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# Measuring productivity growth under factor non-substitution: An application to US steam-electric power generation utilities

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ABSTRACT

A theoretical framework is developed for decomposing partial factor productivity and measuring technical inefficiency when the underlying technology is characterized by factor non-substitution. With Farrell's (1957) radial index of technical inefficiency being inappropriate in this case, Russell non-radial indices are adapted to measure technical inefficiency in a *Leontief*-type model. A system of factor demand equations with a regime specific technical inefficiency term is proposed and estimated allowing for dependence across inputs using a copula approach. Then the paper presents a complete decomposition of partial factor productivity changes using a dataset of US steam-power electric generation utilities.


## 1. Introduction

The decomposition of productivity growth has been explored and measured extensively to include efficiency changes over time in addition to scale effects and technical change components (see Fried et al., 2008, for a recent overview). This partitioning of the different contributions is important since different incentives influence different components. For example, expansionary investment involves impacting the scale effect of the growth decomposition, while replacement investment acts on the technical change effect. Decisions and incentives associated with learning to extract the full potential of implemented technologies are acting on the efficiency change component of promoting growth.

The core theoretical concept for building these measures is the production technology, where one can define formally the notions of technical efficiency (operating on the boundary of the feasible technology set), technical progress (shifting the boundary of this set) and scale effects (moving along the boundary of an existing set). The abundant economic literature on the estimation of stochastic production frontier functions and the subsequent measurement of technical inefficiency has assumed, in general, that the underlying production technology displays some degree of substitutability between factors of production.[1] This is not unusual as a production technology with zero input elasticity of substitution would imply that the cost-minimizing inputs are independent of their prices, which is a restrictive assumption in many real world applications.

However, certain types of production activities may exhibit a zero or limited elasticity of substitution among inputs. In some sectors or industries technological conditions are characterized by *ex ante* limited substitutability between inputs for a given level of output but also by substantial economies of scale. A classical example is the transportation sector (i.e., air-carriers, buses, railways), where one expects to find rather limited substitution possibilities between cost driving inputs. Buses, airplanes or trains cannot be operated without drivers or pilots, fuel is worth nothing without planes, buses or trains, etc. Apart from the specificities of the technology itself, it is also possible that these may, in practice, never be substituted for each other in some sectors where outputs or inputs are technologically substitutable, (Barnum and Gleason, 2011). This may arise when managers follow a common industry practice to avoid risk or because local norms or regulations imply the use of a decision heuristic.

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[1] Indeed, Bravo-Ureta et al. (2007) in their meta-regression analysis reviewing 167 empirical studies for measuring productive efficiency in agricultural applications, in both developed and developing countries, found that the vast majority of those hinge either on a *Cobb-Douglas* or a *Translog* functional specification to approximate the underlying production technology allowing for substitution possibilities among factors of production.

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The first study questioning the classical substitution model was Komiya (1962) who addressed economies of scale and technical progress in the generation of steam electric power utilities in the US with two alternative specifications of the production technology; namely, the traditional Cobb–Douglas and a factor limitation model.[2] His study was inspired by the engineering literature which made use of various decision heuristics for estimating the capital cost of plants of different sizes.[3] Komiya (1962) found that the substitution model was unsatisfactory and the limitation model provided a better fit to the production data of steam-fired electric utilities. Several studies followed examining the substitution hypothesis in several countries and different sectors. Lau and Tamura (1972) proposed the use of a non-homothetic *Leontief* production function to analyze the Japanese petrochemical industry, while Haldi and Whitcomb (1967) and Ozaki (1970) used a similar approach based on a homothetic *Leontief* production function in their analysis of economies of scale in US and Japanese steel industries, respectively. Nakamura (1990) utilized a non-homothetic generalized *Leontief* technological structure for empirically analyzing the Japanese iron and steel industry. Buccola and Sil (1996) measured productivity in the agricultural marketing sector and recently Holvad et al. (2004) assumed a *Leontief*-type technology for the Norwegian bus industry. Furthermore, a stream of the literature in agricultural economics addressing the modeling of crop response to different fertilizers' nutrients levels, has maintained zero substitution among crop nutrients using a linear plateau specification motivated by the *von Liebig* farm technology.[4]

Measuring technical inefficiency in the case of *Leontief*-type technologies is of interest given that Farrell's (1957) radial measures are the basis for most applied work on the measurement of efficiency. However, radial measures can be inadequate under such technologies as they may classify inefficient input combinations as being efficient, while input and output measures might not coincide even under constant returns-to-scale.[5] Färe and Lovell (1978), Russell (1985, 1987), Portela and Thanassoulis (2005) and Cherchye and Van Puyenbroek (2009) focus on the non-radial technical efficiency measures that provide a price rationale to evaluate a mixed efficiency factor. Once the technology is governed by a *Leontief*-type structure, it is plausible to have inefficiency displayed by none, all or a subset of the inputs, rendering radial measures unsatisfactory. In addition, output measures may fail to recognize inefficiencies when they affect a subset of the inputs only.

