DEA AND DYNAMIC YARDSTICK COMPETITION IN SCANDINAVIAN ELECTRICITY DISTRIBUTION

PER J. AGRELL, PETER BOGETOFT, AND JØRGEN TIND

Abstract. Multi-period multi-product regulatory schemes for electricity distributors are presented, based on cost information from a productivity analysis model and an agency theoretical decision model. The proposed schemes are operational and demonstrate considerable advantages compared to the popular CPI-X revenue cap regulation. The schemes avoid arbitrariness, excessively high or negative informational rents as well as ratchet effects and they promote rapid productivity catch-up by making full use of available data. More generally, the paper contributes to the theoretical unification between firm-based Data Envelopment Analysis (DEA) productivity models and micro-economic reimbursement theories.

1. Introduction

Irrespective of ownership, either investor owned or publicly owned utilities, any natural monopoly poses a risk to society by accruing excess profits and costs at the expense of members of the population dependent on its services. The problem is a principal-agent problem under asymmetric information with society (the customers represented by a regulator) as the principal and the utility (and its manager) as the agent.

In the case of perfect information, the principal would offer the agent a compensation scheme corresponding to the minimal cost for the desired level of service and the agent would accept the offer at zero profit. Sometimes, the cost function can be estimated using prior knowledge about the industry or using information acquired through a bidding procedure, such as in a public procurement setting.

Generally, however, the natural monopolies (gas, water, electricity) exhibit very varying exogenous preconditions such as customer profile and density, climate and topology. This renders direct assessment of the cost function difficult. Under such circumstances, regulators have often resorted to inflation adjusted revenue caps with stipulated annual productivity improvements, the CPI-X model. However, such revenue caps are associated with severe limitations on the theoretical and operational side, leaving a great deal of the regime open to arbitrariness. This paper is illustrated with the specific conditions pertaining to regulation of the Scandinavian electricity distribution industry and suggests a regulatory framework based on efficiency benchmarking and incentive theory. However, the results may be applied to other regulated industries with multiple-input, multiple-output characteristics as well.

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From a theoretical viewpoint, this paper extends earlier results joining Data Envelopment Analysis (DEA) cost norms with the modern approach to regulation, based on agency theory. In particular, the models in Bogetoft (1997, 1999, 2000) and Agrell, Bogetoft and Tind (2002) are taken as a starting point for the dynamic framework. The emphasis of this paper, however, is not on the derivation of theoretical results per se. Rather, we stress the application to practical regulatory problems in a particular industry. By offering a comparison to the popular CPI-X scheme and to a more advanced DEA-based cost scheme implemented in Norway, the paper provides a fragment of a regulatory manual.

The outline of the paper is as follows. In Section 2, we introduce the most common regulatory models and in Section 3 we review the literature on the efficiency of Nordic electricity distribution. The basic DEA benchmarking model is developed in Section 4. The DEA based regulatory model is developed in the single-period single-agent case in Section 5 and in the multiple-period multiple-agent case in Section 6. A comparative study of three regulatory regimes using paneldata from the Swedish electricity distribution is presented in Section 7. The paper ends with discussion in Section 8 and some conclusions in Section 9.

2. Regulation of Electricity Distribution

Various regulation regimes have been applied to electricity distribution: nationalization, cost-plus regulation, rate-of-return regulation, CPI-X revenue caps, and yardstick competition. The idea behind nationalization is to gain an informational advantage and use this to maximize social welfare, e.g., by introducing marginal cost pricing. Anecdotal evidence of low cost efficiency and resulting high costs has caused the wide-spread abandonment of this option in the favor of privatization. Cost-plus regulation is likewise an early low-powered alternative with incentives for over-investment and inefficiency. Rate-of-return regulation is currently found in many countries, including the United States, as a low-powered option that regulates the profitability of the industry. Early studies by Averch and Johnson (1962) point out the incentives for overcapitalization to increase the rate base with this regime. Empirical evidence summarized below suggests that this was the case for the Scandinavian distribution industry before the recent reorganization.

CPI-X revenue cap regulation is a high-powered regime. It has been applied to power distribution, e.g., in England and Wales (cf. Pollitt, 1995). Liston (1993) shows that the fixed income induces cost efficiency by the agent's cost minimization. However, several theoretical and practical problems are associated with the CPI-X model:

- If the cap is set too tight (low), the result may be non-participation or bankruptcy.
- If the cap is too loose (high), the informational rents will be excessive.
- The update of the cap encourages strategic behavior on behalf of the agents, who fear being penalized in subsequent periods for productivity improvements. This is the so-called ratchet effect, cf. Freixas, Guesnerie and Tirole (1985) and Weitzman (1980)
- The cap basis lacks foundation. CPI does not necessarily have any connection to the input prices. The improvement factor X, in its turn, lacks solid specification. In setting out to combine historical performance with

conjectures about future developments, industry often requires bargaining with, further aggravating the risk of strategic behavior .

- The CPI-X model does not accommodate changes in the output profile. Hereby, revenue cap regulation provides disincentives to product innovation and quality development.

The yardstick competition regime (Shleifer, 1985) is an interesting addition to the regulatory arsenal. The idea is to set an individual cost target for each distributor that equals the realized cost by other (comparable) agents. If the residual profit is retained by the distributor, and if all distributors produce the same product under the same conditions, the yardstick competition provides an optimal incentive scheme in solving the first two of the CPI-X problems stated above. The endogenous determination of the cost norm solves the problem of arbitrariness. The main problem of the basic yardstick model is the comparability between agents and in particular its inability to accommodate variations in the output profiles and operating conditions between the agents[1].

The key to effective regulation is found in the access to information. We therefore propose a dynamic extension of the yardstick competition model using DEA. By utilizing the maximum amount of information in a rich production model and by reducing the regulatory lag, five positive effects are obtained. First, by tailoring the revenue cap to the individual agent in a close sense, the total informational rent is minimized. Second, by reducing the time lag from evaluation to reimbursement and repeating the evaluation more frequently, the risk and the consequences of misrepresenting an agent in a yardstick sense are minimized. Third, by excluding the evaluated unit from the basis of comparison, the ratchet effect can be effectively dealt with. Fourth, by using observed production cost rather the estimated consumer prices, the arbitrariness of the CPI may be avoided. Similarly, the need of postulating a negotiated X factor may be substituted by an actually realized productivity improvement. Finally, by using the richer production description in DEA, changes in production profile can easily be taken into account.

3. Nordic Efficiency Studies

The Scandinavian electricity market has been undergoing a major transformation since the late 1990s, heading towards the world's largest free-competition electricity market. In the deregulation, each of the four functions of the electricity sector (production, transmission, distribution and retail) is met with a different market form. The energy production and retail markets in Norway, Sweden and Finland have constituted free markets since the end of the millennium, whereas the liberalization process in Denmark is likely to be delayed for a few more years. The transmission industry in Sweden and Norway is allotted to a state monopoly, analogously to the road and railway infrastructure in these countries. The distribution market, as a natural monopoly, will be subject to various regulatory regimes in all four countries, thus providing an excellent showcase for the potential strengths and weaknesses of the applied theory.

[1]Truly, Shleifer (1985) acknowledged such variations, but his remedy of using e.g. linear regression to rectify this, is ad hoc and disconnected from the formal analysis of the scheme.

