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STOCHASTIC TECHNICAL EFFICIENCY ANALYSIS OF ELECTRICAL POWER PLANTS CENTERED ON AVAILABILITY

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Abstract. *This work proposes a theoretical framework for the technical efficiency analysis of electrical power plants maintenance management using the stochastic frontier analysis methodology. The analysis evaluates the success of 36 hydropower plants on implementing and sustaining maintenance programs directed to improve the levels of operational availability. The model proposed here is employed to answer the following question: How effectively are the power plants employing corrective maintenance, time-based preventive maintenance, condition-based preventive maintenance programs, RCM or TPM programs? For a snapshot of the plant performance in the year 2000, the analysis shows that the plants employing RCM have a high technical efficiency. This type of analysis may be used to measure the mean performance of the sector, to detect underperforming plants and to set performance targets. This methodology is suggested as one tool for regulatory policymaking and enforcement.*

Keywords: *Maintenance Management, Operational Availability, Electrical Power Generation, Regulatory Policymaking*

1. Introduction

The technical efficiency analysis is a diagnostic tool that quantifies the quality of the actual state of maintenance management of a given power plant, generating information that allow an assessment of the best practices employed by the electrical power generation companies. The techniques applied in a technical efficiency analysis can provide a way of identifying underperforming units (Epstein and Henderson, 1988) regarding the transformation process of using resources to obtain a desired output.

Many methodologies have been developed in an attempt of correctly assessing all the complexity involved with the analysis of real-world technical efficiency problems. Two main methodological lines can be generically identified as the non-parametric approaches, consisting mainly of the Data Envelopment Analysis, DEA, and its developments (Charnes et al., 1997), and the parametric approaches, such as the Stochastic Frontier Analysis, SFA, (Kumbhakar and Knox Lovell, 2000). The former are based on linear and non-linear mathematical programming techniques, and the later are based on statistical and econometric techniques.

A few works related to the efficiency analysis of electrical utilities using these approaches (mainly the DEA) have been published. For instance, the economics in the production of electricity has been treated by Fare et al. (1989a, 1990), the effects of environmental regulations by Fare et al. (1989b), impacts of privatization on the efficiency of generation by Hammond (1992), Powell (1993) and Bunn (1994). Other works related to electrical utilities are Bateson and Swan (1993), Golany et al. (1994), Athanassopoulos et al. (1999). Greene (1990) and Park and Lesourd (2000) discuss the use of SFA of technical efficiency of power plants and electrical utilities.

Although some of these works (e.g., Athanassopoulos et al., 1999) treat the problem of plant availability, to the author's knowledge, nothing has been published focusing the problem of maintenance management and the operational availability as a function of maintenance programs.

The Stochastic Frontier Analysis is proposed as a method of maintenance management efficiency diagnostic. The problem is formulated based on some factors that determine the maintenance systems effectiveness and the data measuring these variables are considered to be correlated with the levels of operational availability achieved by the power plant. The term stochastic is used because the actually achieved levels of availability are stochastic in nature, i.e., these levels are not entirely under control of the management due to the random nature of failures and other administrative and corporative factors.

In the following, the availability of power plants is discussed, the SFA method is presented and the efficiency analysis is applied to a set of hydropower plants that represent about 66% of the total installed capacity in Brazil. The article is concluded with an analysis of the use of this type of information in regulatory policymaking.

2. Power Plant Availability

Electrical energy outages have a substantial impact on economy. The actual costs associated to the interruptions of electrical energy supply depend on the degree and nature of the consumption and are a function of the class of consumers (e.g., eletro-intensive industries are the most dependent) and the characteristics of the interruption (frequency, duration, etc.). An outage may be the source of direct and indirect costs, both economic or social. The direct economic costs are related to equipment and facilities damage, production losses, costs of production restart, idle but paid-for resources (labor, capital), spoilage of raw materials or products, extra-time for production recovery, and other related costs, for instance, the acquisition of emergency utilities (Subramanian et al., 1985, Wacker and Billinton, 1989).

