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BENCHMARKING AND INCENTIVE REGULATION OF QUALITY OF SERVICE: AN APPLICATION TO THE UK ELECTRICITY DISTRIBUTION UTILITIES

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Abstract

Quality of service has emerged as an important issue in post-reform regulation of electricity distribution networks. Regulators have employed partial incentive schemes to promote cost saving, investment efficiency, and service quality. This paper presents a quality-incorporated benchmarking study of the electricity distribution utilities in the UK between 1991/92 and 1998/99. We calculate technical efficiency of the utilities using Data Envelopment Analysis technique and productivity change over time using quality-incorporated Malmquist indices. We find that cost efficient firms do not necessarily exhibit high service quality and that efficiency scores of cost-only models do not show high correlation with those of quality-based models. The results also show that improvements in service quality have made a significant contribution to the sector's total productivity change. In addition, we show that integrating quality of service in regulatory benchmarking is preferable to cost-only approaches.

Keywords: quality of service, benchmarking, incentive regulation, data envelopment analysis, electricity

JEL Classification: L15, L51, L94

Benchmarking and Incentive Regulation of Quality of Service:
An Application to the UK Electricity Distribution Utilities

1. Introduction

Since the 1990s, many regulators of infrastructure industries around the world have, as part of the reform initiatives, replaced the traditional rate-of-return regulation of the natural monopoly activities with incentive regulation models. The aim of the incentive regulation is to promote efficiency improvements in the absence of market mechanisms. Such schemes have in particular been popular in the regulation of electricity transmission and distribution networks (Jamasb and Pollitt, 2001).

Against this background, appropriate regulation of quality of service in the reformed industries is increasingly emerging as an important issue. Quality of service comes at a cost and there is a concern that the pursuit of profit incentives by utilities may have an adverse effect on quality of service. Moreover, as a non-tradable product, the resultant quality level tends to deviate from the socio-economic optimum. Recent electricity blackouts in the US and Europe suggest that the economic importance and social value of quality of service is higher in the electricity transmission and distribution networks than in most other industries.

At the same time, innovations in regulation of quality of service have lagged behind the incentive regulation schemes for achieving cost efficiency. The potential trade-off between cost savings and the quality of service necessitates adoption of economically efficient schemes. While some regulators have used benchmarking methods in cost (partial or total) regulation of networks, these have not been extended to regulation of their quality of service.

All stakeholders in the electricity sector can potentially benefit from comparative studies that take into account quality of supply. First, regulators are better informed to set targets for quality delivery and provide companies with incentives to achieve them.

Second, firms can compare their performance against the rest of the sector and identify any weaknesses relative to best practice. Third, electricity consumers can evaluate the standards of service they receive. To our knowledge, no other empirical productivity analysis or regulatory benchmarking studies have incorporated or focused on quality of service aspect of electricity distribution networks. In this paper, by means of an empirical analysis of UK electricity distribution utilities, we attempt to demonstrate whether it is desirable to incorporate quality of service into benchmarking of electricity networks.

This paper presents a benchmarking study of the 14 Distribution Network Operators (DNOs) in the UK for the period between 1991/92 and 1998/99. We calculate quality-incorporated measures of technical efficiency using Data Envelopment Analysis (DEA). We then calculate Malmquist productivity change indices for the sector's performance for the same period. Section 2 discusses the main concepts in price and quality regulation in electricity distribution networks. Section 3 presents the regulation of the electricity distribution sector in the UK. Section 4 summarises the methodology of DEA and Malmquist indices. Section 5 describes the data and DEA models used in the study. Section 6 presents the results. Section 7 is conclusion.

2. Regulation of Electricity Distribution

The paradigm of electricity sector liberalisation systems separates the basic functions of electricity generation, transmission, distribution, and supply (or retailing). Generation plants produce electricity, which is transmitted at high voltage, via the transmission grid, to bulk supply points of low-voltage distribution networks. The networks deliver electricity to industrial, commercial, and residential consumers. The supply function or retailing of electricity can be performed independently of its physical distribution, in which case consumers contract with supply companies that are not necessarily network owners. Generally, while the generation and supply functions can be potentially competitive, the transmission and distribution activities are subject to regulation.

Electricity distribution is prone to market failures caused by market power, imperfect information, externalities and joint provision and consumption (Baker and Trémolet, 2000). First, due to economies of scale (also rendering duplication of infrastructure uneconomical), distribution networks exhibit natural monopoly characteristics. Second, electricity distribution involves the production of `experience goods', such as service quality, which the public might be poorly informed of prior to their actual consumption. Third, there exist external effects, such as environmental pollution and health and safety risks to non-users of networks. Fourth, electricity is, to a large extent, jointly provided and consumed, which means that consumers are unlikely to receive an individually optimal service. These arguments have led to the view that regulation of electricity distribution is more efficient than the outcome of the free market.

2.1 Benchmarking and Incentive Regulation of networks

Benchmarking has become a widely used tool in incentive-based regulation of utilities. Broadly, benchmarking can be defined as comparison of some measure of actual performance against a reference or benchmark performance (Jamasb and Pollitt, 2001). Benchmarking treats firms as production entities, which transform inputs (possibly subject to exogenous factors) into outputs. The variables used in the analysis can be in either physical or monetary; monetary inputs are generally preferable in a regulatory context. Regulators generally do not have sufficient information to establish the efficient level of the regulated firms' costs. Under the assumption that cost data of a group of firms are mutually informative, benchmarking is used to infer the level of attainable costs and in setting the X-factors within periodic price control reviews.

The main benchmarking methods can be classified as either average or frontier-oriented (Jamasb and Pollitt, 2001). The former compare firms against some average level of performance, while the latter measures their performance against the efficient frontier or best practice. The average-based methods lend themselves to the notion of yardstick regulation first proposed in Shleifer (1985). The main average-based methods are ordinary least squares (OLS) and total factor productivity (TFP), while DEA, corrected ordinary least squares (COLS) and stochastic frontier analysis (SFA) are the most widely used frontier-based techniques.[1]

From a regulatory perspective, frontier methods can be used as instruments to close performance gaps at the preliminary phases of regulatory reforms. Average-based approaches are best suited to introduce competition between homogeneous firms. Frontier-oriented techniques typically require more data and relatively large samples of firms to yield robust results.

The benchmarking methods and how the results are used in price controls can differ according to the particular circumstances of each country. For example, in Norway, where the number of utilities is large (approximately 180), the regulator uses the DEA technique and directly converts the benchmarking scores into price caps. In New South Wales, there exist only six distribution companies and no formalised procedure to infer X-factors from efficiency scores has been defined. In the UK, the regulator has applied the regression-based techniques COLS to a relatively small set of 14 utilities.

2.2 Regulation of Service Quality

As mentioned, the relationship between cost efficiency and service quality in deregulated electricity sectors has emerged as a major regulatory issue. Quality of service is important for residential, commercial and industrial customers alike, not least because many functions of modern society critically depend on electricity. However, improving upon a given level of quality of service comes at a cost. At the same time, under the prevalent incentive-based regulatory schemes, electricity utilities face strong incentives to undertake cost savings. This has raised a question as to whether companies respond to cost saving incentives by reducing service quality, rather than by pursuing real efficiency improvements.

[1] See Coelli et al. (1998) for a review of these techniques.

The concern surrounding the impacts of incentive regulation on service quality has been recognised ever since price cap regulation was first implemented as part of the British telecommunication industry restructuring (Waddams Price et al., 2002). However, it was not until recent years that regulators' interest in quality-related issues has surged. Evidently, reforms progressively evolve beyond pure cost efficiency considerations to encompass non-marketable aspects of electricity distribution networks.

In an idealised competitive electricity market, customers would be able to choose a network provider offering a level of service quality that reflected their willingness to pay for it. Assuming that the maximum amount that consumers would pay for quality equals the total quality-induced costs they incur, the socio-economic optimum occurs at a quality level where the sum of the total cost of quality provision by network operators and the total quality-induced costs faced by consumers is minimised. However, in the absence of (incentive) regulation, natural monopolies such as electricity distribution utilities may operate at sub-optimal quality and social cost level. Therefore, in order to prevent inefficient allocation of resources, service quality standards and incentives need to be incorporated in the regulation of the utilities.