Country	Techn. eff.	Cost eff.	Alloc. eff.	Obs.	Year
Sweden (Veiderpass, 1992)	77%	-	-	285	1985
Sweden (Agrell-Bogetoft, 2002)	-	73%	-	234	1997
Norway (Kittelsen, 1994)	93%	72%	77%	171	1989
Denmark (Hougaard, 1994)	78%	-	-	82	1991

TABLE 1. Efficiency analyses of Nordic electricity distributors.

The appropriateness of a particular regulatory policy foremost depends on the prevailing conditions in industry and the societal demands that the policy sets out to protect. The efficiency of the Nordic electricity distribution market has attracted considerable attention from industry research organizations as the liberalization of the market emerged.

Torgersen (1993), Kittelsen and Torgersen (1993) and Kittelsen (1994) investigate the Norwegian electricity distribution system. Kittelsen (1994) uses a data set of 172 distributors in 1989 and a model with three inputs (employee hours, transmission losses in MWh, external services bought) and three outputs (length of power lines, total power deliveries, number of customers). The models in Kittelsen and Torgersen (1993) and Kittelsen (1993) are similar, differing in some additional outputs and inputs and variables to account for background factors. The findings point out the presence of significant technical inefficiency at the distributors, an estimated waste of around 25% of the resources consumed, valued up to 1,8 billion NOK. Their natural monopoly status has in this case lead to a disguised inefficiency rather than excess profits, which would have been expected. The authors conclude that there is a strong need for an efficiency-improving incentive system and make a case for maximum price regulation to replace the profit-based system. The quality dimension of the service is accounted for, either by a delivery insurance system or through delivery thresholds (e.g., minimum capacity).

Studies from the other Scandinavian countries confirm the impression of considerable inefficiencies in the industry. Hjalmarsson and Veiderpass (1992a, 1992b) and Veiderpass (1992), reporting on a study of Swedish electricity distributors during the period from 1970 to 1986, affirm lasting labor inefficiencies and unevenly distributed information rents. Agrell and Bogetoft (2002) study the 1997 cost efficiency of 234 electricity distributors, modeling a short-term activity with fixed grid capital. They show prevailing inefficiency in long-term (27%) as well as short-term operation (27%). The Danish electricity distribution is discussed in Hougaard (1994), who reports an average inefficiency of 20-40% of the resource consumption regardless of company size. The Danish study indicates a connection between overpricing and inefficiency, suggesting that in particular private households bear the cost of technical inefficiency. Further, public utilities are shown to be less efficient than private and cooperative companies in Denmark, as opposed to the Swedish case where Veiderpass (1992) did not find any connection between ownership and efficiency. Some details from the studies are given in Table 1.

In summary, there is substantial evidence of inefficiency in the industry, amounting to large potential cost savings. In time, this inefficiency should provoke the development and active application of effective and flexible regulatory approaches, in the long-term interest of industry and customers alike.

4. The DEA-Benchmarking Model

The idea behind the DEA benchmarking model is to take multiple inputs and outputs into account in order the comparison of a decision making unit (DMU) towards a set of comparable observations. The inherent difficulty with benchmarking is that all DMUs have private information about their ability to transform inputs into outputs, which enables them to extract information rents. The objective of the regulator is to minimize the extraction of information rents while assuring a satisfactory service. Some common inputs for electricity distribution models are staff (labor hours), productive assets (operating capital, transmission lines in km) and energy (transmission losses in MWh). It is assumed that inputs are to be minimized for each given level of outputs, with the exception of productive assets, which may be treated as a fixed input if the period of regulation is too short. The particular conditions that differentiate distributors are called non-controllable inputs, e.g., customer density, climate zone and other environmental factors beyond our control. Kittelsen (1993) uses a corrosion index, maximum power and customer profile as categorical variables that are eliminated through a step-by-step procedure. Non-controllable inputs are not minimized, but included in the model to assure comparable technologies. E.g., it would be meaningless to compare delivered power/employee hours for a rural and a municipal distribution company, since the technology from the municipal distributor cannot be used in a rural setting. Without loss of generality, the non-controllable inputs are formulated so that a lower value signifies a more favorable condition. By means of the inputs, under influence of the non-controllable inputs, a set of outputs is produced. The outputs are found as revenue generators, i.e., an increase in outputs corresponds to a proportional increase in revenue. In addition to the amount of delivered electricity (MWh, divided into household and industrial customers) and peak power capacity (MW), the number of customers (divided into house-holds and industrial customers) is included. Note that all inputs and outputs are given in real terms, even when prices exist. This is done to separate the price-effect from pure resource allocation, enabling us to reuse past production data to construct future cost norms.

To formalize the above, we assume that each of n DMUs, say DMU^i, transform m_x controllable inputs x^i and m_z non-controllable categorical inputs z^i into m_y outputs y^i. The prices, if existing, on the controllable inputs and outputs are $w^i \in \mathbb{R}_+^{m_x}$ and $p^i \in \mathbb{R}_+^{m_y}$.

We assume that the technological possibilities are the same for all DMUs (except for the differences captured by the non-controllable) variables. Specifically, these possibilities may be thought of as the set T of feasible input-output combinations

$$T = \{(x, z, y) | (x, z) \text{ can produce } y\}$$

We shall generally assume that T satisfy

Condition 1. *Free disposability:* $(x, z, y) \in T, x' \geq x, z' \geq z, 0 \leq y' \leq y \Longrightarrow (x', z', y') \in T$.

Condition 2. *Convexity:* $T(z) = \{(x, z, y) | \exists z' \leq z : (x, z') \text{ can produce } y\}$ *is a convex set for all* z.

Condition 3. *r returns to scale,* $(x,z,y) \in T \Longrightarrow (qx,z,qy) \in T, \forall q \in K(r)$ *,where* $k =$ "crs", "drs," *or* "vrs", *and* $K(crs) = \Re_0, K(drs) = [0,1]$ *and* $K(vrs) = \{1\}$, *respectively.*

The associated underlying cost function for a DMU is given by

$$C(y|z,w) = \min_x \{wx|(x,z,y) \in T\}$$

where w are the prices on inputs x.

Given n observations of feasible production plans (x^i, z^i, y^i) the *DEA based cost norm* for a DMU facing input prices w and non-controllable inputs z is $C^{DEA}(.|.,.) : \mathbb{R}_0^{m_y} \times \mathbb{R}_0^{m_z} \times \mathbb{R}_0^{m_x} \to \mathbb{R}$ defined as

$$\begin{array}{rll} C^{DEA}(y|z,w) = & \min & wx \\ & x,\lambda & \\ & s.t. & x \geq \sum_{i=1}^n \lambda^i x^i \\ & & z\lambda^i \geq z^i \lambda^i \\ & & y \leq \sum_{i=1}^n \lambda^i y^i \\ & & \lambda \in \Gamma(r) \end{array}$$

where $\Gamma(crs) = \mathbb{R}_0^n, \Gamma(drs) = \left\{\lambda \in \mathbb{R}_0^n | \sum_i \lambda^i \leq 1\right\}, \Gamma(vrs) = \left\{\lambda \in \mathbb{R}_0^n | \sum_i \lambda^i = 1\right\}$. The second constraint effectively sorts the observations using the categorical variable z, cf. Agrell and Tind (2001). The DEA based cost function gives the minimal cost of producing the output for any output vector, given the local factor prices and the local non-controllable conditions. Observe that the DEA cost program may not always be feasible. In this case we define the costs to be infinite.

To develop the setting into a full regulatory model, we shall make some *behavioral assumptions* as well.

