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Using information about technologies, markets and firm behaviour to decompose a proper productivity index

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ABSTRACT

This paper uses distance functions to define new output and input quantity indexes that satisfy important axioms from index number theory (e.g., identity, transitivity, proportionality and time-space reversal). Dividing the output index by the input index yields a new productivity index that can be decomposed into a measure of technical change, a measure of environmental change, and several measures of efficiency change. A problem with this new index is that it cannot be computed without estimating the production frontier. The paper shows how assumptions concerning technologies, markets and firm behaviour can be used to inform the estimation process. The focus is on the asymptotic properties of least squares estimators when the explanatory variables in the production frontier model are endogenous. In this case, the ordinary least squares estimator is usually inconsistent. However, there is one situation where it is super-consistent. A fully-modified ordinary least squares estimator is also available in this case. To illustrate the main ideas, the paper uses US state-level farm data to estimate a stochastic production frontier. The parameter estimates are then used to obtain estimates of the economically-relevant components of productivity change.

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1. Introduction

Measures of total factor productivity (TFP) can be computed by dividing a weighted average of output quantities by a weighted average of input quantities. These computations are often so simple that decision-makers can make TFP comparisons without knowing anything about technologies, markets or firm[1] behaviour. However, if measures of TFP are to be used to inform economic policy, then decision-makers need to know the maximum TFP that possible, and whether shortfalls in TFP are due to factors that are within or outside the control of firms. Estimating the maximum TFP that is possible involves estimating the output–input combinations that are possible using different technologies in different production environments (equivalently, it involves estimating production frontiers). Explaining shortfalls in TFP requires an understanding of markets and firm behaviour. This paper explains how assumptions about technologies, markets and firm behaviour can be used to frame the econometric analysis of TFP.

The paper makes contributions in five main areas. First, it gives clarity to discussions about technical change by clearly defining important terms and concepts associated with technologies. In this paper, a *technology* is defined as a technique, method or system for transforming inputs into outputs (e.g., a technique for transforming flour into bread, or a method for teaching children to read). For most practical intents and purposes, it is convenient to think of a technology as a book of instructions, or recipe. Most, if not all, technologies are discovered through some type of research process. Moreover, most technologies that have been discovered in the past are still available today. In this paper, the set of technologies that exist in any given period is referred to as a *metatechnology*. If we think of a technology as a book of instructions, then we should think of a metatechnology as a library. In this context, the phrase *technical change* refers to changes in the metatechnology (or the "size of the library"). Elsewhere in the economics literature, researchers use this phrase quite loosely. For example, Solow (1957, p. 312) uses the phrase "[technical change] as a shorthand expression for *any kind of shift* in the production function. Thus, slowdowns, speedups, improvements in the education of the labor force, and all sorts of things will appear as [technical change]" (his italics).

Second, the paper shows how to deal with characteristics of the production environment "upfront". Elsewhere in the productivity literature, such characteristics are often dealt with as an

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[1] In this paper, the term *firm* is used to refer to either a decision-making unit (e.g., a company or an economy) or the manager of a decision-making unit (e.g., a CEO or a President).

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afterthought (e.g., in a "second stage"). In this paper, characteristics of the production environment are formally defined as variables that are physically involved in the production process but never chosen by firms (e.g., rainfall in farming, or the highway network in trucking). The fact that these variables are physically involved in the production process means they affect the output-input combinations that are *technically feasible*. In contrast, characteristics of the regulatory and market environments, for example, are variables that affect the output-input combinations that *firms choose* (e.g., regulations that stop firms from employing children in coal mines). This paper deals with characteristics of the production environment upfront, by including them in the definition of the production possibilities set. This way, firms are not labelled as technically inefficient when output shortfalls are due to variables that are beyond their control (e.g., low rainfall in farming).

Third, the paper contains several new propositions regarding technologies, markets, firm behaviour and efficiency. Formal statements and proofs of these propositions are contained in the Appendix. Most importantly, the paper proves that if firms are price-setters in output markets and demand conditions are sufficiently weak, then revenue maximising firms will choose to operate inside the production frontier (i.e., at less than full capacity). In this paper, this type of resource under-utilisation is referred to as technical inefficiency. In the past, economists have referred to it as "X-inefficiency" (e.g., Leibenstein, 1966, 1979).