In designing quality-incorporated regulatory mechanisms, regulators are faced with the task of determining a market demand curve for service quality. This procedure involves defining appropriate quality measures and subsequently ascertaining how much consumers value them. Robert (2001) identifies the criteria that must be satisfied by service quality measures as being: (i) importance to consumers, (ii) controllability by network operators and (iii) measurability by regulators. Consumer valuation is hindered by inconsistency, context-dependence and insufficiency of information: Individuals often give non-credible responses to surveys (due to free rider effects, for example) and are (naturally) influenced by their previous experience (Waddams Price et al., 2002).

Lack of detailed and accurate data is also a common problem. For instance, the Norwegian regulator estimates interruption costs at an aggregate level, where customers are classified as being either residential/agricultural or industrial/commercial (Langset et al., 2001). Service quality regulation also involves a political aspect that can come into conflict with economic considerations. Although individually tailored service qualities would result in an efficient outcome, it could also expose poorer consumers to socially unacceptable levels of quality.

There exists a number of generic approaches for providing quality incentives to companies, including (i) marginal rewards/penalties, (ii) absolute fines and (iii) quality-incorporated benchmarking (Frontier Economics, 2003). Under the marginal reward and penalty scheme, companies receive rewards (penalties) per unit of quality improvement (degradation), which should be calibrated to reflect the marginal value that customers attribute to quality. In equilibrium, a profit-maximising firm chooses to operate at the efficient level, which varies according to its individual marginal cost curve. Mechanisms of this type are referred to as `decentralised', as they allow firms to choose their own level of quality provision.

Absolute fines have a centralised nature in that they require companies to pay a pre-specified amount if quality drops below a threshold. The regulator sets both the amount and the threshold. Although absolute schemes are economically inferior to marginal ones, they entail broader social and political benefits by ensuring that customers are protected through guaranteed standards of performance. In practice, a regulatory regime may include a combination of marginal and absolute-based components.

Approaches that use quality-incorporated benchmarking are based on the same principles as marginal rewards/penalties. For example, under price cap regulation, a company that delivers increased quality relative to its peers would be allowed to raise its price by an amount that reflects the social value of the increased quality. A corresponding price reduction would be imposed on under-performing companies. Similar to marginal reward and penalty schemes, these methods are decentralised, thus minimising the need for selective intervention on the part of the regulator. Moreover, they aim to introduce the dynamic benefits of competition to quality provision: By using benchmarking, regulated firms effectively compete against each other to deliver an optimal bundle of cost and service quality. Thus, in addition to static gain maximisation (achieved by adjusting the quality level subject to a fixed cost curve), firms also face an incentive to pursue long-term investments that shift quality provision costs downwards.

A challenge associated with introducing quality measures in benchmarking is to maintain well-balanced financial and quality-oriented incentives. However, to this date, few regulators have adopted comparative techniques directly in setting the price caps. A notable exception is Norway which introduced a fully functioning system of quality-dependent revenue caps in 2001 (Heggset et al., 2001; Langset et al., 2001).

While each of the regulatory tools discussed has its strengths and weaknesses, they all aim to provide financial incentives for adequate service quality provision. In terms of incentives, companies should be indifferent as to whether they settle quality-related issues by transacting with the government (through fines) or with consumers (through compensation or reduced prices). However, the latter option is politically more attractive as it compensates those who have experienced poor service quality (Waddams Price et al., 2002).

3. Regulation of Electricity Distribution in the UK

The electricity industry in the UK was unbundled and privatised in 1990. In England and Wales, 12 Public Electricity Suppliers (PESs) replaced the former Area Electricity Boards which had been responsible for distribution and retailing functions. The Scottish and Irish utilities were also privatised but remained as vertically integrated companies. A regulatory authority, the Office of Electricity Regulation (OFFER), was set up to monitor the industry.

In 1999, OFFER and the Office of Gas Supply (OFGAS) merged to form the Office of Gas and Electricity Markets (OFGEM) as the UK's energy regulator. In 1998 and 1999, the supply market was fully opened to competition. This necessitated a legal separation of the PESs' distribution and retailing activities (OFGEM, 2000b). The Utilities Act, which received Royal Assent in July 2000, redefined the supply and distribution as separate licensable activities. The distribution parts of the ex-PESs were now referred to as distribution network operators (DNOs).

Since the reform of the industry in 1990, the distribution utilities have been regulated using a price cap model based on the RPI-X formula that is reset every five years.[2] The sector has completed two price control periods, covering the 1990/91-1994/95 and 1995/96-1999/00 periods, and is currently undergoing the third price control for the 2000/01-2004/05 period. OFGEM's view is that the price cap regulation has performed well (OFGEM, 2002a). In particular, operating costs have fallen in real terms by nearly 30% between privatisation and 2002. Over the same period, network investments were in excess of £30 billion. Moreover, controllable costs of the DNOs are expected to continue to decline at a rate of 2.3% per annum until 2005.

Progress has also been made with regards to quality (Electricity Association, 2002). Between 1995 and 2000, the average number of interruptions per 100 customers has fallen from 87.3 to 85.8. Furthermore, the duration of interruptions has also decreased. The average time lost per connected customer due to planned outages has dropped from 16.3 minutes to 9.4 minutes. The duration of fault-related interruptions has also declined, albeit to a lesser extent.

Price Regulation

The price caps for the first price control period, set by the Department of Energy at the time of privatisation, allowed prices to increase up to 2.5% in real terms. For the second price control period, the regulator OFFER imposed substantial price reductions averaging at 14% for 1995/96 and 12% for 1996/97. The X-factors for the remaining years of the second price control period were set at a constant 3%. However, the separation of distribution and supply activities of the PESs involved one-off modifications of allowed revenue, which took place in 1998/99.

[2] See Beesley and Littlechild (1989) and Clemenz (1991) for reviews of the theory and application of RPI-X regulation.

For the third regulatory period, price controls involved a large X-factor for 2000/01, averaging at 23.4% across firms, followed by annual price reductions of 3% till 2004/05. Pertaining to the price control implementation, the regulator opted for a large initial price cut followed by smaller X-factors. This choice was made on the basis of a consumer preference for substantial immediate price reductions and a company preference for a stable financial profile that did not decline throughout the period (OFGEM, 1999b).

In order to set the X-factors, the regulator determined the companies' allowed costs for each year of the price control period, using 1997/98 as the benchmark. The main cost categories, namely operating expenditures (Opex), which cover the costs of network operation, and capital expenditures (Capex), which refer to spending on long-term assets (e.g. lines and transformers), were treated separately.

The efficient levels of Opex for 1997/98 were determined by benchmarking the DNOs' base operating costs with respect to a composite variable, defined as a weighted sum of customer numbers, units of energy delivered, and network length.[3] The base operating costs were derived from total Opex by deducting non-controllable costs such as transmission system exit charges, asset depreciation, and business rates. Further adjustments were made due to differences in regional characteristics and accounting policies (OFFER, 1999). OFGEM adopted the regression-based COLS technique as well as bottom-up benchmarking analysis of companies’ Opex. The choice of method was influenced by the relatively small sample size and the significant data adjustments required (OFFER, 1999). The COLS results were used to set the allowed Opex for each year in the period 2000/01-2004/05 subject to certain criteria (see OFGEM, 1999b). Inefficient firms were required to attain a 75% reduction of their gap relative to the frontier by 2001/02.

Capex was regulated in a more discretionary manner, using forecasts by the regulator as well as the companies (OFGEM, 1999b). OFGEM allocated a proportion of Capex amounting to £2.30 per customer per year for service quality improvement measures. In

[3] See OFFER (1999, Annex 2) for a detailed specification of the composite size variable.

addition, OFGEM incorporated a further set of criteria in calculating the X-factors. Notably, the frontier firms were expected to achieve further cost savings of 7.5% until 2004/05.

Quality of Service

Between 1990 and 2000, quality of supply was regulated through guaranteed standards of performance, which entitle consumers to compensation if the regulated firm breaches them, and overall standards, which refer to system-level performance. Originally, 10 guaranteed standards were applied and a further one was introduced in 1998. Overall standards were set for each distribution utility. The regulator has progressively tightened the standards over that period and consultations with DNOs and other stakeholders have been carried out. However, there is no direct evidence with regards to effectiveness of the reward and penalty schemes (Waddams Price et al., 2002).