Assume that the DMU's actual cost $c(y)$ in the planning period is the minimal cost $C(y|z,w)$ plus whatever excess cost or slack $s \in \mathbb{R}_0$ is introduced in the production process, i.e.

$$c(y) = C(y|z,w) + s$$

Note that production slack is summarized here as an additional cost, i.e., it is one-dimensional. The DMU (agent) knows $C(y|z,w)$ but the regulator (principal) does not. The regulator does, however, know the input and outputs in n feasible (historical or inferred) production plans, i.e.

$$(x^i, z^i, y^i) \in \mathbb{R}_0^{m_x+m_y+m_z} \qquad i = 1,..,n$$

Drawing on the information from the n production plans, the regulator can infer from the minimal extrapolation property of the DEA model that

$$C(y|z,w) \leq C^{DEA}(y|z,w) \quad \forall y,z,w$$

The regulator has no additional verifiable information about the cost structure. On the other hand, he may have beliefs or subjective probabilities attached to the different possible cost functions. Formally, we let the regulator's beliefs to be given by the probability distribution

$$p(.) : \mathcal{C} \to \mathbb{R}_0$$

on the class $\mathcal{C}$ of increasing convex r return to scale functions satisfying the above inequalities. The belief distribution represents whatever additional information the regulator has and it is used to close the model as a Bayesian Game.

The objective of the regulator is to minimize the costs of inducing the DMU to accept a contract to produce y. The output y is assumed exogenously given and known, as the demand for the produced service or good is fairly inelastic and stable.

The DMU maximizes the weighted sum of profit and slack, the utility function

$$U_A = (b - c(y)) + \rho(c(y) - C(y|z, w))$$

where $b \in \mathbb{R}$ is the reimbursement, c is the actual cost, y is the implemented production plan, z is the non-controllable inputs with w being the prices on the controllable inputs. The parameter $\rho \in [0, 1]$ is the relative value of slack $s = (c(y) - C(y|z, w))$ relative to profits $(b - c)$ for the DMU.

The DMU's reservation utility is assumed to be 0. From a theoretical point of view, this is without loss of generality. In practice, the reservation utility will depend on several factors, including the ownership structure, the possible earnings in other industries, the time-horizon, the access to a well-functioning capital or insurance market etc. In the present applications, the reservation utility depends also on how capital costs are included. If capital costs are reimbursed directly and only operational and maintenance costs are reimbursed via the incentive regulation, deviations from the reservation utility simply reflect short run deviations from normal profit margins. We will return to this in the comparative study below.

From a social point of view it is important which production plans and costs levels are selected under which conditions. For a given cost function $C = C(.|., .)$, given output y, given non-controllable z, and given input prices w, let $c = c[C, y, z, w]$ be the cost level chosen by the DMU. Hence, $c[., ., ., .]$ represents the response function or strategy of the DMU[2]. We shall then say that the implementation is *cost efficient* if and only if

$$c[C, y, z, w] = C(y|z, w) \qquad \forall C \in \mathcal{C}$$

for the given (y, z, w) such that outputs are produced at minimal cost without cost slack. Since (y, z, w) is fixed for a DMU at a given point in time, we shall suppress (y, z, w) in the formulation of the strategy function $c[C, y, z, w]$ and simply use $c[C]$ to denote the chosen cost level.

5. Single-period Single-unit DEA Regulation

In the particular application, the regulator has access to high-quality verifiable information about realized cost c, as well as about outputs y, non-controllable inputs z and input prices w. This means that the regulator can let reimbursements depend on $[c, y, z, w]$, i.e.

$$b = b[c, y, z, w]$$

or suppressing (y, z, w) to simplify the notation as above, $b = b[c]$.

Extending model (P_{V1}) in Bogetoft (2000), we can therefore formulate the *single-period regulatory problem* as a principal-agent model

[2]The outputs may be more or less directly affected by the DMU. We assume however that the outputs can be verified directly by regulator. Hence, there is no real strategic elements in the choice of y (and no reason to introduce a response function w.r.t. outputs). Any deviations from planned output can be avoided costlessly by harsh punishments for deviations, cf. also Bogetoft (2000).

$$\begin{array}{llll} \min\limits_{b, c(C)} & \Sigma_{C \in \mathcal{C}}\ b[c[C]]p(C) & & \\ s.t. & b[c[C]] - c[C] + \rho(c[C] - C(y|z,w)) \geq 0 & \forall C \in \mathcal{C} & (IR) \\ & b[c[C]] - c[C] + \rho(c[C] - C(y|z,w)) \geq & \forall C, c' : & \\ & \quad b[c'] - c' + \rho(c' - C(y|z,w)) & C(y|z,w)) \leq c' \leq b[c'] & (IC) \\ & b[c'] \in \mathbb{R} & \forall c' \in \mathbb{R}_0 & \end{array}$$

The individual rationality (IR) constraints ensure that the DMU is willing to participate and use the cost strategy $c[C]$. The incentive compatibility (IC) constraints ensure that this strategy is in fact the best possible strategy to use for the DMU. Hence, the constraints delineate the behavior of the DMU. The regulator tries to minimize the resulting expected payments to the DMU subject to these constraints.

Our next proposition characterizes the solution to this contracting problem with verifiable costs c. The proposition extends the result of Proposition 2 in Bogetoft (2000) to the present setting.

Proposition 1. *When the DEA cost model is finite*[3]*, an optimal solution* $(b^*[c], c^*[C])$ *to the single period contract design problem is given by*
$c^*[C] = C(y|z,w)$ *(cost efficiency)*
$b^*[c] = c + \rho[C^{DEA}(y|z,w) - c]$ *(DEA-yardstick)*

Proof. The proof of Proposition 1 can be developed along the lines of Bogetoft(2000). We leave out the details here □

Proposition 1 states that the optimal regulatory scheme is what Bogetoft(1997) called a DEA based yardstick competition scheme, $b^*[c] = c + \rho[C^{DEA}(y|z,w) - c]$. The idea of this scheme is to reimburse the actual costs c and to add (or subtract) an incentive bonus (or cost sharing) terms $\rho[C^{DEA}(y|z,w) - c]$, dependent on the deviation between realized costs c and the DEA cost norm $\rho[C^{DEA}(y|z,w)$. Note that if the DMU beats the costs norm, it keeps a fraction ρ of the savings. If on the other hand the DMU spends more than the norm, the fraction ρ of the cost overrun is charged to the DMU. In this sense, the power of the incentive scheme is given by the ρ factor. This scheme is optimal in the setting outlined in the previous section. Most importantly, it is optimal when there is considerable asymmetric information about costs between the regulator and the firm. The regulator only knows that the cost function $C(.|z,w)$ is an increasing, convex r return to scale function and that the DEA cost model is an upper bound on the true cost function. Under the yardstick scheme, the DMU will choose a cost strategy without any slack, i.e. $c^*[C] = C(y|z,w)$. Thus, the scheme induces the DMU to use cost efficient practices. This is an intuitive property of the optimal solution. Its key driver is that the cost-slack is less valuable than profit to the DMU, but equally expensive for the regulator to provide. Therefore, an optimal solution should try to avoid slack.

From a practical point of view, the advantage of this scheme is that it provides an operational yardstick evaluation and shows how to link the performance measure with the reimbursement plan. A disadvantage of the scheme is of course that the relative value of slack ρ may not be easy to assess. An opportunistic DMU will try

[3]This can be ensured by assuming a sufficient number of historical observations as in Bogetoft(1997), by including experimental data, by introducing subjective dual information or by making suitable return-to-scale assumptions.