The interruption of electrical energy supply to the final consumers depends on the overall reliability of the electrical system, including the generation, transmission and distribution systems. One of the most important questions raised when planning the power generation installed capacity in an interconnected system is how much to plan as extra generating capacity above peak demand. This is called the reserve of the power generation and must be properly dimensioned to prevent undue electrical energy shortages caused, for example, by a reduction in the overall level of hydropower plants reservoirs, or the ever present forced outage rates of the power plants. A forced outage demands an extra capacity of the generating system since it can be understood as an addition to the power demand of the consumers from the system. Besides the forced outages, preventive maintenance scheduling can also be viewed as an addition to the demand, influencing the reserve planning. The occurrence of forced outages and scheduled maintenance activities affects the operational availability, which is a measure that depends upon the reliability, maintainability, and maintenance engineering and management.

Equipment maintenance and reliability are important in the effective running of power plants since forced outages and unavailability have direct effects on the production of electrical power. The dependence of continuous process plants and capital-intensive operations, such as electrical power plants, on equipment operation and technology is higher than the dependence of any other type of manufacturing process in achieving the best level of competitiveness (Slack et al., 2002). Since machinery is in charge of production, the generation of electrical power will shut down when the failure forces a complete outage, or will be reduced when the failure results in partial load operation. The main focus of the management of plant maintenance is the minimization of the failure rates and all the efforts are directed to that. However, since equipment failure is unavoidable, the management of an effective maintenance system must also take the steps to guarantee that the plant will be restored to operational status in the shortest time possible, the failure effects on production will be minimized, the plant functionality and life-cycle will be preserved while all social and environmental costs and damage will be avoided or minimized. The operational availability of a system can be defined as the probability that the system will operate satisfactorily when called upon at any point in time under specified operating conditions and in an actual logistic support environment (Blanchard et al., 1995). When a power plant is unavailable, its capacity of generating electrical power is inexistent.

When considering a simple two-state model of a unit with total availability or complete unavailability, the availability factor is an adequate estimator of the probability of not having the capacity installed in a plant available in the future when it is evaluated over a long period of time of operation (Billinton and Allan, 1984; Billinton and Allan, 1987). The binomial probability distribution can be applied to estimate the probability of an out of service capacity when the availability is considered to be the probability of success and the unavailability is considered to be the probability of failure (Billinton and Allan, 1987).

Table (1) presents a capacity outage probability table for two hydropower plants in the Brazilian power generation grid. Plant A has 3 generating units, each one with 425 MW of installed power, with an average availability factor of 76% during the year of 2000. Plant B has 3 generating units, each one with 216 MW of installed power, with an average availability factor of 96.9% during the same year (ANEEL, 2000).

Table 1. Capacity outage probability table for two hydropower plants in Brazil

PLANT A: 1275 MW, 76% availability factor.

Units Up	**Units Down**	**Available Capacity**	**Probability**	**Load Loss**	**Expected Load Loss**
3	0	1275 MW	0.438976	0 MW	0 MW
2	1	850 MW	0.415872	425 MW	176.75 MW
1	2	425 MW	0.131328	850 MW	111.63 MW
0	3	0 MW	0.013824	1275 MW	17.63 MW

PLANT B: 648 MW, 96.9% availability factor.

Units Up	**Units Down**	**Available Capacity**	**Probability**	**Load Loss**	**Expected Load Loss**
3	0	648 MW	0.9098	0 MW	0 MW
2	1	432 MW	0.08732	216 MW	18.86 MW
1	2	216 MW	0.00279	432 MW	1.207 MW
0	3	0 MW	2.98 E-5	648 MW	0.019 MW

It can be seen for Plant A that the probability of not having at least one of the three units available in a given time during the period (one year) is higher than the probability of having the total capacity available. The total expected load loss of this plant is about 306 MW, therefore with this level of availability the actual investment to obtain 1275 MW in the generation system is the investment needed to install the plant with 1275 MW plus another plant with 306 MW (or more if the unavailability of this other smaller plant is also taken into account). The total expected load loss for Plant B is lower due to its higher availability. Actually, this analysis is not that simple since the final power generated depends on the interplay between plant scheduling and plant availability. Nevertheless, we can assume that the base-load plants are indeed greatly affected by the availability factor.

The effect of derated states (partial availability) can also be calculated with the aid of a method based on Markov Chain Processes (Billinton and Allan, 1984). In this case, the production of energy is affected by failures that do not demand the shut down of a unit but reduce the power that could be generated. (e.g., Billinton and Allan, 1984; Wood, and Wollenberg, 1996).

