitive pressure, IOUs have been merging, and many power plants in some regions have been sold to private companies (US EIA, 2005). By 1998, all fifty states and the District of Columbia held formal hearings to consider restructuring. However, the California electricity crisis of 2000 and 2001 halted this transition.

2.3 The Directional Distance Function

This section follows Agee, Atkinson, and Crocker (2010). Consider a production technology in which electric utilities combine N nonnegative good inputs, $\mathbf{x} = (x_1, ..., x_N)' \in R_+^N$, to produce M nonnegative good outputs, $\mathbf{y} = (y_1, ..., y_M)' \in R_+^M$. A utility's production technology, $\mathbf{S}(\mathbf{x}, \mathbf{y})$, is given by

$$\mathbf{S}(\mathbf{x}, \mathbf{y}) = \{(\mathbf{x}, \mathbf{y}) : \mathbf{x} \text{ can produce } \mathbf{y}\}, \tag{2.1}$$

where $\mathbf{S}(\mathbf{x}, \mathbf{y})$ consists of all feasible good input and good output vectors. I can extend (2.1) to include 'bad' outputs (e.g., SO_2, CO_2, and NO_X emissions). Let $\tilde{\mathbf{y}} = (\tilde{y}_1, ..., \tilde{y}_L)' \in R_+^L$ denote a vector of L bad outputs produced jointly with $\mathbf{y}$. Following Chambers et al. (1998), the output directional distance function is defined as

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) = \sup\{\beta : (\mathbf{y} + \beta\mathbf{g}_y, \tilde{\mathbf{y}} - \beta\mathbf{g}_{\tilde{y}}) \in P(\mathbf{x})\}, \tag{2.2}$$

where $P(\mathbf{x})$ is the set of good and bad outputs that can be produced with inputs $\mathbf{x}$ and output direction $(\mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \neq (\mathbf{0}, \mathbf{0})$. For a given level of inputs, the output directional distance function measures the increase in good outputs (decrease in bad outputs) in the direction $\mathbf{g}_y(-\mathbf{g}_{\tilde{y}})$ in order to move to the frontier of P. Differences between the best-practice (frontier) and actual outputs are measures of technical inefficiency in a utility's electricity generation. The measure is equal to zero when the utility is on the frontier of P, and greater than zero when the utility is below the frontier of P.

The output directional distance function has the following properties:

D1. Translation Property:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y} + \alpha\mathbf{g}_y, \tilde{\mathbf{y}} - \alpha\mathbf{g}_{\tilde{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) = \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) - \alpha, \tag{2.3}$$

D2. g-Homogeneity of Degree Minus One:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \lambda\mathbf{g}_y, -\lambda\mathbf{g}_{\tilde{y}}) = \lambda^{-1}\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}), \quad \lambda > 0, \tag{2.4}$$

D3. Good Output Monotonicity:

$$\mathbf{y}' \geq \mathbf{y} \Rightarrow \overrightarrow{D}_\tau(\mathbf{x}, \mathbf{y}', \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \leq \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}), \tag{2.5}$$

D4. Bad Output Monotonicity:

$$\tilde{\mathbf{y}}' \geq \tilde{\mathbf{y}} \Rightarrow \overrightarrow{D}_\tau(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}'; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \geq \overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}), \tag{2.6}$$

D5. Concavity:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \text{ is concave in } (\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}), \tag{2.7}$$

D6. Non-negativity:

$$\overrightarrow{D}_0(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}; \mathbf{0}, \mathbf{g}_y, -\mathbf{g}_{\tilde{y}}) \geq 0 \Leftrightarrow (\mathbf{y}, \tilde{\mathbf{y}}) \in P(\mathbf{x}). \tag{2.8}$$

The translation property says that increasing $\mathbf{y}$ and decreasing $\tilde{\mathbf{y}}$ by α-fold of their respective directions will reduce the directional distance by α. Equation (2.4) implies that if each direction is scaled by λ, then the directional distance will be scaled by λ^{-1}. The next two expressions (2.5) and (2.6) indicate that the directional distance function of a profit-maximizing utility is monotonically decreasing in good outputs, and monotonically increasing in bad outputs. Expression (2.7) imposes concavity of the output directional distance function. In this chapter, I impose D1, which will guarantee D2. I can test for D3 and D4. A normalization after estimation of the directional distance function is needed to make sure that D6 holds.

a. Quadratic output directional distance function. I use a quadratic function to approximate the output directional distance function. In preliminary estimates, the null hypothesis that the squared input terms and the interaction terms among inputs are jointly equal to zero is rejected. I also reject the null hypotheses that the interaction terms between inputs and outputs are equal to zero, and that the interaction terms between restructuring (RE) and annualized capital costs (KSO2, KNOX, KTSP) spent on SO_2, NO_X, and particulate removal devices are equal to zero. The quadratic form of the output directional distance function is:

$$\begin{aligned}
\overrightarrow{D}_{0,it}(\mathbf{x},\mathbf{y},\tilde{\mathbf{y}}) &= \gamma_i d_i + \sum_{n=1}^{N}\gamma_n x_{it,n} + \sum_{m=1}^{M}\gamma_m y_{it,m} + \sum_{l=1}^{L}\gamma_l \tilde{y}_{it,l} \\
&+ \frac{1}{2}\sum_{n=1}^{N}\sum_{n'=1}^{N}\gamma_{nn'}x_{it,n}x_{it,n'} + \frac{1}{2}\sum_{m=1}^{M}\sum_{m'=1}^{M}\gamma_{mm'}y_{it,m}y_{it,m'} \\
&+ \frac{1}{2}\sum_{l=1}^{L}\sum_{l'=1}^{L}\gamma_{ll'}\tilde{y}_{it,l}\tilde{y}_{it,l'} + \sum_{n=1}^{N}\sum_{m=1}^{M}\gamma_{nm}x_{it,n}y_{it,m} \\
&+ \sum_{n=1}^{N}\sum_{l=1}^{L}\gamma_{nl}x_{it,n}\tilde{y}_{it,l} + \sum_{m=1}^{M}\sum_{l=1}^{L}\gamma_{ml}y_{it,m}\tilde{y}_{it,l} \\
&+ \gamma_t t + \gamma_{re}RE + \gamma_{res}RE \times KSO2 + \gamma_{ren}RE \times KNOX \\
&+ \gamma_{ret}RE \times KTSP + \varepsilon_{it}, \qquad (2.9)
\end{aligned}$$

where d_i is a dummy variable for utility i, $i = 1, ..., F$, and

$$\varepsilon_{it} = \nu_{it} + \mu_{it}. \tag{2.10}$$

The composite error ε_{it} is an additive error with a one-sided component, $\mu_{it} \geq 0$, which captures technical inefficiency, and statistical noise, ν_{it}, assumed to be iid with zero mean. I set the left-hand side of (2.9) equal to zero for all observations. To meet the translation property D1, I need to impose the following restrictions:

$$\begin{aligned}
\sum_{m=1}^{M} \gamma_m g_m - \sum_{l=1}^{L} \gamma_l g_l &= -1, \\
\sum_{m=1}^{M} \gamma_{mm'} g_m - \sum_{l=1}^{L} \gamma_{m'l} g_l &= 0, \quad \forall m' \\
\sum_{m=1}^{M} \gamma_{ml'} g_m - \sum_{l=1}^{L} \gamma_{ll'} g_l &= 0, \quad \forall l' \\
\sum_{m=1}^{M} \gamma_{nm} g_m - \sum_{l=1}^{L} \gamma_{nl} g_l &= 0, \quad \forall n.
\end{aligned} \tag{2.11}$$

Symmetry also is imposed on the doubly-subscripted coefficients in (2.9).

