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Johannes Sauer, Klaus Froberg and  
Heinrich Hockmann

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**Black-Box Frontiers and  
Implications for  
Development Policy –  
Theoretical Considerations**

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Center for Development Research

Walter-Flex-Strasse 3

D – 53113 Bonn

Germany

Phone: +49-228-73-1735

Fax: +49-228-73-1869

E-Mail: [zef@uni-bonn.de](mailto:zef@uni-bonn.de)

<http://www.zef.de>

**The authors:**

**Johannes Sauer**, Center for Development Research (ZEF), University of Bonn, Germany  
(contact: [jsauer@uni-bonn.de](mailto:jsauer@uni-bonn.de))

**Klaus Frohberg**, Center for Development Research (ZEF), University of Bonn, Germany  
(contact: [klaus.frohberg@uni-bonn.de](mailto:klaus.frohberg@uni-bonn.de))

**Heinrich Hockmann**, Institute for Agriculture Development in Central and Eastern Europe (IAMO), Halle/Saale, Germany  
(contact: [hockmann@iamo.de](mailto:hockmann@iamo.de))

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## Abstract

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The availability of efficiency estimation software – freely distributed via the internet and relatively easy to use – recently inflated the number of corresponding applications. The resulting efficiency estimates are used without a critical assessment with respect to the literature on theoretical consistency, flexibility and the choice of the appropriate functional form. The robustness of policy suggestions based on inferences from efficiency measures nevertheless crucially depends on theoretically well-founded estimates. This paper addresses stochastic efficiency measurement by critically reviewing the theoretical consistency of recently published technical efficiency estimates with respect to economic development. The results confirm the need for a posteriori checking the regularity of the estimated frontier by the researcher and, if necessary, the a priori imposition of the theoretical requirements.

## Kurzfassung

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Die Verfügbarkeit von Software zur Effizienzbestimmung, die gratis über das Internet zugänglich ist und relativ einfach im Gebrauch ist, führte in letzter Zeit zu einem starken Anstieg entsprechender Anwendungen. Die daraus resultierenden Effizienzwerte werden ohne kritische Betrachtung hinsichtlich theoretischer Konsistenz, Flexibilität und Auswahl der passenden Funktionsform verwendet. Wie haltbar sich Anregungen für die Politik erweisen, die aus Effizienzmessungen abgeleitet wurden, hängt entscheidend von der theoretischen Fundierung der Schätzwerte ab. Diese Arbeit beschäftigt sich mit der stochastischen Effizienzbestimmung und stellt eine kritische Überprüfung der theoretischen Konsistenz kürzlich veröffentlichter technischer Effizienzschätzwerte im Bereich Entwicklungsökonomie dar. Die Ergebnisse bestätigen, dass es notwendig ist die Regularität der geschätzten Effizienzgrenze nachträglich zu überprüfen und gegebenenfalls a priori theoretische Restriktionen aufzuerlegen.

# 1 Introduction

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In the last 15 years applied production economics experienced a clear shift in its research focus from the analysis of the structure and change of production possibilities<sup>1</sup> to those of technical and allocative efficiency of decision making units. Parametric techniques as the stochastic production frontier model dominate the empirical literature of efficiency measurement (for a detailed review of different measurement techniques see e.g. Coelli et al., 1998, or Kumbhakar and Lovell, 2000). The availability of estimation software – freely distributed via the internet and relatively easy to use – recently inflated the number of corresponding applications.<sup>2</sup> The application of the econometric methods provided by these ‘black box’-tools are mostly not accompanied by a thorough theoretical interpretation. The estimation results are further used without a critical assessment with respect to the literature on theoretical consistency, flexibility and the choice of the appropriate functional form. The robustness of policy suggestions based on inferences from efficiency measures nevertheless crucially depends on proper estimates. Most applications, however, do not adequately test for whether the estimated function has the required regularities, and hence run the risk of making improper policy recommendations.

This paper shows the importance of testing for the regularities of an estimated efficiency frontier based on flexible functional forms. The basic results of the discussion on theoretical consistency and functional flexibility are therefore reviewed (Section 2) and applied to the translog production function (Section 3). Subsequently stochastic efficiency measurement is discussed to the background of these findings and essential implications are shown (Section 4). Further some stochastic frontier applications with respect to developing countries are exemplary reviewed with respect to theoretical consistency (Section 5). It is in particular argued that the economic properties of the estimation results have to be critically assessed, that the interpretation and calculation of efficiency have to be revised and finally that a basic change in the interpretation of the estimated function is required.

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<sup>1</sup> Typical issues investigated concern separability, homotheticity as well as the impact of technological change (see e.g. Chambers, 1988).

<sup>2</sup> Here e.g. the software FRONTIER. Since 1990 only with respect to agricultural economics more than 75 (about 5-10%) contributions have been made to *Agricultural Economics*, *American Journal of Agricultural Economics*, *European Review of Agricultural Economics*, *Review of Agricultural Economics* and *The Journal of Productivity Analysis* dealing with the estimation of stochastic efficiency frontiers.

## 2 The Magic Triangle: Theoretical Consistency, Functional Flexibility and Domain of Applicability

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One of the essential objectives of empirical research is the investigation of the relationship between an endogenous (or dependent) variable  $y$  and a set  $i$  of exogenous (or independent) variables  $x_{ij}$  where subscript  $j$  denotes the  $j$ -th observation:

$$y_j = f(x_{ij}, \beta_i) + \varepsilon_j \quad (1)$$

In general the researcher has to make two basic assumptions with regard to the examination of this relationship: The first assumption specifies the functional form expressing the endogenous variable as a function of the exogenous variables. The second assumption specifies a probability distribution for the residual  $\varepsilon$  capturing the difference between the actual and the predicted values of the endogenous variable. These two major assumptions about the underlying functional form and the probability distribution of the error term are usually considered as maintained hypotheses (see Fuss et al., 1978)<sup>3</sup>. Statistical procedures such as maximum likelihood estimation are used to estimate the relationship, i.e. the vector of the parameters  $\beta_i$ .

### 2.1 Lau's Criteria

In general, economic theory provides no a priori guidance with respect to the functional relationships. However, Lau (1978, 1986) has formulated some principle criteria for the ex ante selection of an algebraic form with respect to a particular economic relationship:<sup>4</sup> *-theoretical consistency*: the algebraic functional form chosen must be capable of possessing all of the theoretical properties required by the particular economic relationship for an appropriate choice of parameters. With respect to a production possibility set this would mean that the relationship in (1) is single valued, monotone increasing<sup>5</sup> as well as quasi-concave implying that the input set

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<sup>3</sup> “[...] one should not attempt to test a hypothesis in the presence of maintained hypotheses that have less commonly accepted validity. [...] An implication of this principle is the need for general, flexible functional forms, embodying few maintained hypotheses, to be used in tests of the fundamental hypotheses of production theory.” (Fuss et al., 1978, p. 223).

<sup>4</sup> The ax ante choice problem has to be distinguished from that of ex post choice which belongs to the realm of specification analysis and hypothesis testing.