These two examples above show how important is the availability in the productivity of an electrical power plant. The availability factor itself is not an output of power plants but is directly related to the amount of output a plant produces and is taken as the main indicator of productivity in power generation. We note that the main objective of maintenance systems is to transform resources into a maintained production system (Tsang, 2002). Therefore, the availability factor can be considered an output when the maintenance systems of the plants are considered as a transformation process encapsulated in an enterprise system. This is the basis of the use of the technical efficiency analysis of availability, based for instance in the stochastic frontier analysis, as an assessment or policymaking tool.

3. Stochastic Frontier Analysis of Technical Efficiency

Figure (1) illustrates the basic concept of technical efficiency for a simple transformation process in which a single input produces a single output. A firm is technically efficient if it operates on the production frontier OF, which is the maximum output attainable for each input level. The firm operating beneath the frontier on point B is O/O* technically efficient while the score for the firm operating on the point A is 1. The simple concept illustrated in actual implementations is extended to the multi-input and multi-product cases.

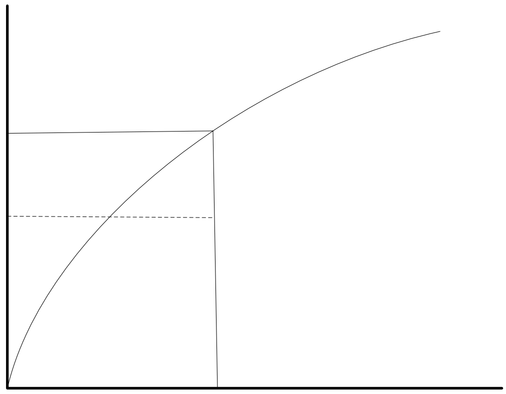

Figure 1. Technical efficiency for a simple transformation process in which a single input I produces a single output O.

The stochastic production frontier models are derived from a deterministic understanding of technical efficiency:

$$y_i = f(x_i;\ \beta).TE_i \tag{1}$$

This model assumes that cross-sectional data (a single observation of every producer) on the quantities of the number of inputs used to produce a single output are available. The value y_i is the scalar output of the producer i, x_i is a vector of n inputs used by producer i, $f(xi;\ \beta)$ is the production frontier, and β is a vector of technology parameters to be estimated. The output-oriented technical efficiency TE_i is defined as the ratio between the observed output and the maximum feasible output:

$$TE_i = \frac{y_i}{f(x_i;\beta)} \tag{2}$$

If $TE_i = 1$, the observed output y_i reaches its maximum possible value defined by $f(x_i;\ \beta)$.

The equation above is deterministic because the entire difference between the observed output and the frontier is attributed to technical efficiency. A stochastic production frontier takes into account the fact that the output is affected by random factors that are not under the control of the producer, as it is the case of power plant availability. Equation (2) is rewritten to incorporate random variation into the analysis:

$$TE_i = \frac{y_i}{f(x_i;\beta).\exp\{v_i\}} \tag{3}$$

The stochastic production frontier is defined as $f(x_i;\ \beta).exp\{v_i\}$. The term $exp\{v_i\}$characterizes the environment where the ratio between the observed and the feasible output occur. An assumption is needed about the form of $f(x_i;\ \beta)$ for estimating TE_i. The log-linear Cobb-Douglas and the translog forms are often used, for instance.

The analysis undertaken follows the general model proposed by Battese and Coelli (1995), in which the stochastic frontier is given by:

$$\ln y_i = x_i\beta + v_i - u_i \tag{4}$$

and the inefficiency model is:

$$u_i = \delta_0 + z_i\delta + w_i \tag{5}$$

The y_i represents the measured availabilities, x_i is the vector of values of the production inputs or other explanatory variables, v_i are independent identically distributed (iid) random variables normally distributed, i.e., $N(0, \sigma_v^2)$, which represents the random statistical noise and exogenous effects beyond the control of the management, and u_i are the nonnegative technical efficiency components representing TE_i in Eq. (3). In Eq. (5), z_i is a vector of function values of factors that are known to affect the technical efficiency, and w_i are iid random variables defined by the truncation of the normal distribution with mean zero and variance σ_w^2. The vectors β and δ are parameters to be estimated. When $u_i = 0$ the production lies on the efficient frontier. The relevant log-likelihood function of the stochastic frontier model, which is expressed in terms of the vectors β, δ, and δ_0, and the variance parameters $\sigma^2 = \sigma_w^2 + \sigma_u^2$ and $\gamma = \sigma_w^2/\sigma^2$, is presented in the cited reference.