Again, following Agee, Atkinson, and Crocker (2010), the fixed-effects approach is used here by including F utility-specific dummy variables to relax the strong distributional assumptions on both the ν_{it} and μ_{it}, and the unlikely assumption of no correlation between the μ_{it} and the explanatory variables that are required in the random-effects approach. The implicit function theorem allows me to examine the partial effect of any individual variable on another variable. For instance, the effect of a good output on another good output is $-(\partial \overrightarrow{D}_0/\partial y_m)/(\partial \overrightarrow{D}_0/\partial y_{m'})$, $\forall m, m'; m \neq m'$, and the effect of a bad output on another bad output is $-(\partial \overrightarrow{D}_0/\partial \tilde{y}_l)/(\partial \overrightarrow{D}_0/\partial \tilde{y}_{l'}))$, $\forall l, l'; l \neq l'$. The effect of an input on another input is $-(\partial \overrightarrow{D}_0/\partial x_n)/(\partial \overrightarrow{D}_0/\partial x_{n'})$, $\forall n, n'; n \neq n'$. Finally, the effects of an input on a good output and a bad output are $-(\partial \overrightarrow{D}_0/\partial x_n)/(\partial \overrightarrow{D}_0/\partial y_m)$, $\forall m, n$, and $-(\partial \overrightarrow{D}_0/\partial x_n)/(\partial \overrightarrow{D}_0/\partial \tilde{y}_l)$, $\forall l, n$, respectively.

b. Measuring TE, EC, TC, and PC. This subsection follows Agee, Atkinson, and Crocker (2010). Estimation of utility-specific TE, EC, TC, and PC proceeds as follows. Since I want to measure EC, TC, and PC in terms of percentage changes, I have to transform output directional distance function measures into Malmquist distance function measures. Following Balk et al. (2008), Malmquist output-oriented distance function measures in period t are

$$D_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) = 1/(1 + \overrightarrow{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it})). \tag{2.12}$$

In the distance function:

$$1 = D_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it})\exp(\epsilon_{it}), \tag{2.13}$$

$\epsilon_{it} = v_{it} + u_{it}$, which are assumed to be two-sided and one-sided error terms, respectively. Taking logs of (2.13) and using fitted values from (2.9) transformed by (2.12), I get

$$0 = \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) + \hat{\epsilon}_{it}, \tag{2.14}$$

or

$$\hat{\epsilon}_{it} = \hat{v}_{it} + \hat{u}_{it} = -\ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}). \tag{2.15}$$

In order to sweep away the statistical noise, $\hat{v}_{it}$, from the composite error, I follow Cornwell, Schmidt, and Sickles (1990) by regressing $\hat{\epsilon}_{it}$ on F utility dummies and the interactions of time with utility dummies:

$$\hat{\epsilon}_{it} = \sum_{i=1}^{F} \psi_i d_i + \sum_{i=1}^{F} \phi_i d_i t + \zeta_{it}, \tag{2.16}$$

where the random error term ζ_{it} is uncorrelated with the regressors. The fitted values, $\tilde{u}_{it}$, of (2.16) are consistent estimates of u_{it}.

As u_{it} needs to be nonnegative, I transform $\tilde{u}_{it}$ by subtracting $\tilde{u}_t = \min_i(\tilde{u}_{it})$, which is the estimated frontier intercept, and obtain $\tilde{u}_{it}^F = \tilde{u}_{it} - \tilde{u}_t \geq 0$. Adding and subtracting $\tilde{u}_t$ from the estimated (2.14) yields

$$\begin{aligned} 0 &= \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) + \hat{v}_{it} + \tilde{u}_{it} + \tilde{u}_t - \tilde{u}_t \\ &= \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) + \tilde{u}_t + \hat{v}_{it} + \tilde{u}_{it} - \tilde{u}_t \\ &= \ln \hat{D}_0^{F,t}(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) + \hat{v}_{it} + \tilde{u}_{it}^F, \end{aligned} \tag{2.17}$$

where $\ln \hat{D}_0^{F,t}(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) = \ln \hat{D}_0^t(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it}) + \tilde{u}_t$ is the log of the fitted frontier shadow distance function in period t. Utility i's technical efficiency in period t is defined as

$$TE_{it} = \exp(-\tilde{u}_{it}^F). \tag{2.18}$$

$EC_{i,t+1}$ is the change in TE or the rate of catching up to the frontier from t to $t+1$, defined as

$$EC_{i,t+1} = TE_{i,t+1} - TE_{it}. \tag{2.19}$$

Technical change, $TC_{i,t+1}$, is estimated as the difference between $\ln \hat{D}_0^{F,t+1}(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it})$ and $\ln \hat{D}_0^{F,t}(\mathbf{x}_{it}, \mathbf{y}_{it}, \tilde{\mathbf{y}}_{it})$, holding all inputs and outputs constant:

$$TC_{i,t+1} = \ln \hat{D}_0^{t+1}(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}) + \tilde{u}_{t+1} - [\ln \hat{D}_0^t(\mathbf{x}, \mathbf{y}, \tilde{\mathbf{y}}) + \tilde{u}_t]. \tag{2.20}$$

TC is interpreted as a shift in the frontier over time. Given $EC_{i,t}$ and $TC_{i,t}$, I obtain

$$PC_{it} = EC_{it} + TC_{it}. \tag{2.21}$$

c. Standardizing Units. As discussed in Agee, Atkinson, and Crocker (2010), the output directional distance function involves inputs and outputs that have different units. I cannot compare a certain absolute increase in kilowatt hours of electricity to an absolute decrease in tons of NO_X emissions. I need to standardize all input and output measures to a zero mean and unit variance, except for dichotomous variables. Then the marginal effect of a variable on another variable is in standard deviations.

d. Choosing Direction. Also as discussed in Agee, Atkinson, and Crocker (2010), the direction is not a parameter that can be estimated. Instead, I can pre-assign the directions with a broad range of values expressing different assumed value judgments relevant to the tradeoffs between good and bad outputs.

2.4 Data and Empirical Results

a. Data. The data set used in this chapter is an extended version of the panel of utilities originally analyzed by Fu (2009). The primary sources for Fu's data are the U.S. Energy Information Administration's *Electric Power Annuals, Forms EIA-767, EIA-906, EIA-920*, and the Federal Energy Regulatory Commission's *Forms FERC-1, FERC-423*. The sample consists of 78 privately-owned U.S. utilities whose electricity generation is fossil fuel-based. A list of the utilities is provided in Table 2.3. The panel spans from 1988 to 2005, in which major changes in environmental regulations relevant to omission reductions and the wave of industry restructuring took place. During this period, 28 of these utilities stopped their steam electricity generation.

The outputs include two good outputs, residential and industrial-commercial electricity (SALR and SALIC) in 10 millions of kilowatt hour sales, and three bad outputs (SO_2, CO_2, and NO_X emissions) measured in tons. The inputs initially are fuel, labor, and capital. The quantity of fuel is the heat content in mmBtu from all fossil fuels burned. The quantities of labor and capital are defined as the ratios of input expenditures to prices.

Table 2.3: Utilities in the Sample

No.	Utility	No.	Utility
1	Alabama Power Co.	40	KGE, A Western Resources Company
2	Central Illinois Public Service Co.	41	Long Island Lighting Co.
3	Union Electric Co.	42	Louisville Gas and Electric Co.
4	Appalachian Power Co.	43	Minnesota Power and Light Co.
5	Arizona Public Service Co.	44	Mississippi Power Co.
6	Atlantic City Electric Co.	45	Montana Dakota Utilities Co.
7	Baltimore Gas and Electric Co.	46	Montana Power Co.
8	Boston Edison Co.	47	New England Power Co.
9	Carolina Power and Light Co.	48	New York State Electric and Gas Corp.
10	Central Hudson Gas and Electric Corp.	49	Niagara Mohawk Power Corp.
11	Central Maine Power Co.	50	Northern Indiana Public Service Co.
12	Central Power and Light Co.	51	Northern States Power Co.
13	Cincinnati Gas and Electric Co.	52	Ohio Edison Co.
14	Central Louisiana Electric Co. Inc.	53	Ohio Power Co.
15	Cleveland Electric Illuminating Co.	54	Oklahoma Gas and Electric Co.
16	Columbus Southern Power Co.	55	Pacific Gas and Electric Co.
17	Commonwealth Edison Co.	56	PacifiCorp West and East
18	Consolidated Edison Co. of NY	57	PECO Energy Co.
19	Dayton Power and Light Co.	58	Pennsylvania Power and Light Co.
20	Delmarva Power and Light Co.	59	Potomac Edison Co.
21	Detroit Edison Co.	60	Potomac Electric Power Co.
22	Duke Power Co.	61	PSC of Colorado
23	Duquesne Light Co.	62	PSC of New Hampshire
24	Entergy Arkansas, Inc.	63	PSC of New Mexico
25	Entergy Gulf States, Inc.	64	PSI Energy, Inc.
26	Entergy Louisiana, Inc.	65	Public Service Electric and Gas Co.
27	Entergy Mississippi, Inc.	66	Rochester Gas and Electric Corp.
28	Entergy New Orleans, Inc.	67	San Diego Gas and Electric Co.
29	Florida Power and Light Co.	68	South Carolina Electric and Gas Co.
30	Florida Power Corp.	69	Southern California Edison Co.
31	Georgia Power Co.	70	Southwestern Electric Power Co.
32	Gulf Power Co.	71	Southwestern Public Service Co.
33	Houston Lighting and Power Co.	72	Tampa Electric Co.
34	Illinois Power Co.	73	Texas Utilities Electric Co.
35	Indiana Michigan Power Co.	74	United Illuminating Co.
36	Indianapolis Power and Light Co.	75	Virginia Electric and Power Co.
37	Interstate Power Co.	76	West Penn Power Co.
38	Kansas City Power and Light Co.	77	Wisconsin Electric Power Co.
39	Kentucky Utilities Co.	78	Wisconsin Public Service Corp.