<sup>5</sup> This simply implies that additional units of any input can never decrease the level of output. Hence this equals the statement that all marginal productivities  $dy/dx_i$  are positive and is finally derived from the basic assumption of rational individual behavior.

is required to be convex<sup>6</sup> (see appendix A1).<sup>7</sup> However, this indicates no particular functional form. - *domain of applicability*: most commonly the domain of applicability refers to the set of values of the independent variables  $x_i$  over which the algebraic functional form satisfies all the requirements for theoretical consistency. Lau (1986) refers to this concept as the *extrapolative domain* since it is defined on the space of the independent variables with respect to a given value of the vector of parameters  $\beta_i$ .<sup>8</sup> If, for given  $\beta_i$ , the algebraic functional form  $f(x_i, \beta_i)$  is theoretically consistent over the whole of the applicable domain, it is said to be globally theoretically consistent or globally valid over the whole of the applicable domain. Fuss et al. (1978) stress the *interpolative robustness* as the functional form should be well-behaved in the range of observations, consistent with maintained hypotheses and admit computational procedures to check those properties, as well as the *extrapolative robustness* as the functional form should be compatible with maintained hypotheses outside the range of observations to be able to forecast relations. - *flexibility*: a flexible algebraic functional form is able to approximate arbitrary but theoretically consistent economic behavior through an appropriate choice of the parameters.<sup>9</sup> The production function in (1) can be said to be *second-order flexible* if at any given set of non-negative (positive) inputs the parameters  $\beta$  can be chosen so that the derived input demand functions and the derived elasticities are capable of assuming arbitrary values at the given set of inputs subject only to theoretical consistency.<sup>10</sup> “Flexibility of a functional form is desirable because it allows the data the opportunity to provide information about the critical parameters.” (Lau, 1986, p. 1544). - *computational facility*: this criteria implies the properties of ‘linearity-in-parameters’, ‘explicit representability’, ‘uniformity’ and ‘parsimony’. For estimation purposes the functional form should therefore be linear-in-parameters, possible restrictions should be linear.<sup>11</sup> With respect to the ease of manipulation and calculation the functional form as well as any input demand functions derivable from it should be represented in explicit closed form and linear in parameters. Different functions in the same system should have the same ‘uniform’ algebraic form but differ in parameters. In order to achieve a desired degree of flexibility the functional form should be parsimonious with respect to the number of parameters. This to avoid methodological problems as multi-co linearity and a loss of degrees of

<sup>6</sup> This is essentially equivalent to assuming that the law of the diminishing marginal rate of technical substitution  $(dy/dx_i)/(dy/dx_k)$  for  $i = 1, \dots, n$  and  $k = 1, \dots, m$  holds. It implies that if  $x_i$  and  $x_k$  are both elements of  $V(y)$ , then their convex combination  $x_1 = \theta x_i + (1-\theta)x_k$  is also an element of  $V(y)$  and capable of producing  $y$ .

<sup>7</sup> In the following we only consider a production function relationship. However, the same arguments apply for a cost, profit, return or distance function each showing different exogenous variables. A general discussion would require relatively complex arguments without providing any further insights.

<sup>8</sup> The set of  $k$ 's for which a given functional form  $f(x, \beta(k)) \equiv f(x, k)$  will have a domain of theoretical consistency (in  $x$ ) that contains the prespecified set of  $x$ 's is called the interpolative domain of the functional form characterizing “[...] the type of underlying behavior of the data for which a given functional form may be expected to perform satisfactorily.” (Lau, 1986, p. 1539).

<sup>9</sup> Alternatively flexibility can be defined as the ability to map different production structures at least approximately without determining the parameters by the functional form. The concept of flexibility was first introduced by Diewert (1973 and 1974), Lau (1986) and Chambers (1988) discuss local and global approximation characteristics with respect to different functional forms.

<sup>10</sup> This implies that the gradient as well as the Hessian matrix of the production function with respect to the inputs are capable of assuming arbitrary non-negative and negative semi definite values respectively.

<sup>11</sup> If necessary a known transformation should be applied. Fuss et al. (1978) nevertheless stress that the tradeoff between the computational requirements of a functional form and the thoroughness of empirical analysis has to be weighted carefully.

freedom. - *factual conformity*: the functional form should be finally consistent with established empirical facts with respect to the economic problem to be modeled.<sup>12</sup>

## 2.2 The Concept of Flexibility

It is important to have a more detailed look on the concept of flexibility: A functional form can be denoted as “flexible” if its shape is only restricted by theoretical consistency. This implies the absence of unwanted a priori restrictions and is paraphrased by the metaphor of „providing an exhaustive characterization of all (economically) relevant aspects of a technology“ (see Fuss et al., 1978).

If  $F(\beta, \mathbf{x})$  is an algebraic form for a real-valued function including variables  $\mathbf{x}$  and a vector of unknown parameters  $\beta$ .  $F$  shall approximate the function value  $F$ , the gradient  $F'$  and the Hessian  $F''$  of an unknown function  $F^-(\mathbf{x})$  at an arbitrary  $\mathbf{x}^-$ . Flexibility of  $F$  implies and is implied by the existence of a solution  $\beta(\mathbf{x}^-; F^-, F^{-'}, F^{-''})$  to the following set of equations:<sup>13</sup>

$$F(\beta; \mathbf{x}^-) = F^-, \quad \nabla F(\beta; \mathbf{x}^-) = F^{-'}, \quad \nabla^2 F(\beta; \mathbf{x}^-) = F^{-''} \quad (2)$$

with respect to certain consistency conditions on the variables  $x$  and possible values  $F^-, F^{-'}, F^{-''}$  depending on the behavioral function  $F$  is representing. Due to our production framework  $F$  denotes a production function, therefore the solution is subject to non-negativity of  $\mathbf{x}^-, F^-$  and  $F^{-'}$  as well as negative semi-definiteness of  $F^{-''}$  such that  $F^- = \mathbf{x}^- F^{-'}$  and  $F^{-''} \mathbf{x}^- = 0$ .<sup>14</sup> Hence for an arbitrary vector of exogenous variables  $\mathbf{x}^-$ , a vector  $\beta$  exists such that the value of the function, its gradient as well as its Hessian matrix are equal to some  $F^-, F^{-'}, F^{-''}$ . The set of  $F^-, F^{-'}, F^{-''}$  for which this is true includes all possible theoretically consistent values. Due to this framework, a flexible functional form can provide a local second order approximation of an arbitrary function, either formulated as a differential approximation, as a Taylor series or as a numerical approximation. Hence this form is called ‘locally flexible’<sup>15</sup>. For the counter-example of a Cobb-Douglas production function the set of  $\beta$  that yields consistent  $F^-, F^{-'}, F^{-''}$  is the same at any  $\mathbf{x}^-$ . Only such  $F^-, F^{-'}, F^{-''}$  can be produced which are consistent with unity elasticities of substitution. In other words: as the mapping relation between the set of all

<sup>12</sup> Here e.g. the well confirmed fact that the elasticities of substitution between all pairs of inputs are not all identical in the three or more-input case.

<sup>13</sup> Where the vertical bars denote the numerical value of the respective terms, determined at  $\mathbf{x}^-$  (see Feger, 2000).

<sup>14</sup> See Lau (1986, p. 1540).

<sup>15</sup> See Chambers (1988, p.160). Feger (2000, p.77) notes: “The local approximation property of flexible functional forms is often referred to as the property constituting flexibility, and it is the historical starting point of the theory of flexible functional forms.”

admissible  $\beta$  to the set of all valid  $F^-$ ,  $F^-'$ ,  $F^-''$  is not surjective, the Cobb-Douglas model is not flexible.