The SFA is designated a parametric approach because assumptions about the stochastic properties of the data are necessary and a particular functional form is imposed where the efficiency is determined relative to a frontier which is statistically estimated. The distribution characteristics of v_i and u_i follow assumptions necessary to estimate the parameters of the model. The noise component is conventionally assumed to be a iid normal distribution $N(0, \sigma_v^2)$. The technical efficiency component may assume distributions such as the half normal, the exponential, and the gamma distribution. The model used assumes the half-normal distribution. A full presentation and discussion of the model assumptions and implications is given by Battese and Coelli (1995), and Kumbhakar and Knox Lovell (2000).

After deciding which assumptions are applicable, the model parameters estimation can be carried out with methods including the ordinary least squares method, OLS, and the maximum-likelihood method (Kumbhakar and Knox Lovell, 2000).

4. Model of Factors Affecting Plant Availability

The ANSI/IEEE (ANSI/IEEE, 1987) standard with definitions for reporting electric generating unit reliability, availability, and productivity defines unit states and capacity terms used to understand the possible states of a power plant with respect to the production of electrical power. The availability factor, AF, is defined as:

$$\mathrm{AF} = \frac{\mathrm{AH}}{\mathrm{PH}}.100 \tag{6}$$

where, AH is the number of hours a unit was in the available state and PH is the period of analysis (generally one year). Equation (5) represents an observed availability, since the AH is the sum of hours that the plant was in the available state. The theory of reliability and maintainability generally treats the problem of unit availability with a different formulation, focusing more on the understanding of the internal processes that define the availability of a plant rather than on the measurement of the resulting times, as it is done with the previous index. The operational availability, A0, also understood as the availability factor, AF, can be expressed as (Blanchard, 1995):

$$\mathrm{A}_0 = \frac{\mathrm{MTBM}}{\mathrm{MTBM} + \mathrm{MDT}} \tag{7}$$

where MTBM is the mean time between maintenance, which is a function of planned and unplanned maintenance:

$$\mathrm{MTBM} = \frac{1}{1/\mathrm{MTBM}_u + 1/\mathrm{MTBM}_s} \qquad (8)$$

MTBM_u is the mean time between unplanned (or unscheduled) maintenance and MTBM_s is the mean time between planned (or scheduled) maintenance.

The maintenance downtime, MDT, is the sum of total time spent to repair and restore a system to a level of performance or to retain and maintain it at that level. The MDT considers the mean active time, $\overline{\mathrm{M}}$, the mean time effectively spent on preventive or corrective maintenance activities, and the administrative, ADT, and logistics delay times, LDT:

$$\mathrm{MDT} = \overline{\mathrm{M}} + \mathrm{ADT} + \mathrm{LDT} \qquad (9)$$

Some authors (e.g., Smith and Knezevic, 1998a,b) also express the operational availability as a function of a mean time to support, MTTS, which includes the delay times with logistic and administrative tasks. The emphasis on time to support is important because this is practically the only factor under the total control of management, even though this control is not complete due to equipment design, environment, and operating conditions.

The equations above demonstrate that the availability is a function of plant reliability, maintainability and the effectiveness of maintenance management. Reliability and maintainability are system design characteristics that address the failure rates of the equipment, and the ease, accuracy, timeliness, and economy of maintenance actions (Blanchard et al., 1995). Maintenance is an action performed in the event of a failure or to prevent a failure. Many of the factors affecting the achieved availability are not under the control of the plant maintenance management and therefore must be considered when evaluating the technical efficiency of maintenance management.

Plant type, size, age, design, manufacturing, procurement and construction are uncontrollable factors affecting plant availability. Generally thermal plants have the lower levels of availability due to their higher complexity, and as the size of the plant increases, the complexity also becomes a problem to reliability. The age of a power plant affects the availability because the failure rates follow a pattern known as the bathtub curve: the failure rates are generally higher in the first years after commissioning, because of learning and debugging processes, and after a period of constant relatively low level the failure rates increase again due to, mainly, the aging of equipment (Vardi and Avi-Itzhak, 1981). Figure (3) shows the bathtub curve for the failure rates of 36 hydroelectrical power plants in Brazil assessed for the year 2000 (ANEEL, 2000).