Table 2.4: Annual Average Quantities of Inputs and Outputs

Year	X_{FUEL}	X_{LABOR}	X_{CAPITAL}	X_{KSO2}	X_{KNOX}	X_{KTSP}
1988	1.838e+08	1438.5	93944.5	577.2	177.0	306.8
1989	1.869e+08	1477.8	107547.1	598.9	183.6	318.3
1990	1.834e+08	1437.1	106106.6	613.0	189.0	320.2
1991	1.816e+08	1389.7	117412.2	637.9	201.8	327.1
1992	1.821e+08	1333.3	124243.1	647.1	201.2	324.2
1993	1.864e+08	1290.2	137101.1	648.9	205.1	325.2
1994	1.925e+08	1202.6	123890.3	684.7	217.6	333.2
1995	1.920e+08	1101.6	132710.1	741.9	292.0	345.5
1996	1.973e+08	1045.1	134429.2	773.9	355.2	346.0
1997	2.051e+08	1075.2	138174.4	783.6	393.3	350.4
1998	2.145e+08	990.1	151183.8	799.9	406.7	357.3
1999	2.202e+08	1086.7	119609.4	897.1	431.8	357.9
2000	2.260e+08	919.3	121483.3	1030.0	680.0	363.9
2001	2.182e+08	938.8	126314.8	1194.2	801.9	404.2
2002	2.127e+08	1049.7	132421.9	1151.2	869.4	429.5
2003	2.063e+08	1038.5	144887.8	1169.8	909.1	436.3
2004	2.134e+08	972.1	152384.1	1292.4	1024.8	482.0
2005	2.228e+08	968.0	154425.1	1362.1	1101.8	508.0

Year	Y_{SALR}	Y_{SALIC}	$\tilde{Y}_{\mathrm{SO_2}}$	$\tilde{Y}_{\mathrm{CO_2}}$	$\tilde{Y}_{\mathrm{NO_X}}$
1988	671.6	1320.3	133690.7	15917121	57665.0
1989	685.2	1371.7	141195.2	16600847	60173.0
1990	697.0	1400.0	137864.9	16147149	57361.6
1991	723.7	1412.2	135269.8	16005175	56489.8
1992	705.8	1429.8	131928.5	15899603	54820.4
1993	751.5	1468.0	129788.6	16372633	55903.1
1994	757.6	1512.9	122010.2	16390949	53374.0
1995	789.2	1547.0	99771.3	16259466	52353.9
1996	808.5	1578.0	106228.7	17042418	55511.4
1997	803.5	1612.3	109588.5	17694204	57010.7
1998	845.4	1650.3	101956.3	20365926	57531.8
1999	903.0	1762.3	97846.8	21035890	58636.0
2000	935.2	1785.1	93913.2	21868134	59789.8
2001	963.9	1802.5	91808.4	21020438	36360.8
2002	973.1	1727.0	89818.1	20656698	36836.7
2003	981.1	1717.5	88446.3	20369512	35975.3
2004	996.1	1776.8	91267.0	20956468	38734.1
2005	1041.6	1798.8	96342.2	21821084	54388.3

Notes: X_{FUEL} is the heat content in mmBtu. X_{CAPITAL} is the expenditure on capital (in \$10,000) divided by the yield of the utility's latest issue of long-term debt. X_{KSO2}, X_{KNOX}, and X_{KTSP} are in \$10,000. Y_{SALR} and Y_{SALIC} are in 10 millions of kilowatt hour sales. $\tilde{Y}_{\mathrm{SO_2}}$, $\tilde{Y}_{\mathrm{CO_2}}$, and $\tilde{Y}_{\mathrm{NO_X}}$ are omissions measured in tons.

I compile three new inputs, namely, annualized capital costs KSO2, KNOX, and KTSP spent on SO_2, NO_X and particulate removal devices. Since a control equipment can be used for several boilers in a power plant, I classify boilers into groups that share the same removal devices. Then I compute attributes of each group based on primary data for specific boilers from the U.S. Energy Information Administration's *Forms EIA-767 and EIA-860.* These attributes are plugged into the Integrated Environmental Control Model (IECM) developed by the Department of Engineering and Public Policy at Carnegie Mellon University to obtain KSO2, KNOX, and KTSP at group level. Finally, I aggregate them up to the utility level. Table 2.4 reports the annual averages for the quantities of all inputs and outputs.

b. Empirical Results. I standardize the data and estimate the directional distance function (2.9). Table 2.5 presents the function estimates corresponding to three alternative sets of direction vectors, following Agee, Atkinson, and Crocker (2010). In column two with an output direction vector $(g_y, -g_{\tilde{y}}) = (2, -1)$, the translation property requires a two standardized unit increase in the good outputs for every one standardized unit decrease in the bad outputs, holding all inputs constant, in order to move towards the frontier. In other words, $(g_y, -g_{\tilde{y}}) = (2, -1)$ weights an increase in good outputs twice as much as a decrease in bad outputs. I focus on the output direction vector $(g_y, -g_{\tilde{y}}) = (1, -1)$ shown in column three of Table 2.5 since I assume equal weights on increases in good outputs and reductions in bad outputs.

Before examining partial impacts among the outputs and inputs, I compute the partial derivatives of the directional distance function with respect to the outputs given in Table 2.6. They are averages weighted for electricity sales (including residential and industrial-commercial) made by utilities[2]. The directional distance function is decreasing in the good outputs, (i.e., residential and industrial-commercial electricity sales), and increasing in the bad outputs (i.e., SO_2, CO_2, and NO_X emissions). These results are consistent with the

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[2] Hereinafter, all partial effects are calculated in this way.

Table 2.5: Estimation Results

Variable	Coefficient (standard error)		
	$g_y = 2; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -2$
Outputs:			
SALIC	-0.17395	-0.28888	-0.24108
	(0.0137)**	(0.0247)**	(0.0205)**
SO_2	0.01217	0.02058	0.02410
	(0.0042)**	(0.0070)**	(0.0055)**
CO_2	0.08624	0.19067	0.17353
	(0.0076)**	(0.0115)**	(0.0084)**
NO_X	-0.01963	-0.03015	-0.01815
	(0.0053)**	(0.0089)**	(0.0071)**
$(SO_2)^2$	-0.00204	-0.00867	-0.01336
	(0.0041)	(0.0068)	(0.0054)**
$(CO_2)^2$	0.21482	0.24697	0.07436
	(0.0203)**	(0.0235)**	(0.01284)**
$(NO_X)^2$	0.00130	-0.00885	-0.01441
	(0.0047)	(0.0079)	(0.0063)**
SALR × SALIC	-0.13293	-0.13108	-0.04378
	(0.0143)**	(0.0283)**	(0.0249)*
SALIC × SO_2	0.02414	0.03557	0.02678
	(0.0074)**	(0.0127)**	(.0104)**
SALIC × CO_2	-0.01422	-0.01168	-0.00274
	(0.0125)	(0.0189)	(0.0143)
SALIC × NO_X	0.01536	0.02051	0.01526
	(0.0073)**	(0.0128)	(0.0109)
$SO_2 \times CO_2$	-0.02352	-0.02773	-0.00232
	(0.0077)**	(0.0096)**	(0.0056)
$SO_2 \times NO_X$	-0.00361	-0.00484	-0.00402
	(0.0048)	(0.0080)	(0.0063)
$CO_2 \times NO_X$	-0.01630	-0.01573	0.00267
	(0.0094)*	(0.0118)	(0.0078)
Inputs:			
FUEL	-0.03130	-0.07959	-0.08270
	(0.0082)**	(0.0133)**	(0.0102)**
LABOR	-0.01391	-0.02657	-0.02402
	(0.0041)**	(0.0069)**	(0.0055)**
CAPITAL	0.00895	0.01799	0.01385
	(0.0039)**	(0.0066)**	(0.0052)**

Variable	Coefficient (standard error)		
	$g_y = 2; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -2$
KSO2	0.01629	0.01393	0.00346
	(0.0102)	(0.0171)	(0.0136)
KNOX	-0.00563	-0.00888	-0.00108
	(0.0042)	(0.0070)	(0.0056)
KTSP	0.05820	0.10042	0.06261
	(0.0259)**	(0.0438)**	(0.0355)*
FUEL^2	0.08597	0.11243	0.05370
	(0.0150)**	(0.0227)**	(0.0165)**
LABOR^2	-0.00172	0.00170	0.00230
	(0.0031)	(0.0054)	(0.0043)
CAPITAL^2	-0.00723	-0.02098	-0.01951
	(0.0040)*	(0.0068)**	(0.0054)**
(KSO2)^2	-0.00707	-0.01450	-0.01518
	(0.0064)	(0.0108)	(0.0086)*
KNOX^2	0.02496	0.04114	0.02792
	(0.0045)**	(0.0076)**	(0.0060)**
KTSP^2	-0.01195	-0.01731	-0.01179
	(0.0093)	(0.0156)	(0.0124)
FUEL × LABOR	0.01077	0.01459	0.00289
	(0.0055)*	(0.0082)*	(0.0058)
FUEL × CAPITAL	0.03782	0.04417	0.02509
	(0.0063)**	(0.0089)**	(0.0063)**
FUEL × KSO2	0.02933	0.03543	0.01712
	(0.0079)**	(0.0125)**	(0.0090)*
FUEL × KNOX	0.01737	0.02196	0.00102
	(0.0078)**	(0.0112)**	(0.0074)
FUEL × KTSP	0.02974	0.02598	0.00303
	(0.0084)**	(0.0138)*	(0.0106)
LABOR × CAPITAL	0.00024	-0.00641	-0.01090
	(0.0029)	(0.0049)	(0.0039)**
LABOR × KSO2	0.02324	0.03663	0.02089
	(0.0040)**	(0.0066)**	(0.0053)**
LABOR × KNOX	0.00027	0.00236	0.00217
	(0.0020)	(0.0035)	(0.0029)
LABOR × KTSP	0.01078	0.00938	0.00191
	(0.0027)**	(0.0046)**	(0.0037)
CAPITAL × KSO2	0.00838	0.01419	0.01436
	(0.0035)**	(0.0059)**	(0.0047)**