Category	Name	Amount	Unit	Price, w	Unit
Output, y	Clients	29,114			
	Delivered energy	848,070	MWh		
Input, x	Labor	97	fte	285,215	NOK/fte
	Losses	57,989	MWh	149	NOK/MWh
	Capital	547,410	kNOK	10.1	%
Non-controllable inputs	Climate zone	5			
	Customer space	0.535	km^2		

TABLE 2. Data for hypothetical electricity distributor D.

Category	Amount	Unit
Historical cost, wx	81,980	kNOK
$C^{DEA}(y\|z,w)$	72,200	kNOK
Slack value, ρ	25	%
Revenue cap, $b\,(c)$	$c+0.25\,(72,200-c)$	kNOK
Revenue cap, $b\,(72,200)$	72,200	kNOK
Revenue cap, $b\,(70,000)$	70,550	kNOK

TABLE 3. Reimbursement for hypothetical electricity distributor D.

to signal a high value of ρ in order to increase his informational rents. However, as long as we can at least find an upper bound on the value of ρ, we can use this as the basis for compensation and the (IR) and (IC) constraints will be fulfilled for all smaller values of ρ (Bogetoft, 1997).

Example. Consider a slightly masked distributor (D) from the set of Norwegian distributors NVE (1997), with data for model $C^{DEA}(y|z,w)$ as in Table 2 below. Using the entire data set as reference, the DEA cost norm of the distributor is determined to 72.2 MNOK compared to the actual cost 81.98 MNOK. This estimate is based only on distributors that have a climate zoning equal or worse than D and an inverted customer density not less than that of D. The contract offered in Table 3, using a slack value $\rho = 0.25$, gives D a bonus amounting to a quarter of the difference between the attained costs and the DEA cost norm. Since the DEA norm is an upper bound to the true cost function $C(y|z,w)$, it is feasible for D to attain cost efficiency. With the current value of slack, $\rho = 0.25$, D is indifferent between $C(y|z,w) = 72,200$ kNOK and further improvements of the operational cost. This is the case because a 1kNOK improvement (reduction in slack) is rewarded with 0.25 kNOK in bonus which gives the same utility as 1 kNOK in slack. In case D does not lower its historic costs for an unchanged output y, the revenue cap $b\,(81,980) = 81,980 + \rho\,(72,200 - 81,980) = 79,535$ kNOK will effectively discourage the consumption of slack, $81,980 - 72,200 = 9,780$ kNOK since it will generate a cash loss of $81,980 - 79,535 = 2,445$ kNOK, the value of which is equal to the utility value of the slack. Moreover, the cash loss will - if we stick to the reservation utility of 0 - be in conflict with the assumed individual rationality constraint.

FIGURE 1. Timeline for the multi-period regulatory review period.

6. Multi-period Multi-unit DEA Regulation

The relevance of a multiple period regulatory regime is quite obvious. Specific investments are not likely to be undertaken at the optimal level unless the regulatory principles are settled for at least some years. Thus, it is natural to think of the historical data as referring to a prior review period and to assume that the regulator commits to a regulatory system for periods $1, ..., T$. This is depicted in Figure 1 below.

We will now extend our single-period regulatory scheme to an operational multi-period model. Let $y_1^i, ...y_T^i$ be the desired production plans, $w_1^i, .., w_T^i$ the input prices and $z_1^i, .., z_T^i$ the non-controllable categorical variables over the planning period $t = 1, ..., T$.

The regulator now faces two fundamental problems. The first problem is a *control problem* of inducing minimal cost in any given period given the information available. The second problem is a *learning problem* of taking into account the progressively revealed information about the cost. These are well-known problems in planning theory and dynamic decision making without conflicting interests, cf. e.g. Faludi (1973). In this literature, a classical control mode is here-and-now planning or blue print planning, and a simple combined control and learning mode is sequential up-dating of the plans. We will define analogous incentive plans here.

The first dynamic regulation model is a simple *here-and-now* or *blueprint incentive model*. It implies committing to a conditional revenue cap

$$b_t^i = c_t^i + \rho \left[C^{DEA}(y_t^i | z_t^i, w_t^i) - c_t^i \right] \qquad t = 1, .., T$$

at the outset of the regulation period and sticking to these levels for the full term. This is relatively simple approach. The regulator develops the cost model at the outset of the planning period and uses it to determine revenue caps throughout the period. The DMU is willing to accept such a contract since $C(y|z, w) \leq C^{DEA}(y]z, w)$ for all (y, z, w). Also, it provides incentives to minimize costs as all the gains are retained by the firm. In this respect, it is similar to a CPI-X scheme. It is more advanced, though, in the way it accounts for changes in the output and prices, cf. below.

Instead of fixing the standards in the base year 0, it may be advantageous to re-estimate the cost structure every year as more and more information accumulates. This can be done without adversely affecting the DMUs behavior, i.e., without the drawback of the rachet effect, as long as no DMU affects its own norm. This leads to the *sequential incentive model* with revenue caps

$$b_t^i = c_t^i + \rho \left[C_t^{DEA-i}(y_t^i | z_t^i, w_t^i) - c_t^i \right] \qquad t = 1, .., T \tag{6.1}$$

where C_t^{DEA-i} is a DEA cost model using the historical information from all but the evaluated unit plus the base period information about the evaluated unit,

$$\begin{aligned} C_t^{DEA-i}(y|z,w) = \quad & \min_{x,\lambda} \quad wx \\ & s.t. \quad x \geq \textstyle\sum_{j \neq i} \sum_{s=0}^{t-1} \lambda^{js} x^{js} + \lambda^{i0} x^{i0} \\ & \qquad z\lambda^i \geq z^{js} \lambda^{js} \qquad j \neq i, s = 0, ..., t-1 \text{ or } (j,s) = (i,0) \\ & \qquad y \leq \textstyle\sum_{j \neq i} \sum_{s=0}^{t-1} \lambda^{js} y^{js} + \lambda^{i0} y^{i0} \\ & \qquad \lambda \in \Gamma(r) \end{aligned}$$

This scheme has numerous advantages, in comparison to the CPI-X regulation. The main advantage of this planning mode is that it utilizes information as it becomes available. It hereby eliminates the problem of excessive rents, cf. Proposition 1, as well as the risk of bankruptcy due to overestimated productivity improvement potentials. The resulting cost norm, as well as any derived productivity improvement rate X, are endogenously determined by the actual performance of the operators. Moreover, the scheme explicitly addresses the ratchet effect. In a repeated relationship, if the regulator can set up a target based on the DMU's previous performance, the DMU will anticipate the inflation of targets and he will then disguise his potential by inflating cost (with slack) in earlier periods to gain more long term utility. To handle this drawback, we use $C_t^{DEA-i}(y|z,w)$ instead of an all-encompassing reference technology, based on all information for all DMUs. This may not be the least expensive way to cope with the ratchet effect, but certainly a pragmatic and feasible one. Based on the DEA multi-output technology, the model copes elegantly with the problem related to changes in input and/or output profile. Finally, price changes are accommodated by using an updated price vector on the underlying physical production opportunity set.

In practice, additional considerations may matter in the design of the regulatory system. It may be unrealistic to assume that a DMU, who is severely inefficient at the outset, is able to eliminate the entire inefficiency over-night before the start of the planning period. To take into account the possible *time lag in eliminating initial inefficiency* we may proceed as follows.