Each relevant aspect of the concept of second order flexibility is assigned to exactly one parameter: the level parameter, the gradient parameters associated with the respective first order variable, and the Hessian-parameters associated with the second order terms. As a functional form cannot be second-order flexible with fewer parameters, the number of free parameters provides a necessary condition for flexibility. With respect to a single-product technology with an  $n$ -dimensional input vector, a function exhaustively characterizing all of its relevant aspects should contain information about the quantity produced (one level effect), all marginal productivities ( $n$  gradient effects) as well as all substitution elasticities ( $n^2$  substitution effects). As the latter are symmetric beside the main diagonal with  $n$  elements, only half of the off-diagonal elements are needed, i.e.  $\frac{1}{2}n(n - 1)$ . The number of effects an adequate single-output technology function should be capable of depicting independently of each other and without a priori restrictions amounts to a total of  $\frac{1}{2}(n + 2)(n + 1)$ . Hence a valid flexible functional form must contain at least  $\frac{1}{2}(n + 2)(n + 1)$  independent parameters.<sup>16</sup> Finally it has been shown that the function value as well as the first and second derivatives of a primal function can be approximated as well by the dual behavioral representation of the same technology (see Blackorby and Diewert, 1979). With respect to the relation between the supposed true function and the corresponding flexible estimation function the following concurring hypotheses can then be formulated (see Morey, 1986):

(I) *The estimation function is a local approximation of the true function.*

This simply means that the approximation properties of flexible functional forms are only locally valid and therefore value, gradient and Hessian of true and estimated function are equal at a single point of approximation (see Figure 1). As only a local interpretation of the estimated parameters is possible, the forecasting capabilities with respect to variable values relatively distant from the point of approximation are severely restricted.<sup>17</sup> In this case e.g. at least the necessary condition of local concavity with respect to global concavity can be tested for every point of approximation (see Section 4).<sup>18</sup>

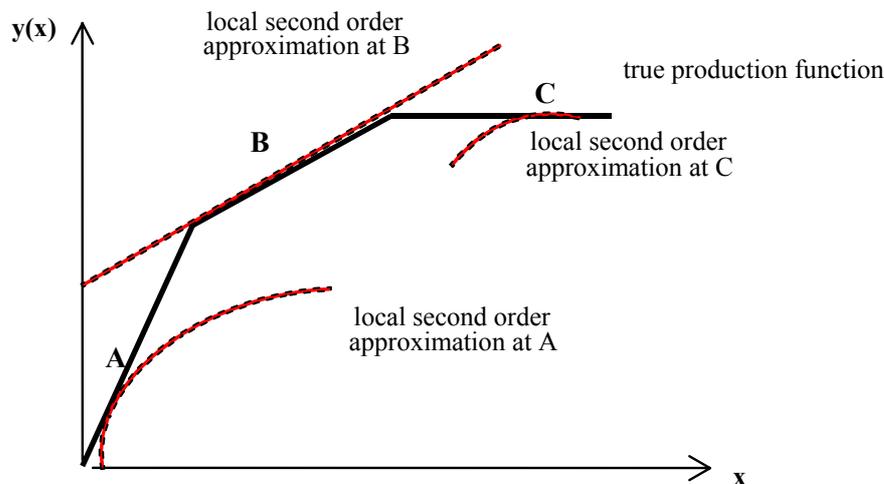
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<sup>16</sup> See Hanoch (1970) and following him Feger (2000).

<sup>17</sup> In the immediate neighborhood of the approximation point each flexible functional form provides theoretically consistent parameters only if the true structure is theoretically consistent (see Morey, 1986 and Chambers, 1988).

<sup>18</sup> Nevertheless as initially LAU (1986, pp. 418) pointed out, this must not be intrinsically concave. Morey (1986) raises the question about the location of the approximation point and stresses that there is no way to infer from the approximation function to the location of the approximation point. Commonly, the point of approximation is held to be located at some mean of variables over all observations. However, Feger (2000) stresses that this view emanates from erroneously interpreting the point of approximation and the point of expansion as synonyms.

Figure 1: Local Approximation



(source: after Morey, 1986 and Feger, 2000)

*(II) The estimated function and the true structure are of the same functional form but show the desired properties only locally.*

Most common flexible functions can either not be restricted to a well-behaved function without losing their flexibility (e.g. the translog function) or cannot be restricted to regularity at all (e.g. the Cobb-Douglas function). Points of interest in the true structure can be examined by testing the respective points in the estimation function.<sup>19</sup> However, a positive answer to the question whether the estimation function and the true structure are still consistent with the properties of a well-behaved production function if the data does not equal the examined data set is highly uncertain. This uncertainty can only be illuminated by systematically testing all possible data sets.

*(III) The estimated function and the true structure are of the same functional form and show the desired properties globally.*

A flexible functional form which can be restricted to global regularity (e.g. the Symmetric Generalized McFadden Function<sup>20</sup>) without losing its flexibility allows for the inference from the estimation function to the true structure and hence allows for meaningful tests of significance as the model is theoretically well founded (see Morey, 1986).<sup>21</sup> This approach of a flexible functional form promotes a concept of flexibility where the functional form has to fit the data to the greatest possible extent, subject only to the regularity conditions following from

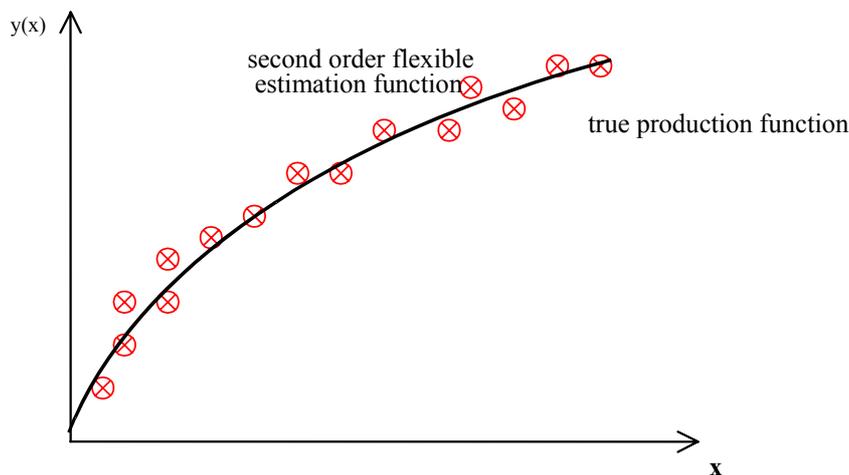
<sup>19</sup> See e.g. the studies by Curtiss (2002) or Voigt (2003) for applying this not very elegant procedure with respect to the translog function and checking for concavity locally at all points of approximation.

<sup>20</sup> See Diewert and Wales (1987). Applications can be found in Rask (1995) and in Frohberg and Winter (2003). Khumbhakar (1989), Pierani and Rizzi (2001), Tsionas et al. (2001) as well as Sauer and Frohberg (2004) applied it to estimate efficiency.

<sup>21</sup> On the other side, a serious problem arises for the postulates of economic theory if a properly specified flexible function which is globally well-behaved is not supported by the data (see Feger, 2000).

economic theory and independently depicting all economically relevant aspects (see Figure 2). As Feger (2000) concludes: “The argument that any flexible functional form can approximate any other flexible functional form and any arbitrary data generation process does not suspend the researcher from the issue of reducing the specification error to the greatest possible extent in selecting the most appropriate functional form for the entire data.”<sup>22</sup>

Figure 2: Global Approximation



(source: after Morey, 1986 and Feger, 2000)

### 2.3 The Magic Triangle

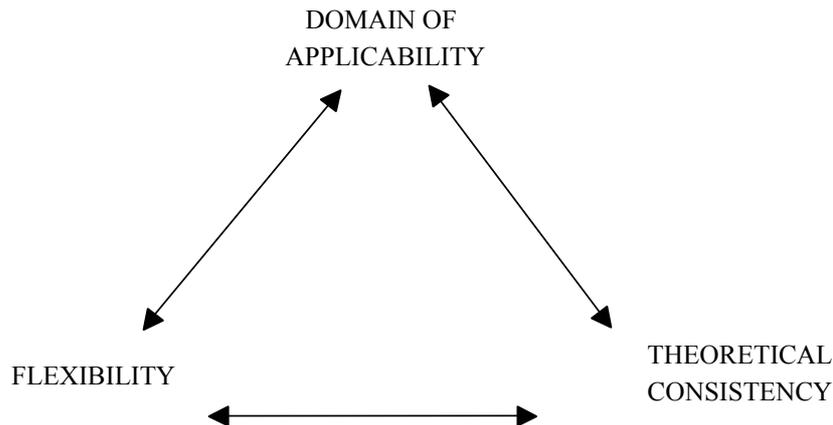
Hence, it is evident that the quality of the estimation results crucially depends on the choice of the functional form. The latter has to be chosen so that:

- it provides all economically relevant information about the economic relationship(s) investigated,
- shows a priori consistency with the relevant economic theory on producer behavior to the greatest possible extent,
- it includes no, or as few as possible, unwanted a priori restrictions, i.e. is flexible,
- it is relatively easy to estimate,
- it is parsimonious in parameters,
- it is robust towards changes in variables with respect to intra- as well as extrapolation,
- it finally includes parameters which are easy to interpret.