Variable	Coefficient (standard error)		
	$g_y = 2; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -2$
CAPITAL × KNOX	-0.00671	-0.01021	-0.00505
	(0.0027)**	(0.0046)**	(0.0037)
CAPITAL × KTSP	0.00210	-0.00110	-0.00065
	(0.0036)	(0.0060)	(0.0048)
KNOX × KTSP	0.00844	0.01349	0.00285
	(0.0047)*	(0.0082)*	(0.0067)
KNOX × KSO2	-0.01303	-0.02053	-0.01567
	(0.0023)**	(0.0039)**	(0.0032)**
KTSP × KSO2	-0.00039	0.00470	0.00877
	(0.0045)	(0.0074)	(0.0059)
Interaction terms among Inputs and Outputs:			
FUEL × SALIC	-0.01399	0.00513	0.00193
	(0.0141)	(0.0214)	(0.0154)
FUEL × SO_2	0.03721	0.06938	0.05167
	(0.0098)**	(0.0144)**	(0.0098)**
FUEL × CO_2	-0.16882	-0.24292	-0.12721
	(0.0157)**	(0.0207)**	(0.01313)**
FUEL × NO_X	0.01857	0.03780	0.02536
	(0.0129)	(0.0183)**	(0.0123)**
LABOR × SALIC	0.00786	0.01629	0.01560
	(0.0056)	(0.0096)*	(0.0079)*
LABOR × SO_2	-0.00364	-0.01315	-0.01623
	(0.0029)	(0.0049)**	(0.0039)**
LABOR × CO_2	-0.00923	-0.00173	0.01360
	(0.0059)	(0.0083)	(0.0058)**
LABOR × NO_X	-0.00320	-0.00412	-0.00142
	(0.0036)	(0.0061)	(0.0049)
CAPITAL × SALIC	-0.02481	0.00539	-0.04658
	(0.0048)**	(0.0081)**	(0.0066)**
CAPITAL × SO_2	-0.00481	-0.00929	-0.01209
	(0.0036)	(0.0060)	(0.0048)**
CAPITAL × CO_2	-0.01031	0.00061	0.00669
	(0.0052)**	(0.0075)	(0.0057)
CAPITAL × NO_X	-0.00372	0.00368	0.00742
	(0.0038)	(0.0064)	(0.0050)
KSO2 × SALIC	-0.04275	-0.04927	-0.02403
	(0.0086)**	(0.0147)**	(0.0123)**
KSO2 × SO_2	-0.00105	-0.00229	-0.00256
	(0.0022)	(0.0037)	(0.0030)

Variable	Coefficient (standard error)		
	$g_y = 2; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -1$	$g_y = 1; -g_{\tilde{y}} = -2$
KSO2 × CO_2	-0.01287	-0.00954	0.00213
	(0.0056)**	(0.0074)	(0.0045)
KSO2 × NO_X	-0.00302	-0.00705	-0.00840
	(0.0030)	(0.0051)	(0.0041)**
KNOX × SALIC	0.00525	0.00536	0.00525
	(0.0047)	(0.0084)	(0.0070)
KNOX × SO_2	0.00544	0.00766	0.00272
	(0.0032)*	(0.0054)	(0.0043)
KNOX × CO_2	-0.02991	-0.03509	-0.00986
	(0.0065)**	(0.0084)**	(0.0054)*
KNOX × NO_X	0.00650	0.00353	-0.00056
	(0.0032)**	(0.0054)	(0.0044)
KTSP × SALIC	0.00033	-0.02045	-0.00938
	(0.0131)	(0.0226)	(0.0190)
KTSP × SO_2	-0.00770	0.00395	0.01697
	(0.0061)	(0.0100)	(0.0075)**
KTSP × CO_2	-0.00842	-0.01448	-0.01381
	(0.0062)	(0.0096)	(0.0072)*
KTSP × NO_X	-0.00205	-0.00150	0.00037
	(0.0037)	(0.0064)	(0.0051)
Time:			
TIME	0.00577	0.01021	0.00814
	(0.0003)**	(0.0006)**	(0.0005)**
Industry Restructuring:			
RE	-0.01535	-0.02371	-0.01987
	(0.0043)**	(0.0072)**	(0.0058)**
RE × KNOX	-0.00933	-0.01998	-0.01660
	(0.0040)**	(0.0067)**	(0.0053)**
RE × KTSP	0.00567	0.01442	0.01470
	(0.0051)	(0.0086)*	(0.0069)**
RE × KSO2	0.00798	0.02110	0.01868
	(0.0045)*	(0.0074)**	(0.0059)**

Notes: Estimated utility dummies are not reported in this table.

** (*) denotes significance at the 0.05 (0.10) level.

Table 2.6: Partial Derivatives of the Directional Distance Function with Respect to Outputs (Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

Good Outputs:	$\partial \overrightarrow{D}_0 / \partial y$
SALR	-0.73043
SALIC	-0.33642
Bad Outputs:	$\partial \overrightarrow{D}_0 / \partial \tilde{y}$
SO_2	0.06340
CO_2	0.00230
NO_X	0.00115

Note: These partial derivatives are averages weighted for electricity sales (including residential and industrial-commercial) by utilities.

properties D3 and D4 stated above.

In addition, the directional distance function is decreasing with industry restructuring. This variable has an average partial effect of -0.0241. It implies that, in markets where electricity prices are no longer set by state regulators but determined by competitive markets instead, deregulated utilities are closer to the frontier. The discipline of competitive markets improves their performance, as expected. However, the partial effect of restructuring on KNOX is different from Fowlie's findings (see Table 2.7). While below-average utilities (with KNOX below average) in deregulated markets tend to invest 20 percent less on NO_X control equipment, above-average utilities (with KNOX above average) tend to invest 50.7 percent more. The story for KTSP is the opposite. Restructuring induces below-average utilities to spend 2.66 percent more and above-average utilities to spend marginally 0.87 percent less on particulate control systems. However, for the whole sample, restructuring increases annualized capital costs for NO_X, particulate, as well as SO_2 removal devices. Further, as a result of restructuring, these utilities reduce their residential and industrial-commercial electricity sales by 0.06 and 0.87 percent, respectively.

Table 2.7: Partial Effects of Restructuring (percent)
(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

	Below-average utilities	Above-average utilities	All utilities
$\frac{\partial \text{KNOX}}{\partial \text{RE}}$	-19.97	50.74	5.01
$\frac{\partial \text{KSO2}}{\partial \text{RE}}$	25.14	5.33	18.49
$\frac{\partial \text{KTSP}}{\partial \text{RE}}$	2.66	-0.87	1.26
$\frac{\partial \text{SALR}}{\partial \text{RE}}$	-0.20	0.02	-0.06
$\frac{\partial \text{SALIC}}{\partial \text{RE}}$	-0.93	-0.84	-0.87

As power plants face more and more stringent environmental regulations on emissions, they have to switch to 'greener' fuels or technologies, install more expensive removal devices, buy emission permits whose overall limits are decreasing, reduce plant utilization, or even stop generation. Either compliance strategy means that they operate increasingly farther from the best-practice frontier than in the absence of these restraints. This is reflected by a positive and significant estimate of 0.010 for the time variable.

Regarding partial effects among the outputs, the estimated coefficients of the quadratic function between SALR, SALIC, SO_2, CO_2, and NO_X emissions indicate that these good and bad outputs may be substitutes or complements. Table 2.8 shows that a 10 percent increase in residential electricity sales is associated with a reduction of 39.7 percent in industrial-commercial electricity sales for below-average utilities (with both SALR and SALIC below average) and a reduction of 21.5 percent for above-average utilities (with both SALR and SALIC above average)[3]. These two good outputs are understandably substitutable since electricity generated is sold for either residential or industrial-commercial usage. CO_2 and SO_2 emissions are also substitutable for two groups of utilities. However, taking into account utilities having one emission below average and the other emission above average, CO_2 and

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[3] Utilities with one quantity above average and one quantity below average are excluded in the following comparisons.