The third price control review in 1999 set company-specific quality standards for 2004/05 on the basis of their historic performance (OFGEM, 1999a). At the time of the review, the regulator and the companies generally supported the introduction of an incentive-based regime for service quality regulation (OFGEM, 1999b). However, since the necessary foundation work had not been carried out, it was proposed that the incentive mechanisms should be developed as part of a work programme, known as the Information and Incentives Project (IIP), and applied from 2002/03.

The IIP is divided into two parts. The first part, culminated in September 2000, defined output measures for service quality, set guidelines for improving their measurement accuracy, and constructed a framework for reporting and monitoring (OFGEM, 2000a). Regarding measurement accuracy, it was estimated that the quality measurements conducted by DNOs involved errors of up to 30% (OFGEM, 2000a). OFGEM requested the companies to install measurement systems capable of 95% accuracy by April 2002 and an independent auditor was appointed to examine measurement issues across all DNOs. Reporting under the IIP commenced in April 2001 and the audit of the companies' measurement systems and the first full year of data reported by them was carried-out from June to August 2002. To the extent that no business confidentiality issues arise, OFGEM intends to publish all data collected for the IIP (OFGEM, 2000a).

The second part of the IIP, announced in December 2001, focused on designing an incentive scheme for service quality regulation. The incentive scheme, which came into operation in April 2002 and will apply until the end of the third control period (March 2005), links the quality performance of DNOs to their allowed revenue. It consists of mechanisms that: (i) penalise companies for not meeting their quality of supply targets, (ii) reward companies that exceed them, and (iii) reward frontier performance by guaranteeing less strict standards for the next control period (OFGEM, 2001). In order to mitigate regulatory risk, caused by the scheme's deployment between price control reviews, it was decided to limit the exposure of revenue to the scheme to 2% (£4 million per company, per year, on average). In practice, the IIP scheme is a mechanism similar to the marginal penalties/rewards scheme discussed previously, with the addition of a cap on the payments. However, it is unlikely that these marginal incentives have been calibrated to reflect the social value of quality (Frontier Economics, 2003).

The current regulatory arrangements in the UK treat Opex, Capex and service quality measures separately. This may provide firms with distorted incentives that lead them to adopt an inefficient output mix. Under the current regime, whereby only Opex is regulated through benchmarking, a firm receives greater benefits from an Opex saving than by an equal amount of Capex reduction (OFGEM, 2003). Thus, firms may seek to capitalise Opex to obtain higher efficiency scores and allowed revenue. Similarly, unless companies face incentives that reflect the social value of service quality, they are unlikely to provide their services at socially optimal levels of quality.

A further issue is related to the periodicity of the price review process. Under the present scheme, companies retain 27% of the present value of a cost reduction made in the first year of a price control period but only 6% of the present value of an equal cost saving made in the final year (OFGEM, 2003). As a result, companies may delay efficiency improvements and/or distort capital investment programmes.

4. Methodology

4.1 Data Envelopment Analysis[4]

DEA is a non-parametric method and uses piecewise linear programming to calculate (rather than estimate) the efficient or best-practice frontier in a given set of decision-making units (DMUs) such as firms (see Farrell, 1957; Charnes et al.1978; Färe et al., 1985). The DMUs that make up the frontier envelop the less efficient firms and the relative efficiency of the firms is calculated in terms of scores on a scale of 0 to 1, with the frontier firms receiving a score of 1. DEA can calculate the allocative and technical efficiency, and the latter can be decomposed into scale, congestion, and pure technical inefficiency.

DEA models can be input and output oriented. The models can be specified as constant returns to scale (CRS) or variable returns to scale (VRS). Output-oriented DEA models maximise output for a given quantity of input factors. Conversely, input-oriented models minimise input factors required for a given level of output. An input-oriented specification is generally regarded as the appropriate form for electricity distribution utilities, as demand for distribution services is a derived demand that is beyond the control of utilities and has to be met.

The linear program calculating the efficiency score of the *i*-th firm in a sample of N firms in CRS models takes the form specified in Equation (1) where θ is a scalar (equal to the efficiency score) and λ represents an $N\times1$ vector of constants. Assuming that the firms use E inputs and M outputs, X and Y represent $E\times N$ input and $M\times N$ output matrices respectively. The input and output column vectors for the *i*-th firm are represented by x_i and y_i respectively. The equation is solved once for each firm. In VRS models a convexity constraint $\Sigma\lambda=1$ is added to the model. This additional constraint ensures that the firm is compared against other firms with similar size.

[4] The method description in this section is draws heavily on Jamasb and Pollitt (2003).

$$
\begin{aligned}
&\min_{\theta,\lambda} \theta, \\
&s.t. \\
&-y_i + Y\lambda \geq 0, \qquad (1) \\
&\theta x_i - X\lambda \geq 0, \\
&\lambda \geq 0
\end{aligned}
$$

In Equation (1), firm *i* is compared to a linear combination of sample firms which produce at least as much of each output with the minimum possible amount of inputs. Figure 1 illustrates the main features of an input-oriented model with constant returns to scale. The figure shows three firms (G, H, R) that use two inputs (e.g. capital K, labour L) for a given output Y. The vertical and horizontal axis represent the capital and labour input per unit of output respectively and the line PP shows the relative price of the two inputs.

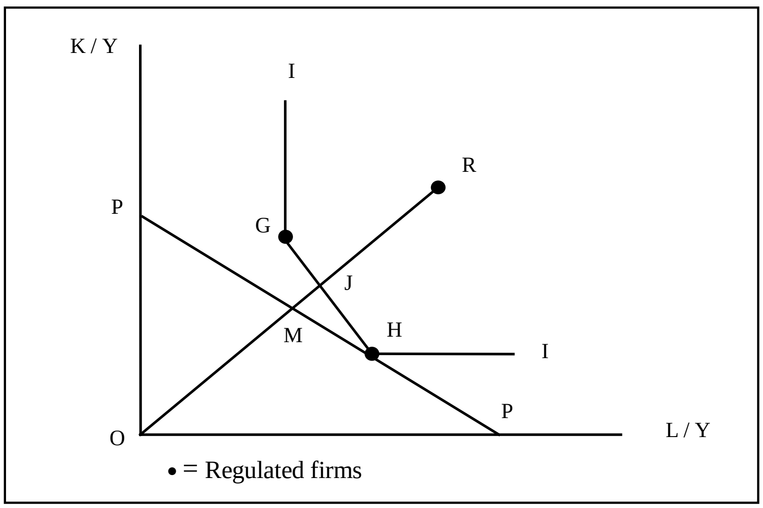

Figure 1: Calculating technical input efficiency in DEA.

Firms G and H produce the given output with lower inputs and form the efficient frontier that envelops the less efficient firm R. The technical and allocative efficiencies of firm R relative to the frontier can be calculated from OJ/OR and OM/OJ ratios respectively. Technical efficiency measures the ability of a firm to minimise inputs to produce a given level of outputs. Allocative efficiency reflects the ability of the firm to optimise the use of inputs given the price of the inputs. The overall efficiency of firm R is measured from OM/OR.

A central step in DEA is the choice of appropriate input and output variables. The variables should, as far as possible, reflect the main aspects of resource-use in the activity concerned. DEA can also account for factors beyond the control of the firms that can affect their performance (environmental variables).

An advantage of DEA is that inefficient firms are compared to actual firms rather than some statistical measure. In addition, DEA does not require specification of a cost or production function. However, the efficiency scores tend to be sensitive to the choice of input and output variables, and the method does not allow for stochastic factors and measurement errors. Further, as more variables are included in the models, the number of firms on the frontier increases, so it is important to examine the sensitivity of the efficiency scores and rank order of the firms to model specification.