Fourth, the paper uses the output distance function (ODF) and the input distance function (IDF) to define new output and input quantity indexes. Unlike several well-known indexes (e.g., the Fisher and Törnqvist indexes), these new indexes satisfy a suite of important axioms from index number theory (e.g., identity, transitivity, circularity, weak monotonicity, proportionality, and time-space reversal). Dividing the output quantity index by the input quantity index yields a new TFP index. This new TFP index is a general index in the sense that it nests several other TFP indexes as special cases. For example, if (i) firms are price-takers in output and input markets, (ii) they maximise profit, (iii) all prices and quantities are strictly positive, and (iv) the ODF is a Cobb–Douglas (CD) function, then it collapses to a geometric Young (GY) TFP index. Other special cases include the Lowe TFP index defined by O'Donnell (2012c) and the Färe-Primont (FP) TFP index defined by O'Donnell (2014).

Finally, the paper explains how different econometric estimators can be used to decompose TFP indexes into measures of technical change, environmental change, firm efficiency change and, in some cases, changes in statistical noise. The focus is on the large sample properties of least squares (LS) estimators when the explanatory variables in frontier models are endogenous. The paper discusses situations where the explanatory variables are endogenous and where ordinary least squares (OLS), fully modified ordinary least squares (FMOLS) and/or two-stage least squares (2SLS) estimators are either consistent or super-consistent. For example, if at least one of the explanatory variables is I(1) (i.e., integrated of order one) and the dependent and explanatory variables in the model are cointegrated, then, even though the explanatory variables may be endogenous, OLS estimators of the slope parameters in the model (and therefore the components of TFP change) are super-consistent.

The outline of the paper is as follows. Section 2 lists common assumptions concerning technologies and metatechnologies. A handful of these so-called regularity assumptions are sufficient for distance, revenue and cost functions to exist. Importantly, the existence of these functions does not have any implications for firm behaviour. The existence of the revenue function, for example, does not imply that firms choose outputs to maximise revenue. Section 3 discusses two cases where firms do, in fact, choose outputs to maximise revenue. This section proves that revenue maximising firms do not necessarily choose output-input combinations that are on the boundary of the production possibilities set. Section 4 defines several measures of efficiency that are associated with either the production environment or the actions of the firm. For example, measures of output- and input-oriented technical efficiency are measures of how far a chosen output-input combination is from the boundary of the production possibilities set. Some of these measures can be traced back to the 1950s. However, several other measures are new (or relatively new). Section 5 uses the ODF and IDF to define new output, input and TFP indexes that satisfy important axioms from index number theory. One of the most important of these axioms is transitivity. This axiom says, for example, that if firm A produces twice as much as firm B, and firm B produces twice as much as firm C, then the index that compares the outputs of firms A and C must take the value four (indicating that firm A produces four times as much as firm C). Indexes that are not transitive include the well-known Fisher and Törnqvist indexes. Section 6 explains that common assumptions concerning technologies, markets and firm behaviour have important implications for the structure of the new indexes. For example, if the metatechnology is output homothetic (OH) and technical change is implicit Hicks output neutral (IHON), then the new output quantity index does not depend on inputs or environmental variables. Section 7 explains how information about technologies, markets and firm behaviour can also be used to identify the components of TFP change. For example, if output markets are perfectly competitive, firms maximise revenue, the ODF is a CD function, and the metatechnology exhibits constant returns to scale (CRS), then the new TFP index collapses to a measure of technical and environmental change (in the growth accounting literature, this measure is known as the *Solow residual*). Section 8 explains how different econometric estimators can be used to estimate the slope parameters of a deterministic frontier model. The asymptotic properties of these estimators depend in part on the assumption that the explanatory variables in the model are not endogenous. If this assumption is not true, then the model is, in fact, a stochastic frontier model. Section 9 explains how LS and maximum likelihood (ML) estimators can be used to estimate the slope parameters of a stochastic frontier model. The focus in this section is on the properties of LS estimators when the explanatory variables are endogenous. Section 10 contains an empirical illustration. In this section, LS and ML estimators are used to estimate the slope parameters of a stochastic production frontier model when one or more inputs and/or environmental variables are endogenous. The estimated parameters are then used to decompose a GY TFP index into economically-meaningful components. Section 11 concludes the paper.

2. Technologies and metatechnologies

In this paper, a *technology* is defined as a technique, method or system for transforming inputs into outputs. It is common make assumptions about technologies by way of assumptions about what they can and cannot produce. For example, it is common to assume that (i) it is possible to produce zero output, (ii) there is a limit to what can be produced using a finite amount of inputs, (iii) a strictly positive amount of at least one input is needed in order to produce a strictly positive amount of any output, (iv) if an input vector can be used to produce a particular output vector, then it can also be used to produce a scalar contraction of that output vector, (v) if an output vector can be produced using a particular input vector, then it can also be produced using a scalar magnification of that input vector, (vi) the set of outputs that can be produced using a given input vector contains all the points on its boundary, and (vii) the set of inputs that can produce a given output vector

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