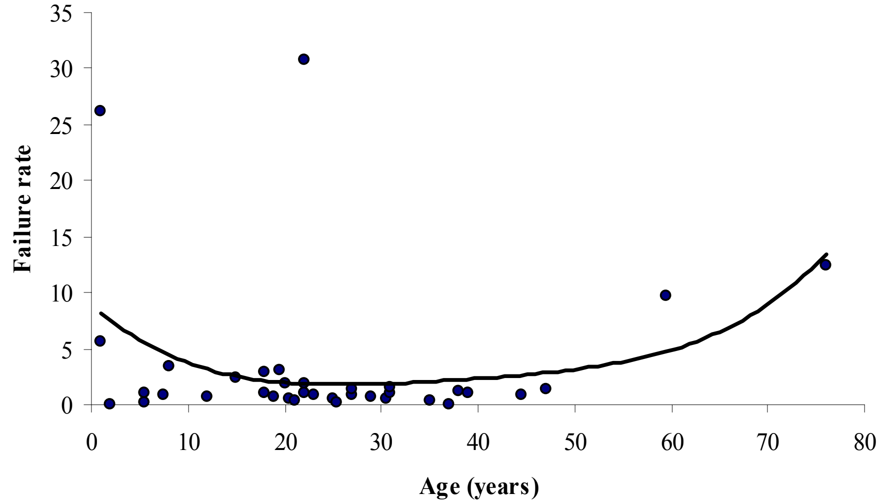

Figure 3. Failure rate plotted as a function of plant age, showing the bathtub shape.

The design and manufacturing of equipment and the construction of the power plant affect availability in the sense that different designs, technologies and manufacturers, with different production processes, might result in equipment with different reliability and maintainability. These are beyond the control of the maintenance management, unless in the case of repowering when maintenance criteria may be taken into account. The factors under the control of management are all the factors that constitute the organization necessary to the maintenance system of the plant. These factors include maintenance policy and methods, support systems, human resources, logistic support, and others.

In order to select the data to be collected to perform a technical efficiency analysis, the production inputs must be properly defined. The definition of these inputs depends on the specific analytical needs of the managers or regulatory agencies interested on the answers that this kind of analysis can provide. There are currently a lot of conceptual frameworks for maintenance management performance described in the literature (e.g., Tsang, 2002, Murthy, 2002; Madu, 2000; Visser,1998; Riis et al., 1996) defining the key factors that drive the maintenance systems performance. The model proposed here investigates particularly the methodological part of the maintenance process, meaning that for a successful achievement of plant availability the techniques applied on maintenance planning are the main inputs to the maintenance management. The presupposed idea behind the analysis is that as the methodological aspects of maintenance management become more sophisticated, the achieved availability increases.

This model is also supported by the fact that the analysis of technical efficiency of a number of power plants is subject to the maximum resolution achievable for data collection and analysis. Although it is possible to analyze the number of plants that implemented a new maintenance program, it is not possible to evaluate the quality of the additional necessary training required to implement the program, the quality of information systems used, or other factors, for instance. Another presupposed idea is that when a maintenance program is implemented the levels of input (labor, tools, etc.) are altogether improved, given that additional training, information systems and other factors are necessarily required to successfully implement the program.

The existence of two major types of maintenance programs, corrective maintenance and preventive maintenance, is considered as inputs to the technical efficiency analysis model. The first is defined as the performance of unplanned tasks to restore the functional capabilities of a failed system (Smith, 1993). All plants must have a corrective maintenance program but the existence of only corrective actions will result in low levels of availability, besides other undesirable effects such as safety problems. Preventive maintenance is the performance of inspection and/or servicing tasks that are preplanned for accomplishment at specific points in time to retain the systems functionality (Smith, 1993). Preventive maintenance programs can greatly improve plant availability if correctly managed. The reliability centered maintenance, RCM (Smith, 1993; Moubray, 1997), and total productive maintenance, TPM (Nakajima, 1988), are current concepts of preventive maintenance management.

The model proposed here is employed to answer the following question: How effectively are the power plants employing corrective maintenance, time-based preventive maintenance, condition-based preventive maintenance programs, RCM or TPM programs? It is important to notice that the fact a power plant has a RCM or TPM program implemented does not necessarily improve the availability of the plant. On the other hand, if a plant does not have a RCM or a TPM program, low levels of availability indicate that the plant is not processing the right levels of inputs to produce an increased output, but it might be considered efficient regarding the processing of its inputs.