This paper develops a framework for modeling productivity growth under factor non-substitution that accounts for technical inefficiency and technical progress. The econometric modeling framework accommodates the absence of substitution possibilities among inputs where inefficiency between factors can be correlated. This *Leontief* frontier model adapts the copula approach to modeling the joint distribution between the one-sided error terms that capture factor-specific technical inefficiencies. Factor-specific technical efficiencies are specified and measured using Kopp's (1981) orthogonal indices of technical efficiency, combined into an overall technical efficiency measure using Russell's non-radial index of productive efficiency. Then, we proceed to developing a tractable approach for the analysis of partial factor productivity growth. An application to a panel data set of 72 fossil-fuel fired steam electric power generation utilities in the US observed during the 1986–1996 period follows.

The next section develops the theoretical framework for measuring technical efficiency in production structures that exhibit zero elasticity of substitution among inputs, while Section 3 presents the empirical model discussing briefly the econometric methods used. Section 4 presents the estimation results of an application to US electric utilities and finally, Section 5 provides some concluding remarks and suggestions for future extensions.

## 2. Theoretical framework

Assume that producers in period $t$ utilize a vector of variable inputs $\mathbf{x} \in \Re_+^J$ together with a vector of quasi-fixed inputs $\mathbf{z} \in \Re_+^K$ to produce a single output $y \in \Re_+$ through a technology described by the following closed, nonempty production possibilities set $T(t) = \{(\mathbf{x}, \mathbf{z}, y) : \mathbf{x} \in R_+^J, \mathbf{z} \in \Re_+^K \text{ can produce y at year } t\}$. Accordingly, for every $y \in \Re_+$ we can define the input correspondence set as all the input combinations capable of producing $y$, i.e.,

$$L(y, \mathbf{z}, t) = \{\mathbf{x} \in R_+^J : (\mathbf{x}, \mathbf{z}, y) \in T(t)\} \tag{1}$$

If we assume that the above defined production technology is characterized by *ex ante* limited substitutability between factors of production, we can define the cost function for all $y$ such that $L(y, \mathbf{z}, t) \neq \emptyset$:

$$C(y, \mathbf{w}, \mathbf{z}, t) = \min_{\mathbf{x}}\{\mathbf{w}'\mathbf{x} : \mathbf{x} \in L(y, \mathbf{z}, t)\} \tag{2}$$

which is the minimum cost of producing output quantities $y$ with period's $t$ technology, when the factor prices $\mathbf{w} \in \Re_{++}^K$ are strictly positive. Applying *Shephard's* lemma to (2) we obtain the system of derived demand equations as:

$$\frac{\partial C(y, \mathbf{w}, \mathbf{z}, t)}{\partial w_j} = g_j(y, \mathbf{z}, t) = x_j. \tag{3}$$

Since the elasticity of substitution between any pair of factors of production, holding output constant, is assumed to be zero, the derived demand functions are independent of factor prices. Such a system is used by Komiya (1962) who refers to it as "*plant base factor limitational production function*" and by Haldi and Whitcomb (1967), Ozaki (1970) and Lau and Tamura (1972). The function $g_j(\cdot)$ is a positive real-valued convex function defined and finite for all $y > 0$ with $g_j(0, \mathbf{z}, t) = 0$.

The production function $f(\mathbf{x}, \mathbf{z}, t) : \Re_+^J \to \Re_+$ corresponding to the dual cost function defined in (2) is given by

$$y = \max_y\{y : \mathbf{w}'\mathbf{x} \geqslant C(y, \mathbf{w}, \mathbf{z}, t)\} \tag{4}$$

which means that, for any given set of factor prices, the maximum $y$ is obtained such that the observed cost of production is greater than or equal to the optimum factor cost. The solution of the above optimization problem requires $x_j \geqslant g_j(y, \mathbf{z}, t)\ \forall j$.[6] Assuming that $g_j(\cdot)$ is non-decreasing and lower semi-continuous in $y$, we may define its generalized inverse, and hence the production function may be reformulated as

$$y = \max_y\{y : x_j \geqslant g_j(y, \mathbf{z}, t) \forall j\} = g_j^{-1}(x_j, \mathbf{z}, t) \tag{5}$$

The maximum $y$ satisfying the above optimization problem is then given by

$$y = \min_j\{g_j^{-1}(x_j, \mathbf{z}, t)\} \tag{6}$$

[2] Komiya (1962) utilized an older dataset than ours of US steam electric generation utilities.

[3] The economic-engineering rationale for the Leontief technology specification is that changes in the rate of utilization impacts the thermal efficiency of a steam-power plant after it has started operation. Otherwise a plant's input requirements change little once the plant has been built.

[4] Paris (1992) presents an excellent overview of the historical literature and an econometric estimation approach, and Holloway and Paris (2002) address productive efficiency in the context of the von Liebig specification. Guan et al. (2006) introduce an alternative modeling framework when encountering limited substitution grounded in an agronomic model of nutrient exchange.

[5] Färe and Lovell (1978) proved that if a regular production technology is linear homogeneous then input technical efficiency coincides with output technical efficiency. However, this is not true in *Leontief*-type production technologies.

[6] See Lau and Tamura (1972) pp. 1171–72.