4.2 Malmquist Productivity Change Indices[5]

The DEA techniques can be used to calculate Malmquist Index of productivity change over time (see Färe, 1989 and Coelli et al., 1998), assuming the underlying technology is CRS. We use the Malmquist index as shown in Equation (2) and as described in Thanassoulis (2001).

$$MI = \left[\frac{C\_EF_{T0}^{D1} * C\_EF_{T1}^{D1}}{C\_EF_{T0}^{D0} * C\_EF_{T1}^{D0}} \right]^{1/2} \qquad (2)$$

For example, $C\_EF_{T0}^{D1}$ represents the CRS DEA efficiency score for a decision-making unit measured relative to a technology in year 0 and the unit data for year 1. The left-hand-side ratio measures the efficiency of a DMU using data set from period 1, (D1) with technology from year 0, (T0) to the efficiency of the unit with data and technology of year 0, (D0 and T0). The right-hand-side ratio measures the efficiency of unit *j* using data and technology from year 1, (D1 and T1) to efficiency of the unit with data of year 0, (D0) and technology of year 1, (T1).

The Malmquist indices can be broken down into productivity catch-up and frontier shift components as in Equation (3). The catch-up factor is a measure of the extent to which a unit has moved close to the frontier (the left-hand-side-component) while the frontier shift (the right-hand-side component) reflects industry level technological change and innovation (see Thanassoulis, 2001 and Coelli et al., 1998).

$$MI = \frac{C\_EF_{T1}^{D1}}{C\_EF_{T0}^{D0}} * \left[\frac{C\_EF_{T0}^{D1} * C\_EF_{T0}^{D0}}{C\_EF_{T1}^{D1} * C\_EF_{T1}^{D0}} \right]^{1/2} \tag{3}$$

In addition, the catch-up factor can be decomposed into a "pure technical efficiency" and a "scale efficiency" factor as in Equation (4). Pure technical efficiency catch-up (the left-hand-side component) is similar to the technical efficiency catch-up but is measured against a variable returns to scale using VRS model while scale efficiency catch-up (the middle-component) shows how much a firm has become scale efficient.

$$MI = \frac{V\_EF_{T1}^{D1}}{V\_EF_{T0}^{D0}} * \frac{SC\_EF_{T1}^{D1}}{SC\_EF_{T0}^{D0}} * \left[\frac{C\_EF_{T0}^{D1} * C\_EF_{T0}^{D0}}{C\_EF_{T1}^{D1} * C\_EF_{T1}^{D0}} \right]^{1/2} \tag{4}$$

The components of the Malmquist productivity index as specified in Equations (2-4) can be calculated separately with DEA. The technical efficiency components with data and technology from the same year can be calculated using the basic DEA model described in Equation (1). The cross-time efficiency based on year-0 technology and year-1 data can be calculated from Equation (5) using the specification used in Thanassoulis (2001).

[5] The method description in this section is draws heavily on Hattori et al. (2002).

$$
\begin{aligned}
& \min_{\omega,\lambda} \omega \\
& s.t. \\
& -y_i^1 + Y^0\lambda \geq 0 \\
& \omega x_i^1 - X^0\lambda \geq 0 \\
& \lambda \geq 0
\end{aligned}
\tag{5}
$$

The superscripts 1 and 0 for inputs *x* and outputs *y* of *i*-th unit indicate the relevant time period for data used for calculating efficiency. The superscripts for input matrix *X* and output matrix *Y* indicate the time period for technology used for calculating efficiency. This procedure can be modified in order to calculate relative efficiency for the remaining component of Equation (3) with year-1 technology and year-0 data.

4.3 Quality-Incorporated Malmquist Indices

The Malmquist index formalism can be extended to take into account quality attributes of inputs and outputs in addition to ordinary input and outputs. The method was first applied in Färe et al. (1995) in a productivity analysis of Swedish pharmacies. We extend the standard input-output model of the DMU by introducing an attribute vector *a*, whose components are to be associated with non-marketable goods (such as service quality).

In our analysis of quality of service in electricity distribution utilities we use the number of minutes lost and number of interruptions for each firm during a year as quality attributes of the companies' outputs in which a reduction is regarded as desirable. Following Yaisawarng and Klein (1994), we include the undesirable output attributes as ordinary inputs. In an input-oriented DEA model, this can be interpreted as that a firm can reduce the undesirable output attributes and cost (as an ordinary) input while maintaining a given level of ordinary outputs. The cross-time efficiency model in Equation (5) can be extended to incorporate the quality of service attribute *a* as in Equation (6).

$$
\begin{aligned}
& \min_{\omega,\lambda} \omega \\
& s.t. \\
& -y_i^1 + Y^0\lambda \geq 0 \\
& \omega x_i^1 - X^0\lambda \geq 0 \\
& \omega a_i^1 - A^0\lambda \geq 0 \\
& \lambda \geq 0
\end{aligned}
\tag{6}
$$

Following this approach, we can specify a production possibility set (PPS) for period 1 as in Equation (7).

$$T^1 = \left\{ (x^1, a^1, y^1) : x^1 \ \ and \ \ a^1 \ \ can \ \ produce \ \ y^1 \right\} \tag{7}$$

Furthermore, we define a modified input-oriented technical efficiency measure s^1 as in Equation (8) (see also Chen, 2001).

$$s^1(x^1, a^1, y^1) = \min \left\{ \ s^1 : (s^1 x^1, s^1 a^1, y^1) \in T^1 \right\} \tag{8}$$

Following the above notation, the general (quality-independent) Malmquist productivity change index between periods 0 and 1 in Equation (2) can be expressed as in Equation (9) where the subscript c in h_c denotes evaluation of the PPS under CRS.

$$M^{0,1} = \left[\frac{h_c^0(x^1, y^1) * h_c^1(x^1, y^1)}{h_c^0(x^0, y^0) * h_c^1(x^0, y^0)} \right]^{1/2} \tag{9}$$

The quality-incorporated Malmquist index $M_a^{0,1}$ is then calculated from Equation (10) that is essentially the Malmquist index in Equations (2 or 9) that are extended with the quality attribute *a*.

$$M_a^{0,1} = \left[\frac{s_c^0(x^1, a^1, y^1) * s_c^1(x^1, a^1, y^1)}{s_c^0(x^0, a^0, y^0) * s_c^1(x^0, a^0, y^0)} \right]^{1/2} \tag{10}$$

Following Färe et al. (1995), we then define a quality change index $Q^{0,1}$ as specified in Equation (10).

$$Q^{0,1} = \left[\frac{s_c^0(x^0, a^1, y^0) * s_c^1(x^1, a^1, y^1)}{s_c^0(x^0, a^0, y^0) * s_c^1(x^1, a^0, y^1)} \right]^{1/2} \tag{11}$$

A comparison of Equations (10) and (11) reveals that $Q^{0,1}$ isolates the effects of quality change by making single period input and output evaluations under mixed period quality attributes.

If we assume that s is multiplicatively separable in quality attributes and inputs-outputs, the quality change index can be expressed as a separate component of quality-incorporated Malmquist index $M_a^{0,1}$; i.e. as in Equation (12).

$$s^0(x^0, a^0, y^0) = u^0(a^0) * h^0(x^0, y^0) \tag{12}$$

Then, it is possible to express Equation (12) as in Equation (13) where $M^{0,1}$ is a quality-independent Malmquist index as defined in Equation (9) (Färe et al., 1995).

$$M_a^{0,1} = Q^{0,1} * M^{0,1} \tag{13}$$

Similar to decomposition of the simple quality-independent Malmquist index $M^{0,1}$ in Equations (2) and (3), the quality-incorporated Malmquist index $M_a^{0,1}$ can be decomposed into separate quality, frontier shift F (technology), and productivity catch-up E_c components (Equation 14). The later can be further decomposed into pure efficiency E_v and scale efficiency S components (Equation 15). Using Equations (11) and (15) we arrive at the decompositions in Equations (14) and (15), which separate the, quality, efficiency, scale and technology components of total productivity change.

$$M_a^{0,1} = Q^{0,1} * F^{0,1} * E_c^{0,1} \tag{14}$$

$$M_a^{0,1} = Q^{0,1} * F^{0,1} * E_v^{0,1} * S^{0,1} \tag{15}$$

To the extent that the Malmquist index calculated using Equation (13) is similar to that of the Malmquist index from Equation (10), the quality of service aspect of data (or the nature of the activity under examination) may be interpreted as consistent with the assumption of multiplicative separation. Significant differences in the results from the two approaches may be interpreted as indication that simple quality-independent productivity indices do not reflect the true or holistic measure of productivity (see Färe et al., 1995) and hence may be an unreliable basis for X factor calculations.