The model of production frontier analyzed here has the following factors as inputs:

1 - Use of corrective maintenance
2 - Use of time-directed preventive maintenance
3 – Use of condition-based preventive maintenance
3 - Use of reliability centered maintenance
4 - Use of total productive maintenance

These factors are dummy variables, i.e., the existence of the variable is accounted in an encoded way. The inefficiency model considers the factor known to affect the plant availability:

1 - Age of the plant (years)

The present inefficiency model does not consider other factors because the data was previously organized to classify plants in terms of type and size. The data analyzed in the next section is related to hydropower plants with total installed capacity above 500 MW. Therefore the effects of size and type of power plant are not considered. Other factors such as design, manufacturing and construction constraints are not measured directly and are not considered in the inefficiency model. It is admitted here that they are accounted for in the random effects component of the model.

5. Results and Analysis

Table (2) shows the results of the efficiency estimates of the 36 power plants analyzed. The data analyzed was based on cross-sectional data observed in the year 2000 in Brazil (ANEEL, 2000). The plants observed corresponded to approximately 63% of the total power installed in the country in that year.

The plants with RCM programs achieved an efficiency ranging from 0.95410 to 0.98725, with a presence of an outlier with a technical efficiency of 0.72269. The mean technical efficiency of plants with RCM (excluding the outlier) is 0.952967. This efficiency is lower than the mean efficiency achieved by the plants without any RCM program, which is 0.96515.

TPM programs were still not widely employed by power plants and the single plant with a TPM program achieved a score of 0.9942. Condition-based programs were employed by 34 of the 36 plants. The overall technical efficiency of the plants was 0.9617, with four plants with efficiency below 0.90. We note that a few plants, even without the use of RCM, presented efficiencies above 0.99. A more conclusive analysis of the reasons behind this observation would require, initially, an analysis of panel data (data collected over a longer period of time) in order to detect whether this is a real trend, with more subtle and specific reasons, or this is a momentary observation.

Table (3) lists the results of the analysis with the values of the model parameters estimated. The beta and delta values define the stochastic production frontier, initially the values indicate that RCM programs and condition-based preventive maintenance have strong influence in the definition of the availability output, however, the estimated parameters should be further used with a statistical test to analyze the extent of the influence a particular maintenance program exerts on the availability levels of the power plants. These results would have a particular importance in assessing the improvements a power plant could obtain if any investment in a maintenance program is carried out and this could be used as a support for the decision about the implementation.

Table 2. Efficiency estimates for 36 hydropower plants in the Brazilian interconnected system, sorted by age.

Plant Number	Efficiency	Plant Number	Efficiency
1	0.9356	19	0.7299
2	0.7227	20	0.9855
3	0.9936	21	0.9878
4	0.9873	22	0.9917
5	0.9830	23	0.9853
6	0.9920	24	0.9868
7	0.9541	25	0.9815
8	0.9829	26	0.9877
9	0.9942	27	0.9823
10	0.9832	28	0.9780
11	0.9967	29	0.9900
12	0.9874	30	0.9936
13	0.9697	31	0.9814
14	0.9706	32	0.9797
15	0.9840	33	0.9803
16	0.9855	34	0.9797
17	0.9827	35	0.8951
18	0.9814	36	0.8397

Table 3. Parameter estimates for the production frontier.

coefficient	value	standard-error
β_0	4.5408	1.55E-02
β_1	0.0071	5.84E-03
β_2	-0.0313	2.17E-02
β_3	0.0645	4.96E-02
β_4	0.0043	9.56E-03
β_5	-0.0254	4.66E-03
δ_0	0.1586	3.93E-02
δ_1	-0.0825	1.58E-02
σ^2	0.0075	1.70E-03
γ	0.8500	2.67E-05

6. Conclusion

According to the information available, the analysis demonstrated that the plants studied are generally effective in employing maintenance programs to obtain the level of availability necessary to a proper productivity of electrical energy. The results however should not be considered as conclusive but rather as a preliminary analysis of the situation. The results should also not be considered as a description of the current state of power plants in Brazil given that the data analyzed are based on single observations (cross-sectional data) in the year 2000.

The policy implications of this type of technical efficiency analysis lies first on the fact that this is a regulatory policymaking and enforcement tool which identifies underperforming plants in a sector of public interest, and second on the fact that if the plants with advanced maintenance programs actually do achieve higher technical efficiency, there is an indication that setting targets to the improvement of the electricity generation sector by the employment of maintenance programs will effectively increase the operational availability of the electricity generation.

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