<sup>22</sup> See also Terrell (1995).

However, as was already noted by Lau (1978), one should not expect to find an algebraic functional form satisfying all of these criteria (in general cited as Lau's "incompatibility theorem"). As one should not compromise on (at least) local theoretical consistency, computational facility or flexibility of the functional form, he suggests the domain of applicability as the only area left for compromises with respect to functional choice.<sup>23</sup>

Figure 3: The Magic Triangle of Functional Choice



(own figure)

As figure 3 summarizes, for most functional forms there is a fundamental trade-off between flexibility and theoretical consistency as well as the domain of applicability. Production economists propose two solutions to this problem, depending on what kind of violation shows to be more severe (see Lau, 1986 or Chambers, 1988):

1. the choice of functional forms which could be made globally theoretical consistent by corresponding parameter restrictions, here the range of flexibility has to be investigated;
2. to opt for functional flexibility and check or impose theoretical consistency for the proximity of an approximation point<sup>24</sup> only;

However, a globally theoretical consistent as well as flexible functional form can be considered as an adequate representation of the production possibility set. Locally theoretical consistent as well as flexible functional forms can be considered as an  $i$ -th order differential approximation of the true production possibilities. Hence, the translog function is considered as a second order differential approximation of the true production possibilities.

<sup>23</sup> Hence, even if a functional form is not globally theoretically consistent, it can be accommodated to be theoretically consistent within a sufficiently large subset of the space of independent variables. Even so it has to be stressed that the surest way to obtain a theoretically consistent representation of the technology is to make use of a dual concept such as the profit, cost or revenue function.

<sup>24</sup> Usually at the sample mean.

### 3 The Case of the Translog Production Function

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A prominent textbook example as well as the most often used functional form with respect to efficiency measurement is the Cobb-Douglas production function:

$$\ln y = \alpha_0 + \sum_{i=1}^n \alpha_i \ln x_i \quad (3)$$

This function shows theoretical consistency globally if  $\alpha_i \geq 0$ , but fail with respect to flexibility as there are only  $(n-1)$  free parameters. Similarly often used with respect to stochastic efficiency measurement the translog production function has to be noted:

$$f(x) = \alpha_0 + \sum_{i=1}^n \alpha_i \ln x_i + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \alpha_{ij} \ln x_i \ln x_j \quad (4)$$

where symmetry of all Hessians by Young's theorem implies that  $\alpha_{ij} = \alpha_{ji}$ . It has  $(n^2 + 3n + 2)/2$  distinct parameters and hence just as many as required to be flexible. By setting  $A_{ij} = \sum_{i=1}^n \sum_{j=1}^n \alpha_{ij}$  equal to a null matrix reveals that the translog function is a generalization of the Cobb Douglas functional form.<sup>25</sup> The theoretical properties of the second order translog are well known (see e.g. Lau, 1986): it is easily restrictable for global homogeneity as well as homotheticity, correct curvature can be implemented only locally if local flexibility should be preserved, the maintaining of global monotonicity is impossible without losing second order flexibility.<sup>26</sup> Hence, the translog functional form is fraught with the problem that theoretical consistency can not be imposed globally. This is subsequently shown by discussing the theoretical requirements of monotonicity and curvature.

#### 3.1 Monotonicity

As is well known with respect to a (single output) production function monotonicity requires positive marginal products with respect to all inputs:<sup>27</sup>

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<sup>25</sup> The translog is probably the best investigated second order flexible functional form and certainly the one with the most applications.

<sup>26</sup> Feger (2000) claims that the translog entertains two advantages over all other specifications: first, it is extremely convenient to estimate, and second, it is likely to be a good specification for economic processes. Terrell (1996) applied a translog, generalized Leontief, and symmetric generalized McFadden cost function to the classical Berndt and Wood data. The results suggest that translog extensions to higher order could frequently outperform the Asymptotically Ideal Model (AIM) which is considered as today's state of the art.

<sup>27</sup> Barnett (2002) notes: "In specifications of tastes and technology, econometricians often impose curvature globally, but monotonicity only locally or not at all. In fact monotonicity rarely is even mentioned in that literature. But without satisfaction of both curvature and monotonicity, the second-order conditions for optimizing behaviour fail, and duality theory fails." (p. 199).

$$\partial y / \partial x_i > 0 \quad (5)$$

and thus non-negative elasticities. However, until most recent studies the issue of assuring monotonicity was neglected. Barnett et al. (1996) e.g. showed that the monotonicity requirement is by no means automatically satisfied for most functional forms, moreover violations are frequent and empirically meaningful. In the case of the translog production function the marginal product of input  $i$  is obtained by multiplying the logarithmic marginal product with the average product of input  $i$ . Thus the monotonicity condition given in (5) holds for the translog specification if the following equation is positive:

$$\partial y / \partial x_i = y / x_i * \partial \ln y / \partial \ln x_i = y / x_i * (\alpha_i + \sum_{j=1}^n \alpha_{ij} \ln x_j) > 0 \quad (6)$$

Since both  $y$  and  $x_i$  are positive numbers, monotonicity depends on the sign of the term in parenthesis, i.e. the elasticity of  $y$  with respect to  $x_i$ . If it is assumed that markets are competitive and factors of production are paid their marginal products, the term in parenthesis equals the input  $i$ 's share of total output,  $s_i$ .

By adhering to the law of diminishing marginal productivities, marginal products, apart from being positive should be decreasing in inputs implying the fulfillment of the following expression:

$$\partial^2 y / \partial x_i^2 = [\alpha_{ii} + (\alpha_i - 1 + \sum_{j=1}^n \alpha_{ij} \ln x_j) * (\alpha_i + \sum_{j=1}^n \alpha_{ij} \ln x_j)] * (y / x_i^2) < 0 \quad (7)$$

Again, this depends on the nature of the terms in parenthesis. These should be checked a posteriori by using the estimated parameters for each data point. However, both restrictions (i.e.  $\partial y / \partial x_i > 0$  and  $\partial^2 y / \partial x_i^2 < 0$ ) should hold at least at the point of approximation.

### 3.2 Curvature

Whereas the first order and therefore non-flexible derivative of the translog, the Cobb Douglas production function, can easily be restricted to global quasi-concavity by imposing  $\alpha_i \geq 0$ , this is not the case with the translog itself. The necessary and sufficient condition for a specific curvature consists in the semi-definiteness of its bordered Hessian matrix as the Jacobian of the derivatives  $\partial y / \partial x_i$  with respect to  $x_i$ : if  $\nabla^2 Y(x)$  is negatively semi-definite,  $Y$  is quasi-concave, where  $\nabla^2$  denotes the matrix of second order partial derivatives with respect to  $(\bullet)$  (see appendix A2). The Hessian matrix is negative semi-definite at every unconstrained local maximum<sup>28</sup>, it yields with respect to the translog:

<sup>28</sup> Hence, the underlying function is quasi-concave and an interior extreme point will be a global maximum. The Hessian matrix is positive semi-definite at every unconstrained local minimum.

$$H = \begin{pmatrix} \alpha_{11} & \dots & \alpha_{1n} \\ \cdot & \dots & \cdot \\ \alpha_{1n} & \dots & \alpha_{nn} \end{pmatrix} - \begin{pmatrix} s_1 & \dots & 0 \\ \cdot & \dots & \cdot \\ 0 & \dots & s_n \end{pmatrix} + \begin{pmatrix} s_1 s_1 & \dots & s_1 s_n \\ \cdot & \dots & \cdot \\ s_1 s_n & \dots & s_n s_n \end{pmatrix} \quad (8)$$

where here  $s_i$  denote the elasticities of production:

$$s_i = \partial \ln y / \partial \ln x_i = \alpha_i + \sum_{j=1}^n \alpha_{ij} \ln x_j \quad (9)$$

The conditions of quasi-concavity are related to the fact that this property implies a convex input requirement set (see in detail e.g. Chambers, 1988). Hence, a point on the isoquant is tested, i.e. the properties of the corresponding production function are evaluated subject to the condition that the amount of production remains constant. Given a point  $\mathbf{x}^0$ , necessary and sufficient for curvature correctness is that at this point  $\mathbf{v}'\mathbf{H}\mathbf{v} \leq 0$  and  $\mathbf{v}'\mathbf{s} = 0$  where  $\mathbf{v}$  denotes the direction of change.<sup>29</sup> Hence, contrary to the Cobb Douglas function quasi-concavity can not be checked for by simply considering the parameter estimates.