5. Data and Model Specifications

5.1 Choice of Variables

Choosing the input-output variables is an important step in DEA. However, there is no firm consensus on which variables best describe the operation of distribution utilities. Jamasb and Pollitt (2001) outline the most widely used variables in benchmarking studies of electricity distribution utilities. Operating costs, number of employees, transformer capacity, and network length are among the most commonly used inputs in the models. The most widely used outputs include units of energy delivered, and number of customers. In this study, we employ monetary and physical measures of the most widely used inputs and outputs used in previous benchmarking studies together with quality of service variables.

The monetary variables used are operating expenditures (Opex) and total expenditures (Totex). The Opex data reflect controllable costs and are exclusive of depreciation, transmission grid charges, and tax rates. Totex is defined as the sum of Opex, network investments and non-operational capital expenditures. Although our use of monetary variables is beneficial from a regulatory perspective, it can raise concern about data consistency. Financial quantities can be affected by accounting conventions and policies, which may contain an element of discretion.

Physical variables used in our models are (i) total number of customers (CUST), (ii) units of energy delivered (ENGY), and (iii) total network length (NETL). These variables are among the most important cost drivers of electricity distribution (Burns and Weyman-Jones, 1996; Jamasb and Pollitt, 2003).

The quality of electricity service can be viewed in terms of (i) continuity of supply, characterised by the number and duration of outages, (ii) commercial quality, associated with the relationship between network operators and consumers, and (iii) voltage quality, whose main parameters are signal frequency, amplitude and waveform (Robert, 2001).

In this study we are concerned with the continuity dimension of quality and adopt OFGEM's quality indices, which measure (i) the number of customers interrupted per 100 connected customers (security of supply) and (ii) the average customer minutes lost per connected customer (availability of supply) (OFGEM, 2000a). DEA requires absolute quantities of inputs and outputs in order to calculate the efficiency of DMUs. We use un-normalised values of OFGEM's data on (i) number of interruptions (NINT) and (ii) total customer time lost (TINT) that measure security of supply and availability of supply indices respectively.

5.2 Dataset

The analysis in this study compares the performance of the 14 DNOs in the UK (including the 12 utilities in England and Wales as well as the distribution activity of the two vertically integrated Scottish companies) for the period from 1991/92 to 1998/99.

The monetary and physical data for the input and output variables were obtained from OFGEM.

Although the DNOs report their costs in regulatory accounts, in order to maintain data consistency, we opted to limit the scope of our analysis to the 1991/92-1998/99 period for two reasons. First, the data used on controllable operating expenditures had been harmonised by OFGEM in order to account for firm-specific differences. Second, the legal separation of the distribution and supply businesses of the ex-PESs, which was implemented in 1999 also involved some cost (re)allocations. These adjustments resulted in some changes in the level of cost base for the companies in subsequent years. The data on quality of service used in the analysis here measured in terms of security and reliability of supply are from OFGEM's published performance evaluations of the distribution companies.

Figure 2 illustrates the overall trends of the variables used in the DEA models, averaged across all DNOs. As shown in the figure, both operating and capital expenditures (Opex and Capex) display a downward trend. At the same time, the physical measures of outputs in terms of number of customers, units of energy delivered, and total network length (CUST, ENGY and NETL) are steadily increasing. The quality of service variables measuring security of supply (NINT) and reliability of supply (TINT) exhibit a mild downward trend, indicating that a slow sector-wide improvement has taken place during the period under study.

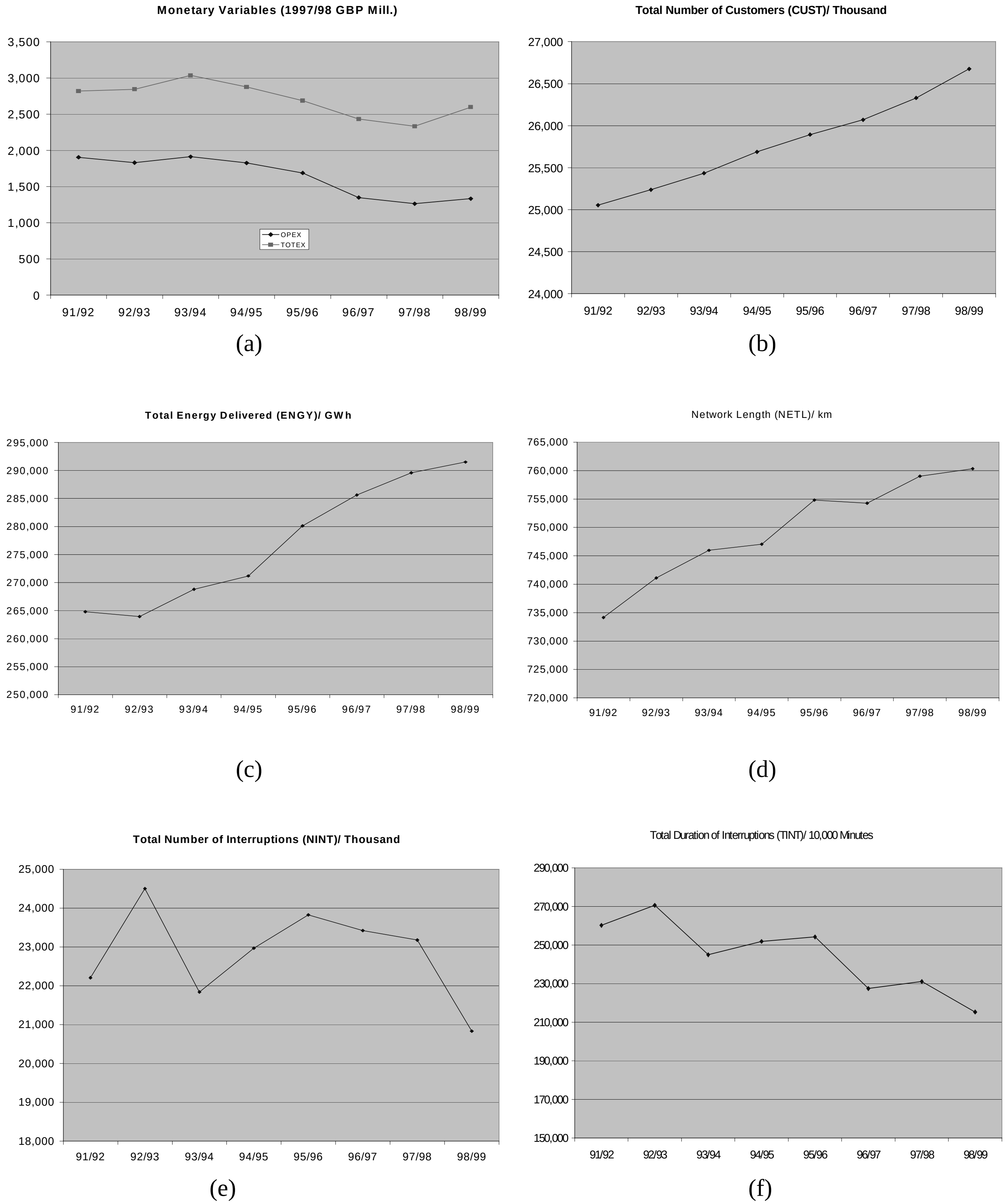

Figure 2: Sector-wide averages of model variables (time is measured in fiscal years).

5.3 Model Specifications

We construct four DEA models, which employ different combinations of the variables introduced in Section 5.1. The aim is to assess policy issues related to the DNOs' performance from the perspective of costs as well as service quality.

As mentioned previously, the quantities of physical outputs delivered by distribution utilities are, due to the derived nature of electricity demand, beyond the control of the management. Therefore, we use input-oriented DEA models to calculate the DNOs' relative efficiency in terms of the extent by which they can reduce their inputs while maintaining a given level of output. Table 1 summarises the cost inputs, outputs, and quality attributes used in the models where quality attributes are treated as inputs as discussed above.