First, we determine the cost efficiency E_0 of the unit in question on the historical data set. Thus, if we plan for DMU^i we first calculate its historical cost efficiency as

$$E_0^i = \frac{C^{DEA}\left(y_0^i | z_0^i, w_0^i\right)}{w_0^i x_0^i}$$

Next, we introduce the fraction δ of the DMU's initial efficiency deficit that it is able to eliminate per year. Using this, the cost norm in period t becomes

$$(1 - \delta(1 - E_0^i))^t \frac{C_t^{DEA-i}(y_t^i | z_t^i, w_t^i)}{E_0^i} \tag{6.2}$$

where the ratio is the cost norm in period t, assuming no individual productivity catch-up by DMU^i and the first factor accounting for the cumulative impact of the limited δ-catch up per period. The factor δ is set such that the total required catch-up never exceeds the initial inefficiency during the regulatory period

$$\frac{(1-\delta(1-E_0^i))^T}{E_0^i} \geq 1$$

E.g., if the initial efficiency is $E_0^i = 0.75$ and the annual catch-up $\delta = 12\%$, we initially allow the cost norm to be inflated by $\frac{1}{E_o^i} = \frac{1}{0.75} = 1.33$ and the annual postulated catch-up factor is $1-\delta\left(1-E_0^i\right) = 1-0.12\cdot 0.25 = 0.97$, resulting in a net extension of cost norm of $1.33 \cdot 0.97 = 1.29$ in period 1, 1.25 in period 2, etc. Hence, a DMU with an excess cost of 33% at the outset of the regulatory period is only required to reduce its inefficiency down to 25% excess cost after two years.

Inserting (6.2) in (6.1), we obtain the *dynamic revenue cap with limited catch-up ability*

$$b_t^i = c_t^i + \rho\left[(1-\delta(1-E_0))^t \frac{C_t^{DEA-i}(y_t^i|z_t^i, w_t^i)}{E_0^i} - c_t^i\right] \quad t = 1,..,T \tag{6.3}$$

As a final remark, if we want to allow for systemwide declines in productivity, we could also eliminate the earlier observations in the estimation. The disadvantage of using short-sighted cost norms that are more sensitive to new information, is that idiosyncratic variations from year to year create significant payment uncertainties. The trade-off between capturing system wide variations and running the risk of capturing idiosyncratic variations, is the general trade-off faced when we go from fixed to more relative performance or tournament-like payment schemes.

7. A Comparative Study

To illustrate the concepts and to contrast the prevailing CPI-X regulation with (i) the existing Norwegian scheme and (ii) the proposed DEA yardstick, we offer a hypothetical dynamic example using the Swedish distribution industry. In the exercise, we will use the actual data available for regulatory use since the liberalization 1996 till 2000. Certainly, the illustration cannot give any insight into the actual behavior of the firms were they to be regulated with the alternative regimes. During the period, the Swedish distribution sector enjoyed a light-handed regime until 1998 when an interim rate-freeze came into effect. Although resembling a price-cap, the regime has a short-term flavor that probably limits the incentives to reveal information.

7.1. **Data.** The panel includes cost and technical data for 238 electricity distribution concessions in Sweden for the years 1996 to 2000. The regulator's records are collected according to the Electricity Act (1997) and consists of audited, public reports. No in-depth analysis has been made of the data, but incomplete or obviously erroneous observations have been excluded. 57 firms in the 1996/1997 analysis and 3 firms in the 1998-2000 analysis were eliminated. Some descriptive statistics are given in Table 4.

7.2. **DEA-models.** The costs of electricity distribution are normally decomposed in capital expenditure (capex, c^{cap}) and operating expenditure (opex, c^o). The capex consists of capital costs and depreciation, whereas the opex normally includes the operating and maintenance costs. From a DEA yardstick viewpoint, it

	Averages for year				
Variable	1996	1997	1998	1999	2000
Firms (observations)	181	181	235	235	235
Financial measures (MSEK)					
Revenues	63,223	64,648	78,530	78,093	78,659
Total cost	49,157	49,952	59,828	60,907	61,185
Operating expenditure	-	-	48,948	48,987	49,232
Capital (book value)	186,296	181,594	174,155	214,603	218,020
Inputs					
Lines, (km)	1,593	1,592	1,860	1,906	1,895
No. LV connections	18,867	18,508	20,798	20,762	20,849
No. HV connections	21	21	25	25	26
Netlosses (MWh)	29,487	18,508	19,461	18,560	18,369
Outputs					
Transferred LV (MWh)	266,804	251,067	277,277	267,271	266,021
Transferred HV (MWh)	93,602	96,992	119.769	130,213	133,899
Max coincidental load[4](MW)	67	65	48	49	50

TABLE 4. Descriptive statistics on Swedish electricity distribution 1996-2000.

is not meaningful to use review periods that are much shorter than the life cycle of the asset, which would give disincentives to capacity investments and jeopardize the amortization of sunk assets. The yardstick would unsuccessfully distinguish managerial slack and capacity utilization, which blurs the construction of the incentive system. The Swedish regulatory benchmarking models, Agrell and Bogetoft (2002) are based on the principle of controllability, where two levels of analysis are undertaken, a long-run and a short-run approach, respectively.

The long-term model LR in Figure 2 incorporates aggregated inputs and outputs and gives an unbiased snapshot of the long-run cost efficiency. The inputs are c^{cap}, c^{o}, netlosses (MWh) and the outputs are coincidental peak load (MW), number of high-voltage connections, number of low-voltage connections, net delivered high-voltage energy, and net delivered low-voltage energy. The non-discretionary categorical outputs are the climate zone and the normalized net length (km), where the latter is a green-field density measure calculated with the actual GIS-located connection points. The model acknowledges limited substitution between the inputs and controls to some extent for exogenous conditions. As all variables are assumed continuous in the long-run, the constant returns to scale model is used, $r = crs$.

The short-run model SR in Figure 3 includes the outputs of the long-range model, but the inputs are restricted to the annual controllability horizon. In the short run, the net is considered as given, which implies that the actual net length and the total energy net losses (in MWh) are treated as exogenous outputs. However, the supplementary cost above market price for electricity is charged to the short-run opex term, c^{o+}. An additional exogenous factor, the number of net stations per installed MW, compensates for the fact that the connection points from the main grid are exogenously given. As scale is given in the short run, the variable returns to scale assumption is evoked, $r = vrs$.

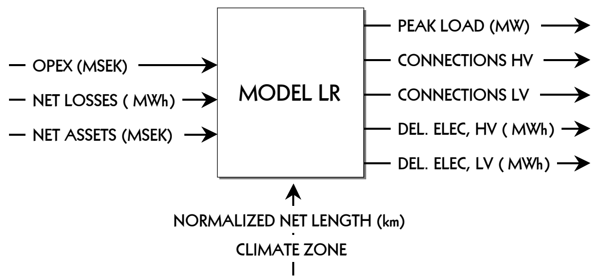

FIGURE 2. DEA Model LR.

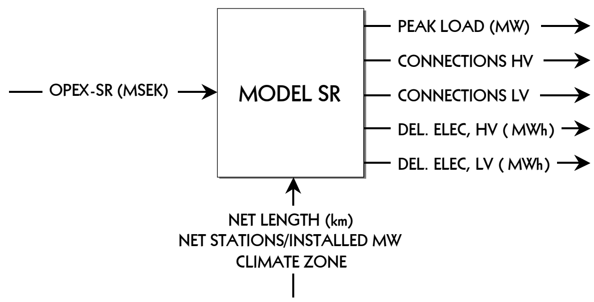

FIGURE 3. DEA model SR.