A matrix is negative semi-definite if the determinants of all of its principal submatrices are alternate in sign, starting with a negative one (i.e.  $(-1)^k D_k \geq 0$  where  $D$  is the determinant of the leading principal minors and  $k = 1, 2, \dots, n$ ).<sup>30</sup> However, this criterion is only rationally applicable with respect to matrices up to the format 3 x 3 (see e.g. Strang, 1976), the most operational way of testing square numerical matrices for semi-definiteness is the eigen - or spectral decomposition.<sup>31</sup> Let  $\mathbf{A}$  be a square matrix. If there is a vector  $\mathbf{X} \in \mathbb{R}^n \neq 0$  such that

$$\mathbf{A} \mathbf{X} = \lambda \mathbf{X} \quad (10)$$

for some scalar  $\lambda$ , then  $\lambda$  is called the eigenvalue of  $\mathbf{A}$  with the corresponding eigenvector  $\mathbf{X}$  (see further appendix A3). Following this procedure the magnitude of the  $m + n$  eigenvalues of the bordered Hessian have to be determined.<sup>32</sup>

With respect to the translog production function curvature depends on the input bundle, as the corresponding bordered Hessian  $\mathbf{BH}$  for the 3 input case shows:

<sup>29</sup> Which implies that the Hessian is negative semi-definite in the subspace orthogonal to  $\mathbf{s} \neq 0$ .

<sup>30</sup> Determinants of the value 0 are allowed to replace one or more of the positive or negative values. Any negative definite matrix also satisfies the definition of a negative semi-definite matrix.

<sup>31</sup> The eigen decomposition relates to the decomposition of a square matrix  $\mathbf{A}$  into eigenvalues and eigenvectors and is based on the eigen decomposition theorem which says that such a decomposition is always possible as long as the matrix consists of the eigenvectors of  $\mathbf{A}$  is square.

<sup>32</sup> Checking the definiteness of a  $2+x \times 2+x$  bordered Hessian ( $x = 1, \dots, n$ ) is not feasible as the determinant  $D_1$  equals always zero.

$$\mathbf{BH} = \begin{pmatrix} 0 & f_1 & f_2 & f_3 \\ f_1 & f_{11} & f_{12} & f_{13} \\ f_2 & f_{21} & f_{22} & f_{23} \\ f_3 & f_{31} & f_{32} & f_{33} \end{pmatrix} \quad (11)$$

where  $f_i$  is given in (6),  $f_{ii}$  is given in (7) and  $f_{ij}$  is

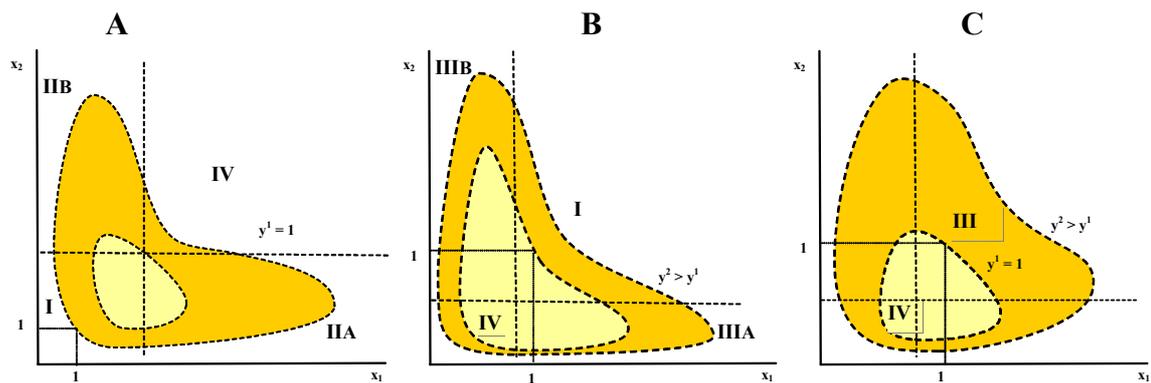
$$\partial^2 y / \partial x_i \partial x_j = [\alpha_{ij} + (\alpha_i + \sum_{j=1}^n \alpha_{ij} \ln x_j) * (\alpha_j + \sum_{i=1}^n \alpha_{ij} \ln x_i) ] * (y/x_i x_j) < 0 \quad (12)$$

For some bundles quasi-concavity may be satisfied but for others not and hence what can be expected is that the condition of negative semi-definiteness of the bordered Hessian is met only locally or with respect to a range of bundles.

### 3.3 Graphical Discussion

In order to provide a more comprehensive treatment of the properties of the translog function we discuss possible forms of isoquants (see Figure 4). We assume that inputs are normalized by their mean which we use as a reference point. The closed form of the graphs is due to the quadratic terms. Although, the graphs look very similar, the characteristics differ significantly. It becomes evident that simple inspection in the form of the isoquants is not sufficient to decide whether theoretical consistency holds or not.

Figure 4: Exemplary Isoquants of a Translog Production Function



(A) and (B) are theoretically consistent at the reference point, (C) is not. Roman numerals denote the properties of the graph  $y = 1$  between the dashed lines. These numbers are not valid for the other isoquants.

		MONOTONICITY	
		yes	no
CURVA- TURE	quasi-concave	<b>I</b>	<b>II</b>
	quasi-convex	<b>II</b>	<b>IV</b>

The graphs in the lower left corner in panel C seem to be typical isoquants. However, the function is actually monotone decreasing and quasiconvex in that regions, e.g. a correct shape is caused by the fact that both conditions for theoretical consistency are not satisfied. In fact, in panel c there is no region where the conditions hold. Panel (A) and (B) differ in so far as the function in (A) has a maximum whereas in (B) the function shows a minimum at the reference point. This differentiation has severe consequences for the region of consistent input values. In panel (A) the consistent values are located in the lower left corner. Moving along the graph would first lead to regions where the monotonicity requirement is violated (area [II]) and after that to the area in which the curvature condition is also not satisfied (area [IV]).<sup>33</sup> However, even there is a region in which theoretical consistency is satisfied the applicability of the estimation is rather limited, because an increase of factor input leads to a reduction of the valid region as a consequence of the monotonicity requirement. In fact, this range is limited to the maximum.

In panel (B) the theoretically consistent regions are located northeast to the maximum. Contrary to panel (A), moving along the graph will lead to a region in which the curvature condition is not satisfied anymore (III).<sup>34</sup> Moreover, the valid regions grow with an increase in inputs. Furthermore, no region exists where production starts to decline like is the case in panel (A). Thus, panel (B) should be the preferred estimation result. Violation of theoretical consistency can be expected at relatively low levels of factor inputs.

As the translog function consists of quadratic terms it shows a parabolic form implying increasing as well as decreasing branches by definition causing inconsistencies regarding the monotonicity requirement ( $\partial y / \partial x_i > 0$ ). Further violations of the curvature condition are caused by the logarithmic transformation of input variables. All functional forms showing these properties are finally subject to possible violations of their theoretical consistency. Unfortunately, all flexible functional forms commonly used in empirical economics belong to the same class as the translog function.