Table 2.8: Partial Effects Among Outputs
(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

	Below-average utilities	Above-average utilities	All utilities
Good Outputs			
$\frac{\partial \text{SALIC}}{\partial \text{SALR}}$	-3.97	-2.15	-2.83
Bad Outputs			
$\frac{\partial CO_2}{\partial SO_2}$	-0.01	-0.01	0.01
$\frac{\partial NO_X}{\partial CO_2}$	7.36	7.59	7.29
$\frac{\partial NO_X}{\partial SO_2}$	0.13	0.39	0.32
Bad vs. Good Outputs			
$\frac{\partial SO_2}{\partial \text{SALR}}$	1646.83	26.69	439.74
$\frac{\partial SO_2}{\partial \text{SALIC}}$	517.20	7.30	121.47
$\frac{\partial CO_2}{\partial \text{SALR}}$	4.34	2.53	3.11
$\frac{\partial CO_2}{\partial \text{SALIC}}$	1.32	0.70	0.80
$\frac{\partial NO_X}{\partial \text{SALR}}$	-34.74	-17.02	-25.32
$\frac{\partial NO_X}{\partial \text{SALIC}}$	-15.57	-2.53	-6.56

SO_2 emissions are complementary for the whole sample[4]. NO_X emissions have a complementary relationship with CO_2 and SO_2 emissions for both groups of utilities and for the whole sample.

I also compute the partial effects of SALR and SALIC on SO_2, CO_2, and NO_X emissions. Larger SALR and SALIC sales typically raise SO_2 and CO_2 emissions, but their impacts on SO_2 emissions vary greatly across two groups. Ten percent increases in SALR and SALIC boost SO_2 emissions from below-average utilities by 16468 and 5172 percent, respectively. Meanwhile, SO_2 emissions from above-average utilities rise by 267 and 73 percent. However, higher SALR and SALIC tend to reduce NO_X emissions.

Now I consider the partial impacts of the inputs on the outputs in Table 2.9. Holding other things constant, an expansion in capital generally decreases residential but increases

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[4] Utilities that do not belong to either below- or above-average group can make partial effects for the whole sample not lie between partial effects for the two groups and even have opposite signs.

Table 2.9: Partial Effects of Inputs on Outputs
(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

	Below-average utilities	Above-average utilities	All utilities
Good Outputs			
$\frac{\partial \text{SALR}}{\partial \text{CAPITAL}}$	0.02	-0.18	-0.08
$\frac{\partial \text{SALIC}}{\partial \text{CAPITAL}}$	0.07	0.07	0.05
$\frac{\partial \text{SALR}}{\partial \text{FUEL}}$	-0.15	-0.93	-0.47
$\frac{\partial \text{SALIC}}{\partial \text{FUEL}}$	-0.64	0.36	-0.004
$\frac{\partial \text{SALR}}{\partial \text{LABOR}}$	-0.03	-0.27	-0.15
$\frac{\partial \text{SALIC}}{\partial \text{LABOR}}$	-0.17	0.004	-0.06
Bad Outputs			
$\frac{\partial \text{SO}_2}{\partial \text{KSO2}}$	34.72	-0.74	8.50
$\frac{\partial \text{SO}_2}{\partial \text{KNOX}}$	14.45	-1.09	5.37
$\frac{\partial \text{SO}_2}{\partial \text{KTSP}}$	-96.10	-1.63	-40.60
$\frac{\partial \text{NO}_\text{X}}{\partial \text{KSO2}}$	1.48	-1.83	-0.25
$\frac{\partial \text{NO}_\text{X}}{\partial \text{KNOX}}$	-0.81	2.40	0.20
$\frac{\partial \text{NO}_\text{X}}{\partial \text{KTSP}}$	3.84	-1.39	2.73
$\frac{\partial \text{CO}_2}{\partial \text{KSO2}}$	-0.01	0.42	0.06
$\frac{\partial \text{CO}_2}{\partial \text{KNOX}}$	0.09	-0.30	-0.04
$\frac{\partial \text{CO}_2}{\partial \text{KTSP}}$	-0.28	-0.39	-0.27

Table 2.10: Average Utility Technical Efficiencies
(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

	Technical Efficiency Score	
Year	Mean	Std. Dev.
1988	0.87291	0.00154
1989	0.89189	0.00115
1990	0.91125	0.00082
1991	0.93141	0.00054
1992	0.95186	0.00032
1993	0.96438	0.00016
1994	0.97450	0.00008
1995	0.97693	0.00008
1996	0.96444	0.00014
1997	0.95219	0.00028
1998	0.94113	0.00042
1999	0.93083	0.00059
2000	0.93066	0.00065
2001	0.95439	0.00047
2002	0.94087	0.00056
2003	0.93089	0.00076
2004	0.92090	0.00099
2005	0.91107	0.00122

Table 2.11: Average Utility PC, TC, and EC
(Direction: $g_y = 1, -g_{\tilde{y}} = -1$)

Year	PC	TC	EC
1989	0.03343	0.01344	0.01914
1990	0.03404	0.01307	0.01965
1991	0.03424	0.01264	0.02012
1992	0.00920	0.01223	0.02065
1993	0.00960	0.00335	0.01254
1994	0.00955	-0.00009	0.01013
1995	-0.00123	-0.00833	0.00244
1996	-0.03353	-0.02412	-0.01249
1997	-0.03437	-0.02459	-0.01226
1998	-0.03751	-0.02495	-0.01186
1999	-0.03662	-0.02526	-0.01144
2000	-0.03703	-0.01332	0.00012
2001	0.07122	0.00984	0.02291
2002	-0.02867	-0.02446	-0.01020
2003	-0.02870	-0.02502	-0.01006
2004	-0.02835	-0.02531	-0.00994
2005	-0.02833	-0.02567	-0.00982

industrial-commercial electricity sales slightly. Increases in fuel and labor lead to small reductions in electricity sales. As these power generating facilities invest 10 percent more on SO_2 control equipment, their SO_2 emissions decrease only for above-average utilities by 7.4 percent but strikingly increase for below-average utilities by 347.2 percent. Hence, for the whole sample, SO_2 emissions rise by 85 percent. The same holds for NO_X control equipment, although its partial effects on NO_X emissions on both groups are reversed. However, larger KTSP installations cut down SO_2 emissions greatly, especially for below-average utilities. In addition, increases in KTSP and KNOX help curb CO_2 emissions marginally.

Table 2.10 provides estimated technical efficiencies for the direction vector $(1, -1)$ for the good and bad outputs. Technical efficiencies are computed using equation (2.18). The weighted-average technical efficiency of the 78 utilities in 1988 is 0.87. This measure implies that if the average utility that year were to combine its inputs as effectively as the best-practice utility, then its electricity sales (SO_2, CO_2, and NO_X emissions) would increase (decrease) by about 15 percent ($1/0.87 = 1.15$). Between 1988 and 1995, average technical efficiency rose from 0.87 to 0.98, but at a decreasing rate. However, after Phase I of the Acid Rain Program came into effect in 1995, the average technical efficiency started to decline at an increasing rate, from 0.96 in 1996 to 0.93 in 2000. The downward trend reversed in 2001 and then continued its momentum afterwards. The short improvement in technical efficiency in 2001 is probably attributed to previous adjustments by these utilities to comply with earlier requirements to reduce emissions. By then, several utilities had even stopped their electricity generation. However, this improvement was quickly undermined by stricter environmental regulations.

Table 2.11 displays average PC, TC, and EC, which are calculated using expressions (2.21), (2.20), and (2.19). Technical change, which measures the shift in the production frontier, exhibits a pattern of change similar to that of technical efficiency. The frontier first shifted outward at a decreasing rate, but began shifting inward in 1994, earlier than the trend decrease in technical efficiency. The inward shift was also interrupted in only 2001. The resulting PC, which is the sum of TC and EC, closely resembles them. The average utility tended to experience declining productivity over time.

2.5 Conclusions

This chapter estimates a multiple-input, multiple-output directional distance function for electric utilities. Estimation is carried out using a panel of 78 utilities spanning from 1988 to 2005 with three alternative sets of direction vectors. During this period, the electric power industry underwent remarkable changes in environmental regulations and a wave of restructuring. The utilities in the sample utilize six inputs (i.e., fuel, labor, capital for generation, and capital investments for SO_2, NO_X and particulate removal devices) to produce two good outputs (i.e., residential and industrial-commercial electricity sales), and three bad outputs (i.e., SO_2, CO_2, and NO_X emissions).

Increases in annualized capital costs spent on SO_2 and NO_X control equipment do not reduce SO_2 and NO_X emissions, respectively. However, expansions of KTSP cut down SO_2 emissions remarkably. And increases in KTSP and KNOX help curb CO_2 emissions marginally. While residential and industrial-commercial electricity sales are substitutable, SO_2, CO_2, and NO_X emissions are generally complementary. In addition, larger electricity sales are likely to increase SO_2 and CO_2 emissions but decrease NO_X emissions.