7.3. **Scenario.** Imagine that Sweden, when liberalizing in 1996, decided to implement regulation in two stages. The first stage, 1996-1997, involves the estimation of the incumbent industry efficiency, to determine the need and character of the regime, and the rate of productivity improvement. During this period, the industry enjoys a fixed revenue cap based on 1996 revenues. The second stage runs from 1998 to 2000 and involves, in three parallel scenarios, (i) a classical CPI-X revenue cap, (ii) a Norwegian-inspired CPI-DEA regime and (iii) a DEA based dynamic yardstick regime as developed in the last section. Let us additionally assume that the introduction of the new regime in 1998 was unexpected, so that no strategic action was initiated during the pre-assessment period 1996/97.

The initial efficiency results from 1996-1997 in the LR model are presented in Table 5. As before, E_o is the cost efficiency. In addition, $M(96, 97)$ is the Malmquist measure of productive improvements between 1996 and 1997, cf. e.g. Coelli, Rao and Battese (1998), $EC(96, 97)$ is the individual catch-up part hereof while $EF(96, 97)$ is the frontier shift part of the productive improvement. The regulator may now conclude that there is a (100-73)% = 27% total cost inefficiency to address in 1997, but that the efficiency change is fairly rapid. Although the drastic 21% frontier change may be the result of increased data quality in the reporting as well as enforced vertical separation, the 12% average efficiency catch-up still rests impressive.

Model LR, $n = 181$	Min	1st quart	Median	Mean	3rd quart	Max
$E_0\,(LR, crs, 1996)$	0.27	0.49	0.62	0.68	0.90	1.00
$E_0\,(LR, crs, 1997)$	0.35	0.55	0.72	0.73	0.94	1.00
$M\,(96, 97)$	0.42	1.09	1.29	1.33	1.51	3.89
$EC\,(96, 97)$	0.40	0.97	1.06	1.12	1.27	2.37
$EF\,(96, 97)$	0.59	1.03	1.19	1.21	1.36	2.30

TABLE 5. Results model LR 1996-1997.

7.4. **Revenue cap CPI-X.** The classical revenue cap (R) is here represented with the volume adjusted regime $b_t^R(y)$,

$$b_t^R(y_t) = \frac{V(y_t)}{V(y_0)} R_0\,(CPI_t - X)^t \tag{7.1}$$

where $t = 0, 1, ..T$ is the regulation period, with $t = 0$ as base year, R_0 is the base year revenue at total delivered energy $V(y_0)$, CPI_t is the consumer price index for year t relative to the base year, X is the annual productivity improvement factor, and $V(y_t)$ is the total delivered energy year t, i.e. an un-weighted summation of energy delivery terms in y_t. Based on the initial analysis, we assume that the regulator moderates the annual improvement to $X = 5\%$ during the first regulatory period. In practice, this factor is usually the result of a negotiation with the industry and other stakeholders, where the initial analysis is but one of the inputs. Our assessment here is a fairly optimistic one, whereas the UK experiences (2.5%) and Norway (2%) suggest fairly conservative estimates. Without loss of generality, we set the consumer price index to unity during the period[5].

7.5. **Norwegian CPI-DEA.** The Norwegian regime is illustrated using two models to clearly distinguish the elements. The core of the regime is a revenue cap (N) with volume adjustment, $b_t^N(y_t)$,

$$b_t^N(y_t) = CPI_t \left(\frac{V(y_t) + V(y_{t-1})}{2V(y_{t-1})} \right) R_0(1 - X^{NVE} - \delta(1 - E_0^{LR}))^t \tag{7.2}$$

where CPI_t is the consumer price index for year t relative to the base year, X^{NVE} is a general efficiency improvement parameter as set by the Norwegian regulator, NVE, δ is the individual efficiency catch-up requirement, and E_0^{LR} is the initial cost efficiency 1996/97. The second term is a volume adjustment factor that smooths out changes in the demand volume $V(y)$. In the illustration, we assume that the efficiency catch-up requirement is allocated as a general term ($X^{NVE} = 0.025$) and as an individual term ($\delta = 0.025$); parameters that closely correspond to actual practice. The scores for cost efficiency E_0^{LR} are obtained from the LR model above, using 1996/97 as the base year. Additionally, we also calculate the implemented revenue window b^{NC}, which specifies floor and ceiling for the allowed revenue. The maximum revenue b_t^{NC} at time t is given as

$$b_t^{NC}(c_t) \leq \eta_{\max}\widehat{x}_t + c_t \qquad t = 1, .., T \tag{7.3}$$

[5]As the consumer price index was less than one during the deflationary period 1996-1999, this actually brings a cautious estimate to the illustration.

where $\eta^{\max}$ denotes the maximum allowed rate-of-return (15% in NVE (1997)), $\widehat{x}_t$ denotes the capital base of the DMU at time t and c_t is the actual cost at time t. The revenue floor is analogously given as

$$b_t^{NC}(c_t) \geq \eta_{\min}\widehat{x}_t + c_t \quad t = 1,..,T \tag{7.4}$$

where $\eta^{\min}$ denotes the minimum prescribed rate-of-return (2% in NVE (1997)). This constraint assures the economic survival of the distributor and may have additional effects on the cost structure of the industry.

7.6. **DEA Yardstick.** The DEA based dynamic yardstick scheme (Y) proposed in this paper is implemented as the formula

$$b_t^Y(y_t) = c_t + R_0 - c_0 + \rho\left(c_t^o E_t^{SR} - c_t^o\right) \tag{7.5}$$

where $c_t = c_t^{cap} + c_t^o$ are the total costs for year t, $R_0 - c_0$ is the gross margin before tax in the base year, ρ is the valuation of slack and E_t^{SR} is the short-run cost efficiency year t using the SR model above. Note that $C_t^{DEA-i}(y_t) = c_t^o E_t^{SR}$, where the cost efficiency E_t^{SR} is calculated using superefficiency. This may render unbounded solutions to the DEA program. In the latter case, we say that the DMU is hyper-efficient and the efficiency bonus $\rho(c_t^o E_t^{SR} - c_t^o)$ expression is substituted by $\gamma(R_0 - c_0)$, an ad hoc allowance of γ multiples of the base year profit. A hyper-efficient DMU is thus rewarded with a profit margin of γ. The sensitivity of the solutions with respect to this assertion will be developed below. The slack valuation is set to 50%, $\rho = 0.5$ which means that half the controllable excess cost is reimbursed (or inversely, half the cost savings are awarded as revenue increases). This latter assertion is also subject to sensitivity analysis, but must be considered as an initial focal point in the regulatory game.