<sup>33</sup> This kind of result is likely when the modes are smaller than the means of the variables.

<sup>34</sup> This kind of function will occur when the modes are larger than the means of the inputs.

### 3.4 Theoretical Consistency and Flexibility

The preceding discussion hence shows that there is a trade-off between flexibility and theoretical consistency with respect to the translog as well as most flexible functional forms. Economists propose different solutions to this problem:

1) Imposing globally theoretical consistency destroys the flexibility of the translog as well as other second-order flexible functional forms<sup>35</sup>, as e.g. the generalized Leontief. However, theoretical consistency can be locally imposed on these forms by maintaining their functional flexibility. Further, Ryan and Wales (2000) even argue that a sophisticated choice of the reference point could lead to satisfaction of consistency at most or even all data points in the sample.<sup>36</sup> Jorgenson and Fraumeni (1981) firstly propose the imposition of quasi-concavity through restricting  $\mathbf{A}$  to be a negative semi-definite matrix.

Imposing curvature at a reference point (usually the sample mean) is attained by setting  $a_{ij} = -(\mathbf{DD}')_{ij} + a_i\delta_{ij} + a_ja_i$  where  $i, j = 1, \dots, n$ ,  $\delta_{ij} = 1$  if  $i = j$  and 0 otherwise and  $(\mathbf{DD}')_{ij}$  as the  $ij$ -th element of  $\mathbf{DD}'$  with  $\mathbf{D}$  a lower triangular matrix. The approximation point could be the data mean. However, the procedure is a little bit different. First, all data are divided by their mean. This transfers the approximation point to an  $(n + 1)$ -dimensional vector of ones. At the approximation point the terms in (7) and (12) do not depend on the input bundle anymore. It can be expected that input bundles in the neighborhood also provide the desired output. The transformation even moves the observation towards the approximation point and thus increases the likelihood of getting theoretically consistent results (see RYAN/WALES, 2000). Imposing curvature globally is attained by setting  $a_{ij} = -(\mathbf{DD}')_{ij}$ . Alternatively one can use LAU'S (1978) technique by applying the Cholesky factorization  $\mathbf{A} = -\mathbf{LBL}'$  where  $\mathbf{L}$  is a unit lower triangular matrix and  $\mathbf{B}$  as a diagonal matrix. However, the elements of  $\mathbf{D}$  and  $\mathbf{L}$  are nonlinear functions of the decomposed matrix, and consequently the resulting estimation function becomes nonlinear in parameters. Hence, linear estimation algorithms are ruled out even if the original function is linear in parameters.

However, by imposing global consistency on the translog functional form Diewert and Wales (1987) note that the parameter matrix is restricted leading to seriously biased elasticity estimates.<sup>37</sup> Hence, the translog function would lose its flexibility.

<sup>35</sup> Second-order flexibility in this context refers to Diewert's (1974) definition where a function is flexible if the level of production (cost or profit) and all of its first and second derivatives coincide with those of an arbitrary function satisfying linear homogeneity at any point in an admissible range.

<sup>36</sup> In fact Ryan and Wales (1998, 1999, 2000) could confirm this for several functional forms in a consumer demand context as well as for the translog and generalized Leontief specification in a producer context. See also Feger (2000) and the recent example by Terrell (1996).

<sup>37</sup> Diewert and Wales (1987) illustrate that the Jorgenson-Fraumeni procedure for imposing concavity will lead to estimated input substitution matrices which are "too negative semi-definite", i.e. the degree of substitutability will tend to be biased in an upward direction. However, if the elasticities would be independent of the input vector by

Any flexible functional form can be restricted to convexity or (quasi-)concavity with the above method – i.e. to local convexity or (quasi-)concavity. The Hessian of most flexible functional forms, e.g. the translog or the generalized Leontief, are not structured in a way that the definiteness property is invariant towards changes in the exogenous variables (see Jorgenson and Fraumeni, 1981). However, there are exceptions: e.g. the Hessian of the Quadratic does not contain exogenous variables at all, and thus a restriction by applying the Cholesky factorization suffices to impose regular curvature at all data points.<sup>38</sup>

2) Functional forms can be chosen which could be made globally theoretical consistent through corresponding parameter restrictions and by simultaneously maintaining flexibility. This is shown for the symmetric generalized McFadden cost function by Diewert and Wales (1987) following a technique initially proposed by Wiley et al. (1973). Like the generalized Leontief, the symmetric generalized McFadden is linearly homogenous in prices by construction, monotonicity can either be implemented locally only or, if restricted for globally, the global second-order flexibility is lost (see Feger, 2000). However, if this functional form is restricted for correct curvature the curvature property applies globally.<sup>39</sup> Furthermore regular regions following Gallant and Golups (1984) numerical approach to account for consistency by using e.g. Bayesian techniques can be constructed with respect to flexible functional forms.<sup>40</sup>

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transformation (assuming  $\alpha_{ij} = 0$  for all  $i$  and  $j$ ) the translog function loses its flexibility as it collapses to the Cobb Douglas form.

<sup>38</sup> It is worth noting, that the Quadratic is disqualified for its incapability of being restricted with respect to linear homogeneity.

<sup>39</sup> Unfortunately, the second order flexibility property is in this case restricted to only one point.

<sup>40</sup> To avoid the disturbing choice between inflexible and inconsistent specifications this approach imposes theoretical consistency only over the set of variable values where inferences will be drawn. Here the model parameters are restricted in a way that the resulting elasticities meet the requirements of economic theory for the whole range of variable constellations that are a priori likely to occur, i.e. a regular region is created.

## 4 Implications for Stochastic Efficiency Measurement

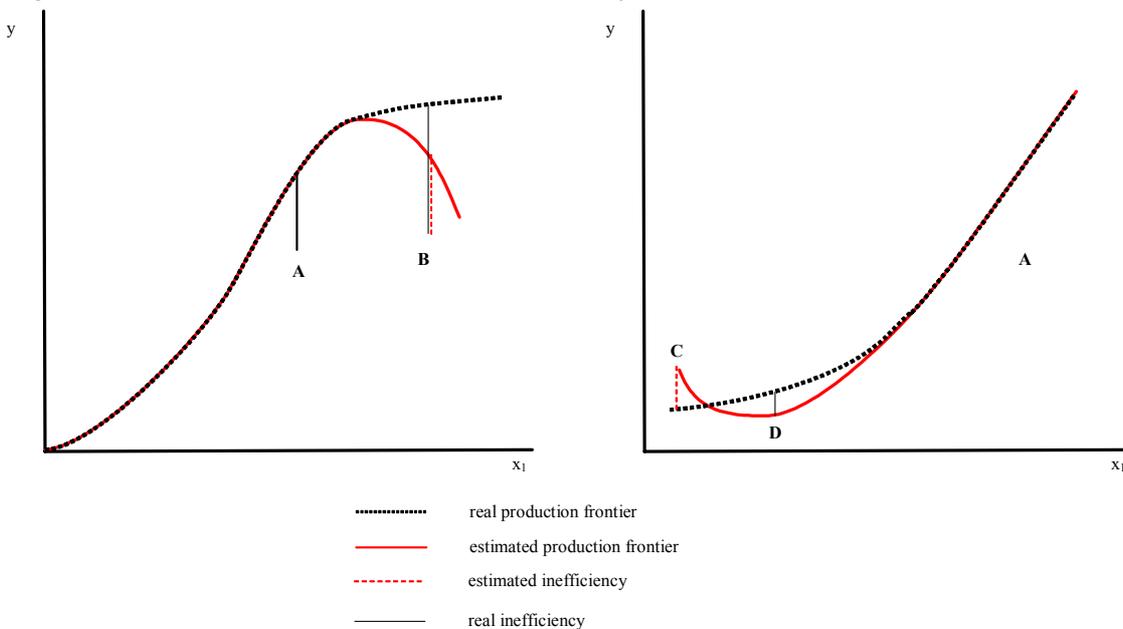
In recent years a shift of the research focus in production economics can be observed. Not the structure and change of the production possibilities<sup>41</sup> is of primary interest but the technical and allocative efficiency of netput bundles. A typical representation of the production possibilities is given by the production frontier:

$$y = f(x) - \varepsilon, \text{ with } 0 < \varepsilon < \infty \quad (13)$$

This trend is accompanied by a shift in the interpretation insofar as the estimated results are not interpreted for the approximation point but for all input values. This is a necessary consequence of the shift of the research focus. While it is possible to investigate the structure of the production possibilities at any virtual production plan, efficiency considerations can only be performed for the individual observations. However, this in turn requires that the properties of the production function have to be investigated for every observable netput vector. The consequences of a violation of theoretical consistency for the relative efficiency evaluation will be discussed using Figures 5 to 8 by showing the effect on the random error term:

Figures 5 & 6:

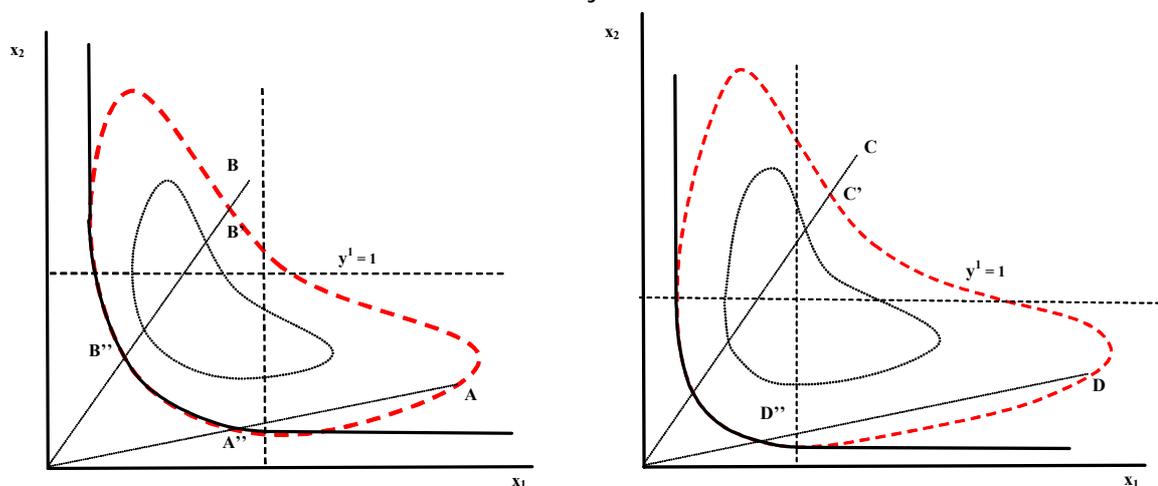
Violation of Monotonicity



<sup>41</sup> Typical questions concern e.g. separability, homotheticity or the impact of technological change. In general, the results were interpreted for the approximation point only.

As becomes clear the estimated relative inefficiency equals the relative inefficiency for the production unit A with respect to the real production function. As the estimated function violates the monotonicity criteria for parts of the function the estimated relative inefficiency of production unit B understates the real inefficiency for this observation. The same holds for production unit C which actually lies on the real production frontier, whereas the estimated relative inefficiency for production unit D again understates the real inefficiency. Figure 7 and Figure 8 show the implications as a result of irregular curvature of the estimated efficiency frontier:

Figures 7 & 8: Violation of Quasi-Concavity



As illustrated by figure 4A area I shows theoretical consistency. The red dotted line describes an isoquant of the estimated production function. The relative inefficiency of the input combination at production unit B measured against the estimated frontier (at B') understates the real inefficiency which is obtained by measuring the input combination against the real production frontier at point B''. Observation A lies on the estimated isoquant and is therefore measured as full efficient (point A). Nevertheless this production unit produces relatively inefficient with respect to the real production frontier (see point A''). The same holds for production unit D (real inefficiency has to be measured at point D''). Finally relative inefficiency of observation C detected at the estimated frontier (C') corresponds to real inefficiency for this production unit as the estimated frontier is theoretical consistent.

The graphical discussion clearly shows the implications for efficiency measurement: theoretical inconsistent frontiers over- or understate real relative inefficiency and hence lead to severe misperceptions and finally inadequate as well as counterproductive policy measures with respect to the individual production unit in question. However, a few applications exist considering the need for theoretical consistent frontier estimation: e.g. Khumbhakar (1989), Pierani/Rizzi (1999), Christopoulos et al. (2001), Craig et al. (2002) as well as Sauer and Frohberg (2004) estimated a symmetric generalized McFadden cost frontier by imposing

concavity and checking for monotonicity.<sup>42</sup> Here global curvature correctness is assured by maintaining functional flexibility. O'Donnell (2002) applies Bayesian methodology to impose regularity constraints on a system of equations derived from a translog shadow cost frontier. However, the vast majority of existing efficiency studies uses the error components approach by applying an inflexible CobbDouglas production function or a flexible translog production function without checking or imposing monotonicity as well as quasi-concavity requirements.

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<sup>42</sup> Whereas Kumbhakar, Christopoulos et al. as well as Sauer and Frohberg uses a non-radial approach, Craig et al. uses a shadow cost frontier to efficiency measurement.

## 5 Theoretical Inconsistent Efficiency Estimates

### - Examples

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Although the majority of applications with respect to stochastic efficiency estimation uses the Cobb-Douglas functional form (see in a development context e.g. Estache (1999), Deraniyagala (2001), Estache and Rossi (2002), Ajibefun and Daramola (2003), Kambhampati (2003), Okike et al. (2004)) we subsequently focus on applications using the translog production function to derive efficiency judgements. This, as we outlined earlier, because of the relative superiority of flexible functional forms: to our opinion the Cobb-Douglas functional form should not be used for stochastic efficiency estimations any longer.

Theoretical consistency of the estimated function should be ideally tested and proven for all points of observation which requires for the translog specification beside the parameters of estimation also the output and input data on every observation. Most contributions fail to satisfactorily document the applied data set at least with respect to the sample means (see e.g. Hossain/Karunaratne, 2004). However, the following exemplary analysis uses a number of translog production function applications published in recent years focusing on development related issues. Here monotonicity - via the gradient of the function with respect to each input by investigating the first derivatives - as well as quasi-concavity - via the bordered Hessian matrix with respect to the input bundle by investigating the eigenvalues - are checked for the individual local approximation point at the sample mean or, if available, for the individual observations.

#### 5.1 "A Primer on Efficiency Measurement"

The World Bank Institute's publication "A Primer on Efficiency Measurement for Utilities and Transport Regulators" by Coelli et al. (2003) is intended to assist infrastructure regulators to learn about the tools needed to measure efficiency.<sup>43</sup> It aims to provide "[...] an overview of the various dimensions of efficiency that regulators should be concerned with" (p. v) and in particular focuses on policymakers interested in measuring relative efficiency and in implementing regulatory mechanisms based on the measurement of efficiency, as e.g. yardstick competition. To give an empirical example on estimating a stochastic production frontier Coelli et al. attempt to estimate a translog production function for 20 railway companies using panel data for a period of five years.<sup>44</sup> However, for all 29 observations the estimated frontier showed to be monoton only with respect to the variable input labor. It is not adhering to the requirement

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<sup>43</sup> It is mainly based on lecture notes from courses the World Bank Institute offers for policy actors from developing countries.

<sup>44</sup> Although the authors point to the relative superiority of flexible functional forms they do not explicitly discuss the potential consequences of irregular efficiency estimates for regulatory measures.

of diminishing marginal productivity as well as not quasi-concave for all input-bundles as required by economic theory (see table 1 for the results of the regularity tests for the 29 observations published<sup>45</sup> and appendix A4. for the numerical details of the tests performed).