This research finds that restructuring has improved the utilities' performance. Below-average utilities in deregulated markets tend to invest less on NO_X and more on particulate control equipment, but their above-average counterparts do the opposite. However, deregulated utilities generally have more investments for these two as well as SO_2 control systems. Moreover, they reduce their electricity sales slightly. I also find that the utilities' production technologies have moved farther from the frontier over time. This is confirmed by the fact that the average technical efficiency started to decline at an increasing rate in 1996. Moreover, the frontier itself has shifted inward since 1993 (except for 2001). This declining productivity is probably attributed to more stringent environmental regulations.

Chapter 3

Did the U.S. Tobacco Industry become more collusive after the Master Settlement Agreement?

3.1 Introduction

November 17th, 1998 marked a milestone in the history of the U.S. tobacco industry when the four largest cigarette companies and the attorneys general of 46 states, as well as of the District of Columbia, Puerto Rico, and the Virgin Islands, entered into the Master Settlement Agreement (MSA). The settlement arose in response to a mushroom in tobacco relevant litigation of three major categories, that is, individual personal injury cases, class action personal injury, and health care cost recovery. The rapidly growing number of cases was partly due to the diffusion of stolen documents from Brown & Williamson with hidden information about the health effects of smoking in 1995 (Mollenkamp et al., 1998), the potential payoff to plaintiffs and their lawyers from filing suits, and the seemingly reasonable cause of ending youth smoking. Therefore, these companies faced a very real threat of bankruptcy.

Under the Agreement, the tobacco companies would pay $206 billion in damages to the states over the next twenty five years to compensate them for the costs of providing medical services to persons with smoking-related illnesses, plus billions more in contingency fees to the lawyers, and conform to significant marketing restrictions. In exchange, the companies would be exempted from private tort liability regarding the harmful effects of smoking. However, they worried that they would lose profits and their market shares to other small cigarette manufacturers who were outside the lawsuit and were free to enter the market or increase their sales with lower prices. This fear was lifted as approximately 41 non-settling companies were forced to join the MSA and did not have to pay damages unless they increased their market shares above their 1998 shares or 125 percent of their 1997 shares, whichever was higher.

As a consequence, the big tobacco companies were provided not only legal but also business protection. They were tempted to negotiate price increases in order to pass much of the costs of the settlement onto consumers who receive nothing of value from the settlement but have to pay more. Therefore, it is very interesting to examine whether the tobacco industry became more collusive after the MSA in 1998. In other words, are there any significant changes in the market structure of the industry before and after 1998? Based on the nonparametric tests of Ashenfelter and Sullivan (1987), I find that the tobacco industry has indeed become more collusive after the introduction of the MSA. Their responses to excise tax changes follow much more closely monopoly model predictions in the post-1998 period. Specifically, when the real tax rates increased, the tobacco companies raised their prices after 1998 much more frequently. Strikingly, even when the nominal tax rates remained constant, they pushed up their prices faster than the national consumer price index for 76.7% of the time.

This chapter is structured as follows. Section 3.2 gives a brief overview of the U.S. tobacco industry and the Master Settlement Agreement. Section 3.3 presents the nonparametric tests, which are applied in section 3.4 to the data on the tobacco industry. Conclusions follow in section 3.5.

3.2 The U.S. Tobacco Industry and the MSA

Since the early 20th century, the U.S. tobacco industry has been characterized by a tight oligopoly. The four major companies (i.e., Philip Morris, R.J. Reynolds, Brown & Williamson, and Lorillard) produced 98.6 percent of the market in 1997. Table 3.1 shows the sales and profits of the five leading companies.[1] The industry on average enjoyed an enormous profit margin of 38 percent. This results from supra-competitive prices, which are in line with most economic models of oligopoly behavior. However, margins varied across companies because they had different positions in the three segments of the market, namely, premium, discount, and the deep discount cigarettes. According to Bulow and Klemperer (1998), while average costs of manufacturing premium cigarettes were only a few cents a pack higher than those of manufacturing discounts, wholesale prices for premiums were 16.5 cents higher than for discounts and 32 cents higher than for deep discounts. Large price differentials imply that the industry's profits were mostly from the premium brands which accounted for 73 percent of total sales (Table 3.2). The strong position of Lorillard in this attractive segment helped explain why it, with a market share of 9 percent, was nearly as profitable as Philip Morris.

The ability of cigarette manufacturers to set prices above competitive levels is also attributed to inelastic demand and barriers to entry. The elasticity of demand by adults for cigarettes is widely estimated to be in the vicinity of -0.4.[2] Since a 1 percent rise in the cigarette price is associated with a 0.4 percent fall in the number of cigarettes sold,

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[1] The fifth largest company is Liggett with a 1.3 percent share. The rest of the market included over 100 fringe companies and importers that in total had 0.1 percent of the market.

[2] Manley et al. (1993) reported the consensus range of elasticity estimates of -0.3 to -0.5. from an expert panel convened by the National Cancer Institute.

Table 3.1: Sales and Profits by Company

Company	Unit Sales (billions of cigarettes)	Market Share (percent)	Operating Revenues ($ million)	Operating Profits ($ million)	Profit as Percent of Revenue
Philip Morris	235	49.2	10,663	4,824	45
R.J. Reynolds	117	24.5	4,895	1,510	31
Brown & Williamson	77	16.2	3,114	801	26
Lorillard	42	8.7	1,915	777	41
Liggett	6.5	1.3	235	20	9
Industry	478	100	20,822	7,932	38

Source: Bulow and Klemperer (1998).

the companies would tend to raise prices further, especially when excise taxes increase. In spite of a significant increase in price, most adult customers not only continue to smoke but also become loyal to a particular brand. In the Report of the Surgeon General (1989), around 10 percent of smokers switch their brands annually, but often to other brands of the same cigarette company. The strong brand loyalty of most consumers and restrictions on advertising effectively block large-scale entry and rapid expansion by new or small companies. As they are not able to inform consumers about the availability and the attributes of their brands, they are not likely to exert a significant constraint on the behavior of the big companies.

Tobacco companies faced a flow of litigation since the mid-1950s when individuals began to sue the companies based on negligence claims in manufacture, advertising, and consumer protection. Up till 1994, more than 800 private lawsuits were brought against tobacco companies across the U.S. But the tobacco companies won all these cases. However, the balance was tipped against the companies when over 4,000 pages of documents stolen from Brown & Williamson with hidden information about the health effects of smoking were copied and distributed anonymously before posted on the web in July 1995 by University of

Table 3.2: Product Mix and Profitability by Company

Company	Percentage of Sales in Premium Segment	Revenue per Pack	Costs per Pack	Profits per Pack
Philip Morris	86	\$0.91	\$0.50	\$0.41
R.J. Reynolds	63	\$0.84	\$0.58	\$0.26
Brown & Williamson	43	\$0.81	\$0.60	\$0.21
Lorillard	94	\$0.92	\$0.55	\$0.37
Liggett	25	\$0.73	\$0.67	\$0.06
Industry	73	\$0.87	\$0.54	\$0.33

Source: Bulow and Klemperer (1998).

California professor Stanton Glantz (Mollenkamp et al., 1998). These documents invalidated the argument that health warnings had been posted on cigarette packages, hence helping plaintiffs win an individual case in Florida in 1996. This success would probably lead to a new flood of individual litigation.

In addition, the attorney general of Mississippi commenced a lawsuit against the tobacco industry in May 1994 (Janofsky, 1994). The justification was that the cigarettes produced by the tobacco industry contributed to health problems, increasing the state's expenditures for medical services provided over the years to poor smokers under the Medicaid law. Therefore, the tobacco companies were claimed to owe to the state those amounts incurred in the treatment of smoking-related illnesses. Approximately 40 states soon followed. In early 1996, Liggett, the fifth largest but on the brink of bankruptcy, broke ranks with other tobacco companies in the legal war and settled early with five states (i.e., Florida, Louisiana, Massachusetts, Mississippi, and West Virginia). Since Liggett had a small market share of 1.3 percent, these states offered it some rewards in return for its handing over secret documents on the dangers of smoking that would become the states' evidence against the other companies (Bulow and Klemperer, 1998).

The increasingly hostile legal environment forced the four largest companies to the bargaining table with the state attorneys general. On June 20th, 1997, they reached an initial agreement called the Resolution, which essentially resembled the eventual MSA. Accordingly, the tobacco companies would pay $365.5 billion to the states over 25 years in exchange for limiting future suits against the companies (Brandt, A. M., 2007). This limitation on future suits required that the Resolution be approved by Congress. In the spring of 1998, both the Resolution and an alternative proposal submitted by Senator John McCain of Arizona were rejected by Congress. Shortly after Congress's rejection, four states (Mississippi, Florida, Texas, and Minnesota) settled separately with the tobacco companies. Those settlement agreements served as models for the MSA, which was signed by the four largest tobacco companies and the attorneys general of the remaining 46 states, as well as of the District of Columbia, Puerto Rico, and the Virgin Islands, on November 17th, 1998.