7.7. **Analysis.** The outcome of three years regulation using the three regimes is given in Table 6 below. Apparently, the actual costs were very stable under the revenue cap that kept the revenues fixed. The regimes have somewhat different profiles, as also illustrated in Figure 4. The CPI-X regime mechanically extracts the rent with equal amount, lowering the last year income cap to below 16,000 MSEK. The Norwegian system is less aggressive, a monotonous extraction that stops at 17,086 MSEK in the final year. The variant of the NVE scheme that floors payments to c_t follows her sister closely, ending at 304 MSEK above. The ABT scheme is relatively stable, although the first decrease is more rapid than the NVE schemes. The final total revenue allowance in the dynamic DEA yardstick regime is at 17,276 MSEK, between the two NVE plans. Table 7 gives the informational rents along with statistics of the number and amount of negative gross results in the final year. Here, we notice that the CPI-X regime achieves a high extraction at a fairly high rate of negative results in the final year; 103 out of 181 distributors cannot cover their total costs. The raw NVE scheme has a milder effect, awarding 9,598 MSEK in total rents over the period and provoking 74 instances of net losses amounting to a total of 263 MSEK in the final year. The floored NVE regime allows an additional 252 MSEK in information rents, but avoids all negative rents. The yardstick regime is closer to the raw NVE scheme and allows 9,679 MSEK in rents over the period. The net losses are at a similar scale (71 instances the last year), but the amount is considerably smaller (163 MSEK against 263 MSEK). The explanation is found in the smoothness of the yardstick schedule, that distributes the rent extraction over

	Year			
MSEK	1997	1998	1999	2000
c_t	14,019	14,059	14,313	14,378
R_t	18,286	18,454	18,351	18,484
$b_t^R(y_t)$		17,582	16,783	15,987
$b_t^N(y_t)$		17,829	17,433	17,086
$b_t^{NC}(y_t)$		17,640	17,570	17,391
$b_t^Y(y_t)$		17,595	17,559	17,276

TABLE 6. Results regulation regimes R, N, NC and Y 1998-2000.

	Year					Losses: $b_t(.) < c_t$		
	1997 MSEK	1998 MSEK	1999 MSEK	2000 MSEK	Total MSEK	*Freq* #	2000 MSEK	Total MSEK
$R_t - c_t$	4,267	4,395	4,038	4,106	12,540	19	66	103
$b_t^R(y_t) - c_t$		3,523	2,470	1,609	7,602	103	406	664
$b_t^N(y_t) - c_t$		3,770	3,120	2,708	9,598	74	263	435
$b_t^{NC}(y_t) - c_t$		3,581	3,257	3,012	9,850	0	0	0
$b_t^Y(y_t) - c_t$		3,535	3,246	2,898	9,679	71	169	553

TABLE 7. Industry rents and occurencies of cost non-recovery for regulation regimes R, N, NC, and Y 1998-2000.

time and according to the local productivity. Whether any of the presented raw schemes could have been implemented is a hypothetical question, but in particular the CPI-X scenario seems likely to provoke a renegotiation in the second year.

Finally, a word on the mechanics of the dynamic DEA based yardstick regime and its parameters that is not visible in the aggregated scores. The yardstick incentive bonus / cost sharing component $\rho\left(c_t^o E_t^{SR} - c_t^o\right)$ for the finite scores amount to -1800, -2102, -2023 MSEK for the years 1998, 1999 and 2000, respectively. This corresponds to a considerable internal transfer of funds, that is only partially compensated for by overpayment for hyper-efficient units 1069, 1081, 654 MSEK for the years 1998, 1999 and 2000, respectively. In Table 7, an increase of the compensation for hyper-efficient units would increase the total rent transfer to the firms, without any change in frequency or gravity of the losses. Analogously, decreasing these transfers would lower the overall transfer, potentially to a level lower than the CPI-X schedule with much lower net losses. However, such opportunistic action is of course contradictory to the yardstick principle where the evaluated unit gets to keep his share of the rent in return for the information supplied.

8. DISCUSSION

Data for the actual productivity and efficiency performance during the period 1998-2000 is given in Table 8. As opposed to the dramatic efficiency improvements in the initial period 1996/97 (Table 5), the later results indicate a very stable technology and behavior. Neither the frontier change (1.01) nor the catch-up factor

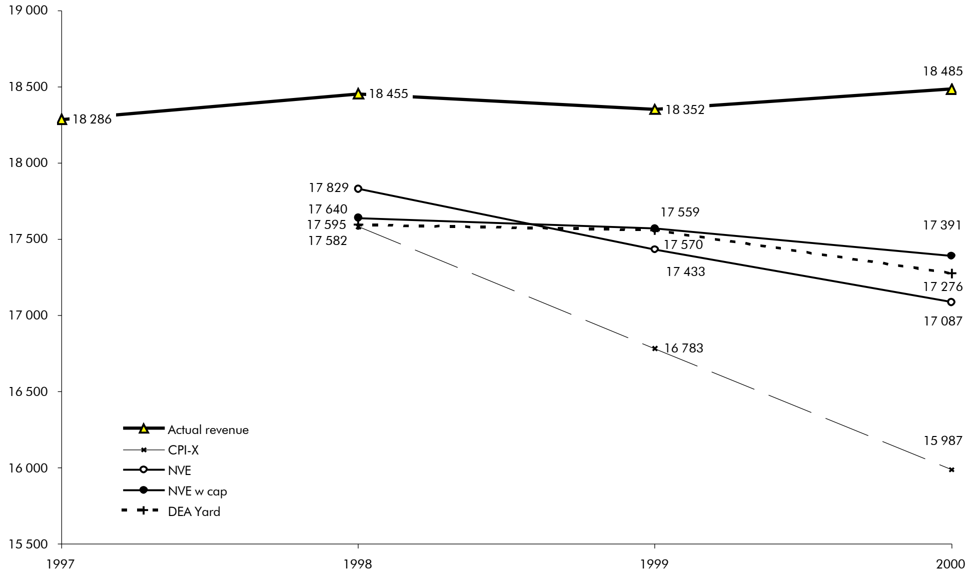

FIGURE 4. Actual costs c_t and reimbursement norms b_t^R, b_t^N, b_t^{NC}, b_t^Y.

(0.98) suggest that the industry would be capable of improvements in the order of 5-10% per year. In fact, institutional information suggests that the initial improvement is more attributable to the data quality improvement process than to any performance improvement. Nevertheless, the point illustrates the difficulty of operating a CPI-X system with *ex ante* productivity improvement requirements. Clearly, the initial data overstate the durable improvement rate, but there are no incentives for the industry to reveal any other information in a negotiation on the X-factor. Given that all firms enjoy the same revenue factor, there are strong incentives to collude on evidence suggesting the infeasibility of high X-factors. The regulator must then rely on objective data, which can be risky in the presence of data errors. The DEA yardstick is more stable in this sense, not requiring the regulator to outguess the industry. The only important parameter to negotiate is the incentive power ρ and the negotiation is less evident then for X. Over-performing firms have private incentives to suggest high-powered contracts, whereas inefficient firms would argue for low-powered contracts. Although only an actual situation could provide evidence on the relative bargaining powers of the firms, our postulated $\rho = 0.5$ seems to be a plausible initial point of departure. In the example, the regulator could resort to a graph as Figure 5 to inform the choice. With the actual data, the total allowable horizon revenue under the CPI-X regime (50,353 MSEK) corresponds to a DEA yardstick with power $\rho = 0.833$. Choosing more high-powered regimes would extract even more rent from the industry than the revenue cap. The uncapped NVE regime b^N corresponds in total horizon revenue to a power $\rho = 0.513$ and the capped b^{NC} to $\rho = 0.473$, which supports the finding in Fig. 4 where the two regimes are very close for the choice $\rho = 0.5$. An important feasibility criterion could also be the expected level of net losses in the industry.

Model LR, $n = 241$	Min	1st quart	Median	Mean	3rd quart	Max
$E_0\,(LR, crs, 1998)$	0.16	0.50	0.60	0.63	0.73	1.00
$E_0\,(LR, crs, 2000)$	0.17	0.49	0.59	0.62	0.73	1.00
$M\,(98, 00)$	0.68	0.94	0.99	1.00	1.04	1.70
$EC\,(98, 00)$	0.67	0.93	0.98	0.99	1.03	1.81
$EF\,(98, 00)$	0.79	0.99	1.01	1.01	1.02	1.09

TABLE 8. Efficiency results, actual data 1998/2000, model LR.