	Model Opex	**Model Totex**	**Model Quality**	**Model Totex-Quality**
Opex	I			
Totex		I		I
NINT			I	I
TINT			I	I
CUST	O	O	O	O
ENGY	O	O	O	O
NETL	O	O	O	O
I: Input, O: Output				

Table 1: Specifications of DEA models

Model Opex is the base model and the specification resembles that of OFGEM's COLS model used in benchmarking of distribution utilities. The model uses Opex as input and outputs are similar to the components of OFGEM's composite size variable (number of customers, energy delivered and network length).

The other models used in this study are Model Totex, Model Quality, and Model Totex-Quality that assess the firms with respect to (i) total costs, (ii) service quality, and (iii) cost and quality combined respectively. The use of Totex in Model Totex is justified on the basis of regulatory concerns about the unbalance in incentives to pursue Opex versus Capex savings. Model Quality treats NINT and TINT as inputs based on the notion that given its physical output levels, firms should minimise the number and duration of interruptions. Model Totex-Quality brings together the inputs used in the Model Totex and Model Quality as discussed in Subsection 4.3.

The Efficiency scores calculated from the model Totex-Quality are equal to the greater of the scores from the corresponding Model Totex and Model Quality. This is a general property of radial efficiency measures, which cannot be reduced by incorporating more variables in a model. Two methodological issues are noteworthy here. First, the standard radial definition of efficiency, which determines the maximum achievable proportional reduction of inputs, while outputs are kept constant. A firm that sets the frontier for a particular input or output receives an efficiency score of 1.00, regardless of how poorly it performs with respect to other inputs and outputs.

Second, small samples can constrain the number of model variables. At the same time, it is important to capture all the key features of the activity in question. This issue could be tackled by incorporating firms from other countries in the sample. However, this would require careful harmonisation of data obtained from disparate sources and extensive international collaboration. An alternative approach is to use simple models that capture the key characteristics of DNOs. The outstanding inter-firm differences and environmental factors can then be accounted for by performing second stage regression analysis of the efficiency scores with respect to these.

6. Results

6.1 Technical Efficiency Scores

The DEA models defined in Section 5 are solved using both CRS and VRS technology structures. The fiscal year 1990/91 was excluded from the analysis due to apparent data anomaly in the number and duration of interruptions, which would distort cross-model comparisons.[6] Table 2 shows the calculated technical efficiency scores for the DNOs, averaged over the period 1991/92-1998/99. The correlation coefficients for the efficiency scores are presented in Table 3. Figure 3 illustrates average annual technical efficiency scores of all firms for Models Opex, Totex, Quality, and Totex-Quality. The average company rankings from the models are shown in Figure 4.

	Model Opex		**Model Totex**		**Model Quality**		**Model Totex-Quality**	
	CRS	**VRS**	**CRS**	**VRS**	**CRS**	**VRS**	**CRS**	**VRS**
Eastern	0.84	1.00	0.96	1.00	0.90	1.00	1.00	1.00
E. Midlands	0.75	0.79	0.80	0.83	0.78	0.82	0.87	0.89
London	0.66	0.71	0.70	0.74	1.00	1.00	1.00	1.00
Manweb	0.78	0.84	0.84	0.87	0.93	0.94	0.97	0.98
MEB	0.78	0.83	0.85	0.89	0.53	0.56	0.87	0.89
Northern	0.62	0.70	0.76	0.85	0.72	0.82	0.83	0.96
NORWEB	0.65	0.69	0.71	0.74	0.91	0.95	0.93	0.96
SEEBOARD	0.80	0.86	0.89	0.92	0.65	0.66	0.90	0.93
Southern	0.91	0.95	0.82	0.86	0.88	0.96	0.93	0.96
SWALEC	0.58	0.75	0.60	0.79	0.37	0.53	0.61	0.83
SWEB	0.67	0.71	0.75	0.79	0.71	0.76	0.79	0.86
Yorkshire	0.80	0.86	0.87	0.91	0.99	0.99	0.99	0.99
Hydro	0.99	1.00	0.94	0.95	0.73	0.78	0.97	0.99
Scottish Power	0.88	0.88	0.92	0.95	0.94	0.97	0.99	1.00
AVERAGE	0.76	0.83	0.82	0.86	0.79	0.84	0.90	0.95

Table 2: Average company efficiency scores (1991/92-1998/99)

	Model						
	Opex (VRS)	**Totex (CRS)**	**Totex (VRS)**	**Quality (CRS)**	**Quality (VRS)**	**Totex-Quality (CRS)**	**Totex-Quality (VRS)**
Opex (CRS)	0.90	0.67	0.65	0.24	0.22	0.48	0.38
Opex (VRS)		0.68	0.73	0.16	0.19	0.42	0.41
Totex (CRS)			0.91	0.28	0.24	0.67	0.55
Totex (VRS)				0.12	0.11	0.51	0.51
Quality (CRS)					0.95	0.78	0.67
Quality (VRS)						0.71	0.68
Totex-Quality (CRS)							0.86

Table 3: Efficiency score correlations

[6] See Figures 3e-3f.

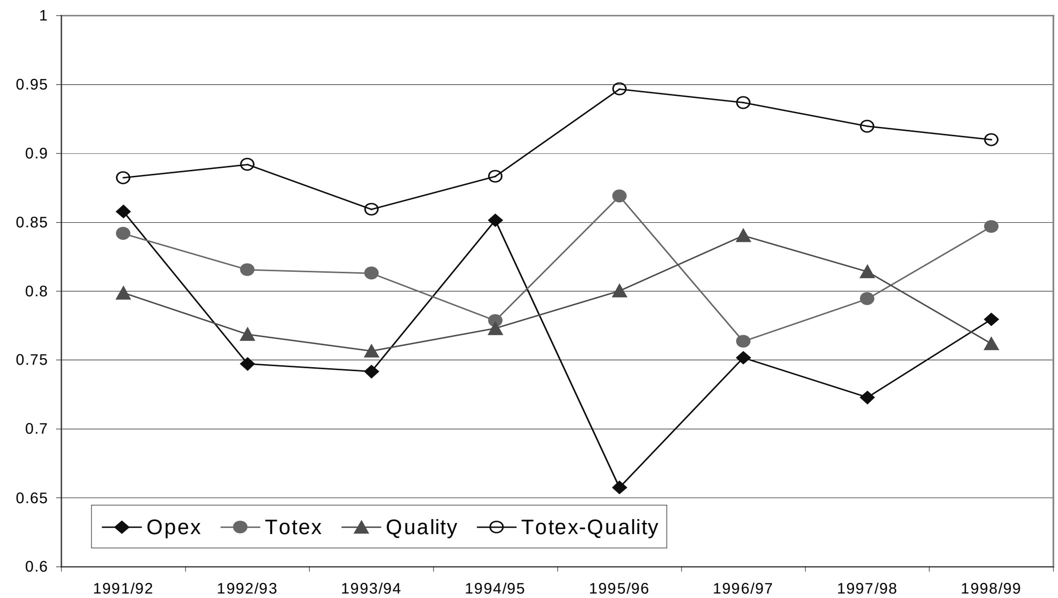

Figure 3: Sector-wide average efficiency scores determined from Models Opex, Totex, Quality and Totex-Quality (1991/92-1998/99)