In the MSA, which did not require Congressional approval, the settling companies agreed to pay $206 billion over 25 years to the states for recovery of their tobacco-related health care costs. In return, they would be exempted from private tort liability regarding the harmful effects of smoking. Annual payments were though allocated among these companies on the basis of their relative market shares as of 1997, rather than of the past damages for which they were responsible. Furthermore, if a settling company cut its price and increased its market share, its annual payments would increase proportionately and its profitability would decrease. Thus, the settling companies were not likely to compete against each other based on prices.

However, they worried that they would lose their profits and market shares drastically to other small, non-settling cigarette manufacturers who were free to enter the market or increase their sales with lower prices. The fear was lifted as the MSA effectively forced approximately 41 other companies to sign the settlement. An incentive to join the MSA was that subsequently settling companies did not make annual payments if they did not increase their market shares beyond their 1998 shares or 125 percent of their 1997 shares, whichever was higher. Otherwise, they would pay allocated amounts as the originally settling companies. The MSA also banned most forms of advertising for tobacco products in order to end youth smoking. But this set up a barrier to large-scale entry and expansion by non-settling companies.

Assigning payments in accordance with the settling companies' relative market shares and providing stringent marketing restrictions, the MSA is claimed to protect the four largest tobacco companies and to eliminate price competition at the expense of smokers. O'Brien (2000) argues that the agreement created a tobacco cartel that benefited both the government and the tobacco companies.

3.3 Nonparametric Tests

There are many empirical studies offering a set of nonparametric techniques that provide simple and illuminating analyses of the traditional questions of producer theory. In this chapter, a nonparametric test of the monopoly model developed by Ashenfelter and Sullivan (1987) based on the revealed preference approach is applied to data for the tobacco industry. The test focuses on seller reactions to changes in the excise tax imposed on a pack of cigarettes.

I now present the Ashenfelter and Sullivan (1987) model. For an industry that is a monopoly with an upward sloping total cost function $C(q)$ and a downward sloping demand function $P(q)$, the chosen level of output is q if any other level of output, $q + \Delta q$, does not gain more profits

$$(q + \Delta q)P(q + \Delta q) - C(q + \Delta q) \leq qP(q) - C(q), \tag{3.1}$$

or

$$\Delta q P(q+\Delta q) + q[P(q+\Delta q) - P(q)] \leq C(q+\Delta q) - C(q). \tag{3.2}$$

It is assumed that a change in an excise tax (t) corresponds to a change in marginal cost. Hence, the total cost function can take the form of $C(q) = C_0(q) + tq$ where C_0 increases in q.

Suppose that for two tax rates t_0 and t_1, $t_0 < t_1$, there are two corresponding output levels, q_0 and q_1, and price levels, $p_0 = P(q_0)$ and $p_1 = P(q_1)$, that maximize profits. Inequality (3.2) indicates that when the tax rate is t_0,

$$(q_1 - q_0)p_1 + q_0(p_1 - p_0) \leq C_0(q_1) - C_0(q_0) + t_0(q_1 - q_0), \tag{3.3}$$

and when the tax rate is t_1,

$$(q_0 - q_1)p_0 + q_1(p_0 - p_1) \leq C_0(q_0) - C_0(q_1) + t_1(q_0 - q_1). \tag{3.4}$$

Adding (3.3) and (3.4), I obtain

$$(t_0 - t_1)(q_1 - q_0) \geq 0. \tag{3.5}$$

Since $t_0 < t_1$, then

$$q_0 \geq q_1, \tag{3.6}$$

and

$$p_0 \leq p_1. \tag{3.7}$$

So an increase in an excise tax must raise the monopoly price and lower the monopoly output.

As the cost function is assumed to be upward sloping or $C_0(q_0) \geq C_0(q_1)$, (3.3) becomes

$$(q_1 - q_0)p_1 + q_0(p_1 - p_0) \leq t_0(q_1 - q_0), \tag{3.8}$$

or

$$q_1p_1 - q_0p_0 \leq t_0(q_1 - q_0). \tag{3.9}$$

This is the principal testable hypothesis of the monopoly model.

If the industry is instead perfectly competitive or firms in that market take the price as exogenously given, then they will select q such that

$$(q + \Delta q)P(q + \Delta q) - C(q + \Delta q) \leq qP(q + \Delta q) - C(q), \tag{3.10}$$

or

$$\Delta qP(q + \Delta q) \leq C(q + \Delta q) - C(q). \tag{3.11}$$

This implies that at other levels of output, $q + \Delta q$, extra revenue earned is not larger than extra cost.

From (3.2) and (3.11), it can be said that the industry has a monopoly index β if

$$\Delta qP(q + \Delta q) + \beta q[P(q + \Delta q) - P(q)] \leq C(q + \Delta q) - C(q) \tag{3.12}$$

holds for all Δq. The index β ranges from 0, in a perfectly competitive industry, to 1, in a monopoly industry. The higher β is, the tighter the oligopoly.

In the case of two excise taxes t_0 and t_1, if $q_0 \geq q_1$ and $p_0 \leq p_1$, then (3.12) implies

$$\beta \leq \frac{(t_0 - p_1)(q_1 - q_0)}{q_0(p_1 - p_0)}, \tag{3.13}$$

which gives the upper bound on the index β.

Suppose there are n firms having increasing cost functions $C_1(q_1)$,..., $C_n(q_n)$, and outputs q_1,..., q_n. With an excise tax t, the first-order condition across the firms indicates that

$$q(t)p'(t) + (p(t) - t)q'(t)n(t) \geq 0. \tag{3.14}$$

If $t_0 < t_1$, I have

$$\int_{t_0}^{t_1} [q(t)p'(t) + (p(t) - t)q'(t)n(t)]\, dt \geq 0. \tag{3.15}$$

If q(t) decreases and p(t) increases in t, then for t between t_0 and t_1, $q(t_0) \geq q(t) \geq 0$ and $0 \leq p(t_0) - t_1 \leq p(t) - t$, and (3.15) can become

$$\int_{t_0}^{t_1} [q_0 p'(t) + (p_0 - t_1)q'(t)n(t)]\, dt \geq 0. \tag{3.16}$$

There exists a $\tilde{t}$ between t_0 and t_1 such that

$$n(\tilde{t}) \geq \frac{q_0(p_1 - p_0)}{(t_0 - p_1)(q_1 - q_0)}, \tag{3.17}$$

which provides the lower bound on the numbers equivalent of firms in the industry.

3.4 Empirical Results

The data used in this chapter consist of the federal and state tax rates, the number of packages of cigarette sold, and the average retail price in each of 51 states from 1970 to 2003. The tax variable is the sum of the federal and state taxes for each state and year in the sample. The tax and price variables are converted to real terms by dividing by the national consumer price index.

As discussed in Ashenfelter and Sullivan (1987), deriving the predictions of the monopoly model in the previous section in inequalities (3.6), (3.7), and (3.9) is based on an implicit assumption that the demand and cost functions applied to both data points in question remained unchanged. However, all of the states might not have shared the same demand and cost functions. The predictions tested below are thus only for pairs of data points in the same state. In addition, since patterns of cigarette consumption have changed slowly in the short term but considerably over the years, predictions are restricted to pairs of data points one or two years apart. As the MSA was signed on November 17th, 1998, the sample is split into two sub-samples for years up to 1998 and after 1998 so that I can compare the tobacco companies' responses to tax changes in the two sub-periods.

Panel A in Table 3.3 shows all pairs of consecutive years in the same state, however the model seems to predict weakly. Of the 1428 changes before the adoption of the settlement, the monopoly predictions in terms of quantity, price, and revenue changes separately are correct only 31.4%, 57.4%, and 28.2%, respectively. But for those changes after 1998, the accuracy of the model improves remarkably, except for price changes. It is interesting to find that the inequality (3.9), which suggests that the revenue lost from producing a non-optimal output level is greater than the decreased tax payments associated with that level holds in percentage in the post-1998 subperiod nearly double that in the pre-1998 subperiod (i.e., 54.5% compared to 28.2%).

The first two rows in Panel A indicate that the evidence in general does not appear to support the monopoly hypothesis in the cigarette industry. It may be attributed to the possibility of measurement error. Not all pairs of consecutive years should be compared because a large number of changes in the real tax rates were caused simply by changes in the consumer price index, which is not really perfect.