An acceptance of the observed level of industry losses in 2000 as a reasonable cost of reorientation, would imply an *aposteriori* choice of $\rho = 0.31$.

The yardstick regime relies heavily on the superefficiency concept, which in itself introduces a parameter. To illustrate this concept, Table 9 provides some data on the regulatory model SR. The average level rests relatively stable around 70%, with occasional high scores. The number of hyperefficient DMUs is between 10 and 11 per year, which also indicates that the determination of the compensation for hyperefficient firms is a relatively limited task that could be handled on a case-to-case basis[6]. In terms of sensitivity analysis, the impact of γ on the overall allowable revenue is a consequence of the scale assumption, $r = vrs$, which makes the largest firms hyperefficient by construction. Since these firms have the largest margins in absolute, but not proportional, terms, the impact is larger than the number of instances suggests. Hence, we argue that these firms could be compared with other reference DMUs or be subject to some *ad hoc* capping of the revenue. The frequency of over-performers in the dataset is illustrated in Fig. 6 below. The histogram clearly shows the rarity of extreme observations, with a bimodal distribution around 0.70 and 0.90. Hence, there is empirical evidence to prove the feasibility of the superefficiency model, which is a prerequisite for the DEA yardstick scheme.

We are here investigating several problems being faced in the implementation of different regulatory schemes and the problems of the new theoretical proposal, the dynamic DEA based yardstick scheme, in particular. This provides useful information and takes the theory of combining operational productivity analysis methods with incentive theory one step further towards application. On the other hand, the comparative study of the different schemes on real life data can never fully capture the differences. The reason is that the actual behavior is guided by the incumbent regime, and not the alternative schemes we consider here. Hence, we only capture part of the effects. To capture the behavioral effects in a model calibrated on real data, we would have to combine the empirical analysis with simulations under alternative behavioral hypothesis.

9. CONCLUSION

In this paper, we have revisited the regulation of the electricity distribution industry and suggested a regulatory framework for the multiple-input, multiple-output, multiple-period case based on efficiency benchmarking and incentive theory.

[6]Eight of the units are hyperefficient in 1998 and 1999 and four are hyperefficient all three years, which suggests a fairly particular technology in these DMUs.

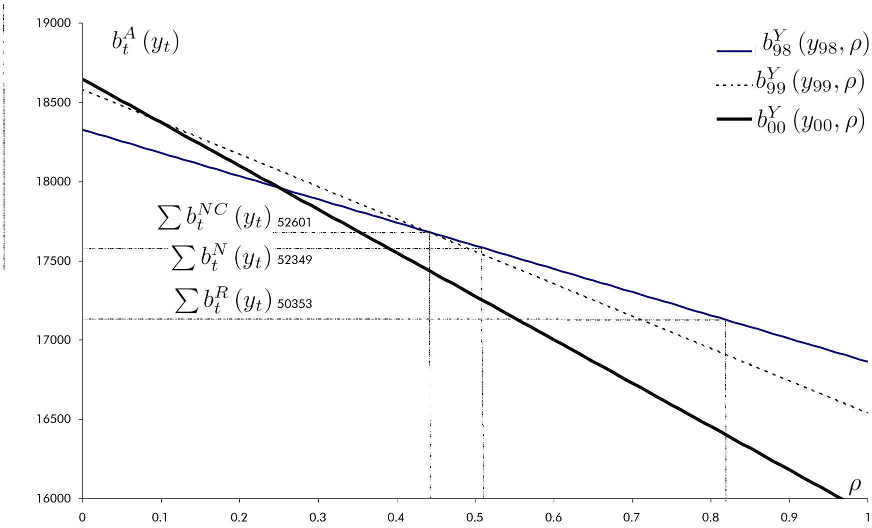

FIGURE 5. DEA yardstick as a function of slackvaluation ρ.

Model SR, $n = 241$	Min	Mean	Max	$\#(E_0 > 1)$	$\#(E_0 \to \infty)$
$E_0(SR, vrs, 1998)$	0.16	0.74	1.91	27	10
$E_0(SR, vrs, 1999)$	0.17	0.68	3.32	18	11
$E_0(SR, vrs, 2000)$	0.17	0.72	2.81	26	11

TABLE 9. Efficiency results, actual data 1998/2000, model SR (superefficiency).

We have shown that the previously developed theory has a practical implementation. In this endeavour, some of the implementation decisions to be made have been discussed, e.g. how to handle hyper-efficient units. Also, we have shown that the DEA based dynamic yardstick model compares favorably to the popular CPI-X model. In particular, the approach solves four essential problems with the CPI-X model: (i) risk of excessive rents (or high participation risk), (ii) the ratchet effect, (iii) the arbitrariness of the parameters CPI and X, and (iv) the inability to accommodate changes in the output profile. Illustrated with a realistic, albeit retrospective case from the Swedish electricity distribution 1996 through 2000, the DEA yardstick regime measures well against the CPI-X models and the Norwegian CPI-DEA model. Following a turbulent initial period that, analogously to the 94/95 initial period in the Norwegian regulation, potentially could have served to inform a revenue cap decision, the technology settles to a stable level. The DEA yardstick reflects this stability in that extraction of rent from inefficient operators take place continuously, rather than progressively over the period. The overall expenditure with a mid-powered regime is at par with the Norwegian regime, but avoids the end-of-period tensions due to escalating losses. Indeed, since the initial periods of a regulation may be more turbulent than later periods, we believe that the dynamic

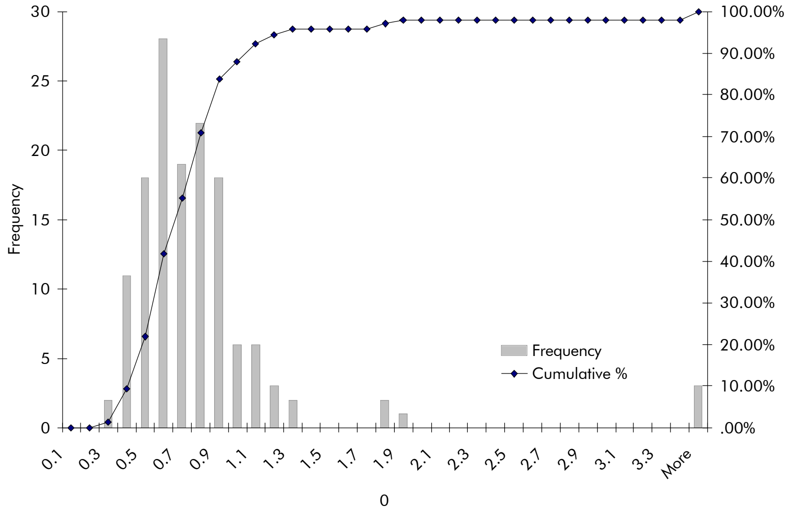

FIGURE 6. Efficiency scores E_0 in SR model (superefficiency) 1998-2000, histogram.

DEA model has particular advantages due to its more immediate response to new information compared to e.g. a CPI-X regime. We also show that the problem with hyper-efficient points is limited, but that care should be taken not to reward firms that are efficient by virtue of *a priori* scale assumptions..

All in all, the dynamic DEA yardstick offers an advanced and potentially promising technique to address some of the many challenges that a regulator is facing in the liberalized electricity market. It also manifests itself as a combination of an *ex post* performance evaluation technique and a microeconomic reimbursement contract, offering the technical sophistication of the former and the economic soundness of the latter. A good marriage, both for the firm and the regulator.

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