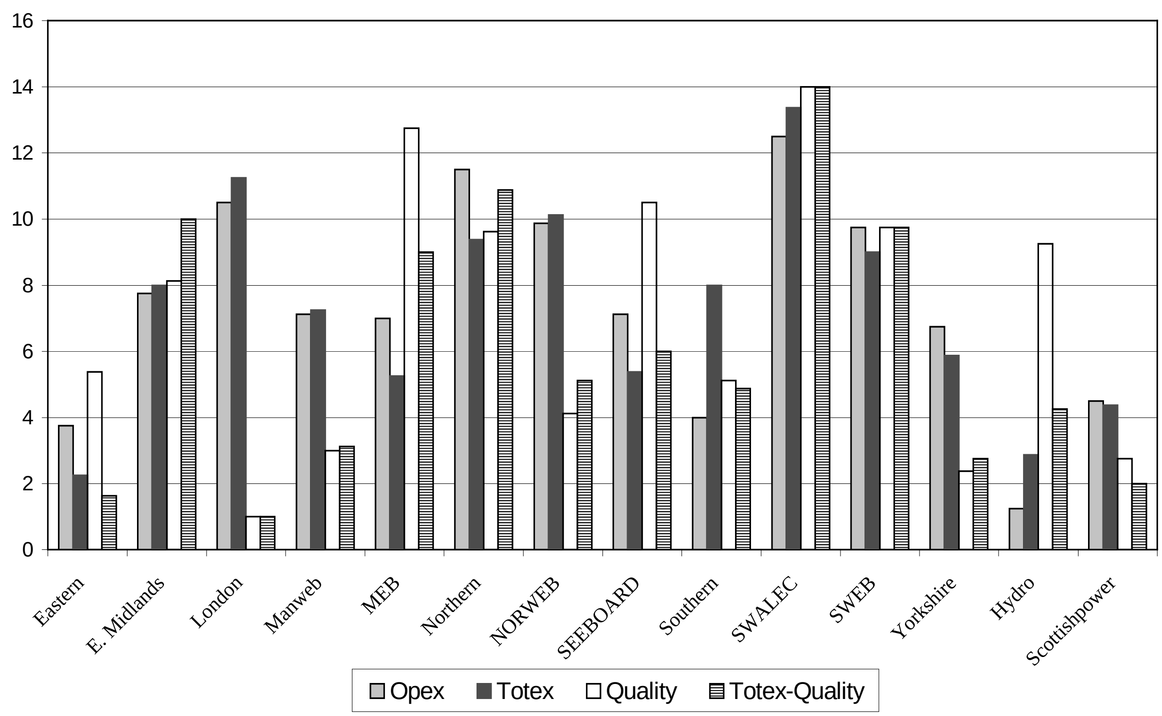

Figure 4: Average annual company rankings from Models Opex, Totex, Quality and Totex-Quality (1 is best, 14 is worst).

First, we consider the base Model Opex. In CRS specification, the sector-wide average efficiency scores from the model exhibit an initial decline followed by an upward trend in the last years (Figure 3). It should be noted that the decline could indicate that the performance gap between the companies may have been widening and does not necessarily imply that the productivity of the sector has been declining. Model Opex identifies Scottish Hydro, Eastern, and Southern as the most efficient DNOs on average (Figure 4).

Turning to the remaining models, we find significant variations in efficiency scores and rank orders of the firms. We discuss the dependence of our model results on (i) the number of variables used, (ii) the technology structure specification and (iii) the choice of input-output set.

Effect of number of variables

A consequence of DEA's mathematical formulation is that DMUs receive higher efficiency scores as the number of model variables increases (Table 2). Model Totex (in CRS), which has four variables, yields that three firms have average ratings greater than 0.90. In contrast, in Model Totex-Quality, which has six variables, the number raises to ten. This is an instance of trade-off between a model's detail and its explanatory power. While Model Totex-Quality captures more features of the operation of distribution utilities, it somewhat limits our ability to draw conclusions on their performance relative to their peers. It should, however, be noted that the firms' rankings and score correlation coefficients across models (Table 3 and Figure 4), are more relevant for our analysis and these are less affected by a general increase in efficiency scores.

Analysis of scale efficiency

As expected, the efficiency scores under VRS assumptions produce higher scores than CRS assessments. In both cost-based and quality-based models, most DNOs receive somewhat higher scale efficiency scores. A notable exception is SWALEC that, while generally scoring low, exhibits significant differences between its CRS and VRS technical efficiency scores. It should be noted that SWALEC is the smallest firm in terms of network length and the second smallest in other inputs and outputs (barring quality measures) The CRS models may underestimate the company's pure technical efficiency by benchmarking it against dissimilar and, presumably, more scale-efficient comparators. Since the DNOs in our sample fall generally in the same size category, the observed high scale efficiency scores do not necessarily imply that companies operate near a universally optimum scale size of production. A confirmation of this requires extending the sample to include firms operating in other size categories.

Efficiency score dependence on input-outputs

Efficiency scores can depend on the choice of input variables. When Totex is taken into account, the companies' scores show an overall improvement. The sector displays a smaller performance gap than an Opex-based benchmarking would suggest (Table 2). This indicates that the base Model Opex can penalise firms that are efficient in Capex. For example, Northern's efficiency score in Model Totex (CRS) is 76%, while its score in Model Opex is 62%. At the same time, Opex benchmarking may distort firms' incentives. For example, in Model Opex (CRS), Southern's efficiency score is 91% (which would result in a low X-factor) while its score in Model Totex is 82%.

Performance differs also significantly between cost and quality-based benchmarking at the company level. The average rankings of DNOs' show that some companies rank high in models with quality variables while they rank low in cost-only Models Opex and Totex (Figure 4). The most characteristic example is that of London, which is a poor performer with respect to cost but is a high performer in terms of service quality. Some DNOs display uniform cost-oriented and quality-oriented rankings.

The score correlation coefficients in Table 3 show that there is a rather weak relationship between the companies' scores in cost-only and quality-only models, i.e. cost-efficient firms are not high-quality providers. In other words, cost-only models have not captured the quality of service aspect of the companies' operation. Therefore, in principle, it is preferable to incorporate quality of service variables in the cost-models such as the Model Totex-Quality.

6.2 Malmquist Productivity Change Indices

In order to assess productivity change over time, we calculate Malmquist indices using DEA and our preferred models. We calculate the productivity change indices for four-year intervals; as year-by-year changes are volatile. The four-year intervals used here are annually recurring and begin in 1991/92; i.e. we consider the four intervals 1991/92-1995/96,1992/93-1996/97,1993/94-1997/98 and 1994/95-1998/99. For the base Model Opex, the total productivity change index is decomposed according to Equation 4 into pure efficiency change, scale efficiency change, and boundary shift.

In order to take into account quality changes, the productivity change index for Model Totex-Quality is decomposed based on Equations 10 and 11 (i.e. distance functions multiplicatively non-separable in quality attributes and input-outputs) and Equation 15 (i.e. distance functions that may be multiplicatively separable in quality attributes and input-outputs). Since Malmquist indices are percentile quantities, we use the geometric mean whenever averaging is carried out.

Table 4 presents our results, averaged over all companies and time intervals. The results from the models suggest that the sector has achieved average productivity gains of between 12% and 38% for the above four-year periods between 1991/2 and 1998/99. However, since the F index significantly outweighs E_c, the strongest driver of productivity change has been an overall shift of the production frontier, rather than performance convergence towards best practice.

It is noteworthy that Model Opex yields a 10% average regress in overall efficiency, suggesting that the inter-firm performance gap has widened. At the same time, the efficient frontier shows a significant outward shift. Model Totex indicates that the performance gap has remained unchanged while the efficient frontier has had a positive shift. Model Quality shows that the quality performance gap has declined and the efficient frontier has shifted outwards.

	Model				
	Opex	**Totex**	**Quality**	**Totex-Quality (Non-Sep.)**	**Totex-Quality (Sep.)**
Productivity change, M / Ma	1.384	1.203	1.139	1.122	1.244
Service Quality change, Q	-	-	-	1.034	1.034
Overall efficiency change, Ec	0.902	1.008	1.042	1.062	1.008
Pure efficiency change, Ev	0.938	1.019	1.025	1.051	1.019
Scale efficiency change, S	0.962	0.989	1.017	1.011	0.989
Boundary shift, F	1.534	1.193	1.092	1.057	1.193

Table 4: Average of the Malmquist productivity indices for the four-year intervals of 1991/92-1998/99 period.

Also, Model Totex-Quality (non-separable) shows a balanced improvement in quality, catch-up, and efficient frontier. The results of the model with multiplicatively separable quality attributes and inputs-outputs show similar albeit stronger results. However, the calculated Malmquist productivity changes form non-separable and separable versions are different, suggesting that the data are not consistent with separability (see Färe, et al., 1995). A two-sample t-test (assuming unequal variances) of the averaged Malmquist indices for the firms for the four-year intervals also rejected the null-hypothesis (at 90%) confidence) that the indices from the two approaches have similar means (Table 5)[7]. We therefore do not pursue the results from the separable version further. However, these results can be interpreted as supporting a non-separable total cost-quality benchmarking approach rather than partial approaches.