Panel B implies that the monopoly model predicts for consecutive years with no changes in the statutory tax rates (shown in the last two rows) much worse than for those with statutory tax changes (in the first two rows). As continuous rises in the national consumer

Table 3.3: Correct Predictions of the Monopoly Model about Changes in Quantity, Price, and Revenue

		Number of cases	Percentage of Correct Predictions				
			$\Delta q \leq 0^a$	$\Delta p \geq 0^b$	$(3.6) - (3.7)^c$	$(3.9)^d$	$(3.6), (3.7), (3.9)^e$
Panel A							
Consecutive Years:	Pre-98	1428	31.4	57.4	28.1	28.2	7.9
	Post-98	255	49.4	57.3	42.4	54.5	26.7
Consecutive Years:	Pre-98	355	51.0	74.6	48.7	31.5	15.5
(Real Increases)	Post-98	126	78.6	92.1	72.2	51.6	45.2
Consecutive Years:	Pre-98	1073	24.9	51.6	21.2	27.0	5.4
(Real Decreases)	Post-98	129	20.9	23.3	13.2	57.4	8.5
Panel B							
Consecutive Years:	Pre-98	411	49.6	71.8	47.0	32.8	16.3
(Statutory Changes)	Post-98	126	78.6	92.1	72.2	51.6	45.2
Consecutive Years:	Pre-98	1017	24.0	51.5	20.5	26.3	4.5
(No Change)	Post-98	129	20.9	23.3	13.2	57.4	8.5
Panel C							
Skip Year Changes[f]:	Pre-98	1377	30.1	59.9	26.7	23.4	8.2
	Post-98	255	60.8	74.9	58.0	49.0	31.0
Skip Year Changes[f]:	Pre-98	210	41.9	65.2	37.1	44.3	21.0
(Flat-Jump-Flat[g])	Post-98	89	61.8	84.3	56.2	55.1	48.3

Notes: [a] Prediction based on (3.6): Quantity consumed will decrease when excise taxes increase.

[b] Prediction based on (3.7): Retail price will increase when excise taxes increase.

[c] Joint prediction that quantity decreases and retail price increases.

[d] Prediction based on (3.9): Revenue loss will be larger than the decreased tax payments.

[e] Joint prediction that changes in quantity, retail price and revenue will comply with the monopoly model.

[f] Pairs of data observations separated by 1 year.

[g] Statutory tax rates unchanged for both data observations and a statutory rise in the intervening year.

price index make the real tax rates in those years with no statutory changes decline, those cases in the last two rows of Panel B as expected compose the subgroup of consecutive years with real decreases in the tax rates in the last two rows of Panel A. And the subgroup with real increases in the tax rates in Panel A are those years with statutory changes in Panel B.

The third and fourth rows of Panel A show that when there was an increase in the real tax rates from the earlier year, the monopoly model performs very well, and substantially better for the post-1998 subperiod than for the pre-1998 subperiod, especially in terms of price changes. Retail prices were raised for 92.1% of 126 cases after the settlement was put in place, but only 74.6% of 355 cases before then. Although there are many exogenous forces, apart from the price, affecting the demand and thus the quantity consumed, the prediction that the quantity consumed should fall when the tax rates increase is correct 78.6% post-1998 and just 51% pre-1998. Hence, the two predictions are observed more strongly after 1998. So do the inequality (3.9) and all three predictions of the monopoly model in the last two columns.

In contrast, for consecutive years when there were no changes in the statutory rates or the real tax rates decreased (in the last two rows of Panels A and B), the price fell in slightly more than half of cases and in less than a quarter of cases for the pre- and post-MSA subperiods, respectively. It means that after 1998, even when the nominal tax rates remained constant, the tobacco companies did raise prices collusively faster than the consumer price index 76.7% of the time. This happened since these companies had their market shares protected by the MSA through its annual payment allocation. Therefore, as panels A and B indicate, the tobacco companies increased prices much more frequently after 1998, not only when the real tax rates rose but also when they declined.

In order to alleviate possible measurement error that may affect the influence of tax changes, pairs of data points separated by one year are compared and shown in Panel C. In general, the model predicts marginally better than it does for all consecutive years (in the

Table 3.4: Correct Predictions of the Monopoly Model for Skip Year Real Increases, Disaggregation by Size of Tax Change

		Number	Percentage of Correct Predictions				
		of cases	$\Delta q \leq 0^a$	$\Delta p \geq 0^b$	$(3.6)-(3.7)^c$	$(3.9)^d$	$(3.6),(3.7),(3.9)^e$
$\Delta t^f < 1$	Pre-98	130	44.6	55.4	40.8	56.9	20.8
	Post-98	81	95.1	93.8	90.1	61.7	55.6
$1 < \Delta t^f < 2$	Pre-98	127	67.7	87.4	66.1	37.0	32.3
	Post-98	33	100.0	100.0	100.0	72.7	72.7
$\Delta t^f > 2$	Pre-98	189	38.1	87.8	37.0	7.9	6.3
	Post-98	79	51.9	97.5	51.9	11.4	11.4

Notes: [a] Prediction based on (3.6): Quantity consumed will decrease when excise taxes increase.

[b] Prediction based on (3.7): Retail price will increase when excise taxes increase.

[c] Joint prediction that quantity decreases and retail price increases.

[d] Prediction based on (3.9): Revenue loss will be larger than the decreased tax payments.

[e] Joint prediction that changes in quantity, retail price and revenue will comply with the monopoly model.

[f] Tax change in 1977 cents.

first two rows of Panel A). For the subset of "Flat-Jump-Flat" where the rates were constant in the first year, jumped in the second year, and remained unchanged in the third year, the model's performance improves a little. Though, the decomposition of "Skip Year Changes" data for increases and decreases in the real tax rates (which is not reported) is similar to that in Panel A.

Table 3.4 displays how the inequalities (3.6), (3.7), and (3.9) work according to the size of the tax changes. As the cigarette companies pushed up their prices for the majority of the cases when the real tax rates fell, attention is restricted to the subgroup where there was an increase in the real tax rates. As the tax change increases from under to over 1 cent (in 1977 dollars), the post-1998 subperiod exhibits a very impressive outcome. Nearly all of the two predictions on the quantity consumed and the price are true, whereas the inequality (3.9) holds for 62% and 73%. In years up till 1998, the percentages of correct predictions rise along with the real tax rates, though much lower than those after 1998. However, for the tax

Table 3.5: Predictions of Different Oligopoly Models for Skip Year Real Increases

Numbers Equivalent	Percentage of Cases Consistent with Numbers Equivalent[a] Skip Year Changes $\Delta q \leq 0$ & $\Delta p \geq 0$ Pre-1998 (207 Cases)	 Post-1998 (147 Cases)
N = 1	38.6	53.1
N = 2	73.4	89.8
N = 3	82.6	94.6
N = 4	86.0	95.2
N = 5	89.4	95.9
N = 6	92.3	96.6
N = 7	93.2	96.6
N = 8	94.7	97.3
N = 9	95.2	98.6
$N = \infty$	100.0	100.0

Note: [a] Consistency means that the inequality (3.17) $n(\tilde{t}) \geq \frac{q_0(p_1-p_0)}{(t_0-p_1)(q_1-q_0)}$ holds for the indicated numbers equivalent of firms.

change greater than 2 cents, the model predicts well only in price changes. As the tobacco companies raised their prices in response to high jumps in the tax rates, smokers failed to cut back their consumption in more than half cases, thus making these firms over 90% of the time incur increases in the tax payments that were bigger than the gains in revenue received.

Table 3.5 presents the degree of consistency of alternative oligopoly models with higher numbers equivalent of firms in light of the "Skip Year Real Increases" data. The inequality (3.17) is derived based on the assumptions that quantity decreases and price increases when the tax rates rise. Hence, only pairs of data points that satisfy these conditions are considered. Table 3.5 indicates that the monopoly model (with 1 firm equivalent) is consistent with more or less half of the cases in the two subperiods. Roughly 90% of the data points can be explained by models with numbers equivalent in excess of 5 for the pre-1998 subperiod and 2 for the post-1998 subperiod. The small number equivalent for the latter subperiod seems to suggest that a duopoly model be examined instead, which should be proceeded with caution since the two conditions above held in only 55.4% of the cases. However, it can be concluded that the model used in the tobacco industry should contain some extent of competition.

3.5 Conclusions

Starting in the mid-1950s, the flow of tobacco relevant litigation surged in the 1990s as the attorneys general of more than 40 states commenced lawsuits against the industry for recovery of their expenditures for medical services provided to poor smokers under the Medicaid law. The prospect of going bankrupt loomed large after the diffusion of over 4,000 pages stolen from Brown & Williamson and Liggett's handing over secret documents with information about the dangers of smoking which would become the states' evidence against the four largest companies. These companies in response negotiated with the states and came up with the Master Settlement Agreement in November 1998. The settlement required that the tobacco companies pay $206 billion to the states over the next twenty five years, plus billions more in contingency fees to the lawyers in exchange for exemption from private tort liability regarding the harmful effects of smoking. However, as the MSA effectively enforced about 41 other companies to join the settlement with annual payments allocated among the tobacco companies in accordance with their relative market shares and stringent marketing restrictions, it is claimed that the MSA helped create a tobacco cartel.

Using the nonparametric tests developed by Ashenfelter and Sullivan (1987), I find strong evidence in support of the above claim. Specifically, when the real tax rates increased, the tobacco companies raised their prices after 1998 much more frequently than before the adoption of the settlement. Strikingly, even when the nominal tax rates remained constant, they pushed up prices collusively faster than the consumer price index for the majority of the time. In addition, it seems that the number equivalent of firms in the industry dropped significantly between the pre-1998 subperiod and the post-1998 subperiod. And the monopoly model should be extended to contain some extent of competition.

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