Figure 5 shows the productivity change and relevant components for individual firms for Model Totex-Quality. As shown in the figure, two companies exhibit productivity regress for the period under study one of which is the only firm in the sample that shows regress in the quality index. Table 6 shows the correlation between productivity change indices and its components for the sector.

[7] Note that the arithmetic mean values of the Malmquist indices in Table 5 are slightly different from the geometric means in Table 4.

	Totex-Quality (Non-Sep.)	Totex-Quality (Sep.)
Mean (arithmetic)	1.127	1.277
Variance	0.01204	0.08715
Observations	14	14
Hypothesized Mean Difference	0	
df	17	
t Stat	-1.775	
P(T<=t) one-tail	0.047	
t Critical one-tail	1.333	
P(T<=t) two-tail	0.094	
t Critical two-tail	1.740	

Table 5: t-test two-sample (assuming unequal variances) of average Malmquist productivity indices of firms (α=0.1).

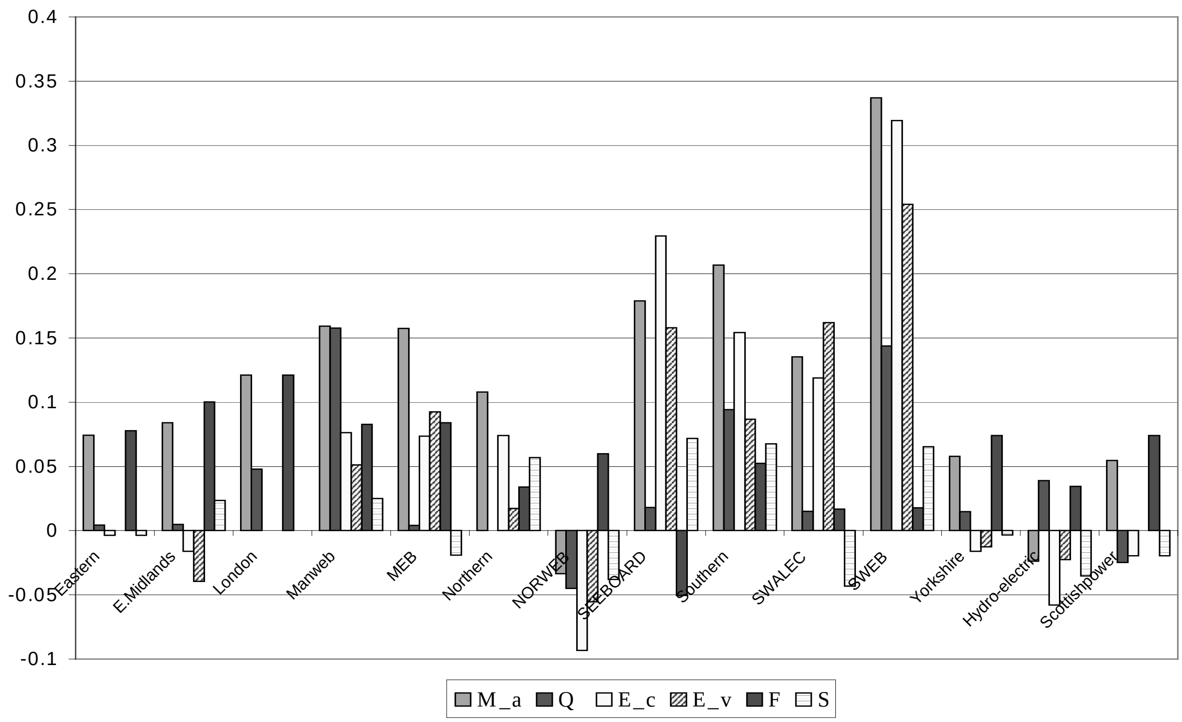

Figure 5: Logarithmic plot of firm-level average Malmquist productivity indices for the four-year intervals in 1991/92-1998/99 period (Totex-Quality Model – Non-separable).

	Produc-tivity change, M	Quality change, Q	Overall efficiency change, Ec	Pure efficiency change, Ev	Boundary shift, F	Scale efficiency change, S
Productivity change, M	1.00					
Quality change, Q	0.70	1.00				
Overall efficiency change, Ec	0.93	0.59	1.00			
Pure efficiency change, Ev	0.87	0.52	0.95	1.00		
Boundary shift, F	-0.29	-0.05	-0.61	-0.61	1.00	
Scale efficiency change, S	0.70	0.51	0.71	0.45	-0.37	1.00

Table 6: Correlation coefficients of average of Malmquist indices for the four-year intervals in 1991/92-1998/99 period (Totex-Quality Model – Non-separable).

As shown in the table, the correlation coefficient between the quality index and technical efficiency measures at the sector level is positive but not very high, indicating that firms that achieve technical efficiency improvement have, to some extent, improved service quality. This observation partially supports the evidence from the efficiency scores, and that the scores in the cost models had low correlation with those of the quality model. It should be noted that the former proposition is based on a inter-model comparison of efficiency "levels" while the latter refers to an intra-model productivity progress or "change". Also, the frontier shift factor is nearly non-correlated with the quality index, indicating that technological change (in a cost sense) is not associated with quality improvement.

7. Conclusions

In this paper, by means of an empirical analysis of UK electricity distribution, we attempted to demonstrate whether it is desirable to incorporate quality of service into benchmarking of electricity networks. We found that the average efficiency score of the sector is higher in our model with total expenditures than the model with operating expenditures as input. We showed that, for some firms, the efficiency scores in cost-only models vary significantly from the efficiency scores in the cost-quality models. Although, we found a notable correlation between the efficiency scores of the cost-only models, the results indicate existence of possible trade-off or differing competencies between operating and capital expenditures.

We also found that some firms that performed well in the cost-only models did not score high in our quality-only model and the correlation coefficients between the cost-only and quality-only scores were somewhat low. This indicates a possible trade-off or differing competencies between costs and quality of service. These findings show that, at least conceptually, it is plausible and desirable to integrate quality of service and capital expenditure in benchmarking and incentive regulation of electricity networks.

The Malmquist indices of our cost-quality model show significant productivity growth in the sector during the 1991/92-1998/99 period. The gains can be attributed to reduced efficiency gap among the firms, frontier shift, and improved quality of service. We found that while the quality index for the sector is relatively correlated with efficiency index or catch-up factor, it is negatively correlated with the frontier shift. At the firm level, however, some firms showed regress in the productivity index or the quality index. We also found some evidence that firms that exhibit technical efficiency progress also achieve quality improvement.

The evidence indicating performance variations in Opex and Capex or possible trade-off between them on the one hand, and between the costs and quality of service on the other suggest that overall benchmarking approaches are preferable to partial approaches. Although the numerical indications of trade-offs between cost and quality may not be very strong their economic and firm-level implications can be considerable. Regulatory benchmarking schemes involving capital expenditures and quality of service still need to address concerns about long-term impacts of leaving investments and quality to benchmarking models instead of approval of investment plans and standards of performance for quality. However, it is more certain that integrated cost-quality benchmarking is a useful tool for overall analysis and progress of the incentive regulation regime.

The analysis of benchmarking and regulation of quality of service in this paper can be extended by explicitly incorporating a value for quality. One approach would be to analyse the allocative and productive efficiency of DNOs by using a price for each of the quality variables used. This would have the advantage of allowing a socially efficient trade-off between quality and financial cost. The efficiency score generated by this approach can then be used to calculate X-factors. Our integrated frontier approach contrasts with two other approaches that have been suggested. First, one could econometrically model the determinants of quality for the sample of DNOs and reward or penalise firms on the basis of their deviation from predicted quality values, using the socio-economic value of the non-delivered energy (ECON, 2000). Second, a simple quality yardstick regulation regime could be used which would compare individual firms' quality measures to those of the best firms in the sample of DNOs. Individual firms would be rewarded or penalised on a scale which reflected their relative distance from best practice (Frontier Economics, 2003; OFFER, 1999; OFGEM, 1999b).

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