## 5.2 Other Exemplary Frontiers

Battese and Broca (1997) estimated technical efficiencies of 109 wheat farmers in Pakistan over the period 1986 to 1991 using land, labor, fertilizer and seed as inputs (see Table 1). Only model 2 fulfilled the monotonicity requirements for all four inputs. Both models evaluated at the sample means failed to adhere to quasi-concavity. Estache et al. (2001) attempted to measure the efficiency gains from reforming ports' infrastructure by using panel data on Mexico for the period 1996 to 1999 and modelling production with and without technical change. However, both model specifications showed monotonicity only for the inputs labour and intermediates and failed with respect to correct curvature. Ajibefun et al. (2002) aimed to investigate factors influencing the technical efficiency of 67 crop farms in the Nigerian state of Oyo for the year 1995. The authors used land, labor, capital as well as hired labor to estimate a translog production frontier. However, the estimated function showed to be monoton in all inputs but not quasi-concave for the input bundle. Sherlund et al. (2002) used panel data from 464 rice plots in Cote d'Ivoire to estimate technical efficiency by including the inputs land, fertilizer, adult -, child -, and hired labor. The estimated efficiency frontier fulfills the monotonicity as well as diminishing marginal returns criteria for all inputs but nevertheless showed to be not quasi-concave. Finally Kwon and Lee (2004) estimated stochastic production frontiers for the years 1993 to 1997 with respect to Korean rice farmers. All efficiency frontiers showed to be non-monoton for the input fertilizer and do not fulfill the curvature requirement of quasi-concavity. To sum up: 100% of all arbitrarily selected translog production frontiers fail to fulfill (at least) local regularity at the sample means.

Table 1 shows the results of the exemplary regularity tests (see appendix A4. and A5. for the numerical details of the regularity tests performed).

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<sup>45</sup> See Coelli et al. (2003), pp. 54.

Table 1: Examples for Local Irregularity of Translog Production Function Models

(x: fulfilled; 0: not fulfilled)

(Note: due to lacking data on each observation for study II) to VI) evaluated at the sample means.)

<b>STUDY</b> (Author, Year, Country)	<b>DATA SET</b> (No. Obs., Years) <b>MODEL OUTPUT INPUTS</b>	<b>MONOTONICITY</b> (for every Input)	<b>DIMINISHING MARGINAL PRODUCTIVITY</b> (for every Input)	<b>QUASI-CONCAVITY</b> (of the input-bundle)	<b>LOCAL REGULARITY</b> (monoton & quasi-concave)
<b>I) COELLI ET AL.</b> (2003) <sup>46</sup>	100, 5 years Railway Output  Capital Labor Other	0 x 0	0 0 0	0	0
<b>II) BATTESE AND BROCA</b> (1997) Pakistan	330, 1986-1991 <b>Model 1</b> Wheat Output  Land Labour Fertiliser Seed  <b>Model 2</b> Wheat Output  Land Labour Fertilizer Seed	x 0 x x  x x x x	x 0 x 0  0 x x x	0     0	0     0
<b>III) ESTACHE ET AL.</b> (2001) Mexico	56, 1996-1999 <b>Model 1</b> Harbor Output  Labor Capital Intermediate Inputs  <b>Model 2</b> Harbor Output  Labor Capital Intermediate Inputs	x 0 x  x 0 x	0 0 0  0 0 x	0    0	0    0

<sup>46</sup> Here evaluated for 29 observations published. The estimated frontier showed the same regularity results for every observation.

Table 1 (continued):

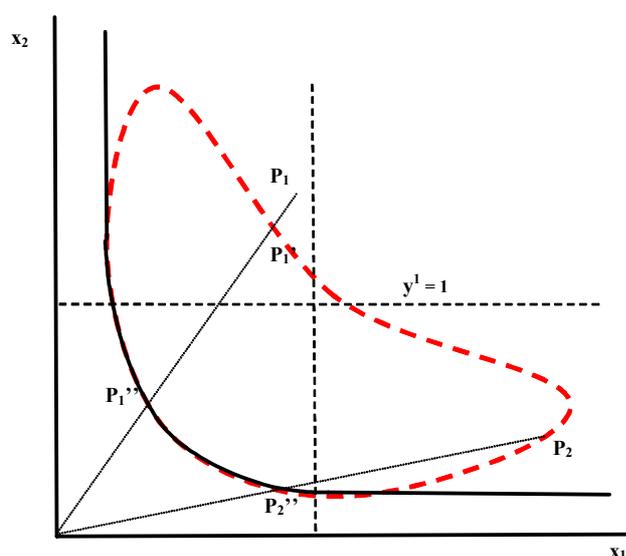
<b>IV) AJIBEFUN ET AL. (2002)</b> Nigeria	67, 1995 Total Crop Output				
	Land	x	0	0	0
	Labor	x	x		
	Capital	x	x		
	Hired Labor	x	x		
<b>V) SHERLUND ET AL. (2002)</b> Cote d'Ivoire	464, 1993-1995 Rice Production				
	Land	x	x	0	0
	Adult Labor	x	x		
	Hired Labor	x	x		
	Child Labor	x	x		
	Fertilizer	x	x		
<b>VI) KWON AND LEE (2004)</b> Korea	1026, 1993- 1997 <b>Models 1993-1997</b> Rice Output				
	Land	x	x	0	0
	Labor	x	x		
	Capital	x	x		
	Fertilizer	0	0		
	Pesticides	x	x		
	Others	x	x		

Hence, as the investigated frontiers are flexible but not regular (at least at the sample mean) derived efficiency scores are not theoretical consistent and therefore are not an appropriate basis for the formulation of policy measures focusing on the relative performance of the investigated decision making units.

## 6 Policy Implications

A short exemplary discussion of the conclusions drawn by Estache et al. (2001) with respect to their (theoretical incorrect) relative efficiency scores for the Mexican port sector should highlight the severity of potential policy implications. The authors draw three main conclusions: (1) the preceding sector reforms would have resulted in significant performance improvements of ports on average and detected efficiency gains could be passed on to port users, (2) performance rankings by port specific efficiency measures would promote yardstick competition as they are superior to those based on partial productivity indicators, and (3) the quality of the data would be crucial for the model specification. As shown above, the efficiency estimates generated by Estache et al. (2001) are not theoretical consistent at the sample mean by not adhering to monotonicity and quasi-concavity requirements. Hence conclusion (1) can not be drawn as the estimated production frontier is not quasi-concave at the sample means. Whether there are efficiency gains at all and if yes, how great such gains are, can not be answered by these (theoretical inconsistent) results. If the estimated relative ‘efficiency position’ of a reformed port is at  $P_1$  in figure 9 its estimated efficiency score (graphically the distance between  $P_1$  and  $P_1'$ ) evidently understates its real relative inefficiency (graphically the distance between  $P_1$  and  $P_1''$ ). If the estimated relative ‘efficiency position’ of a reformed port is at  $P_2$  and hence on the estimated frontier its estimated efficiency score does not account for its real relative inefficiency (graphically the distance between  $P_2$  and  $P_2''$ ). In both cases positive efficiency effects by liberalization measures are much lower in reality and hence “significant performance improvements of ports on average” are also much lower. If such improvements can be linked to preceding policy actions remains unclear and can not be answered by such results. The same holds with respect to the possibility of passing cost savings by ports to the final port users via lower prices.

Figure 9: Quasi-Concave and Not Quasi-Concave Frontier Regions



With respect to conclusion (2) it is to say that global efficiency measures as e.g. multivariate stochastic efficiency frontiers are superior to partial productivity indicators as long as they are adhering to the requirements by economic theory. Regulatory measures based on theoretical consistent partial performance indicators are superior to efficiency estimates invalid because of theoretical inconsistencies. Finally it is true that the quality of the available data on a specific performance measurement problem is crucial for the significance of the policy inferences made. However, the specification of the efficiency model should be at first oriented at ensuring that the production possibility set  $T$  – all inputs  $x$ , exogenous factors  $z$  and output combinations  $y$  - of each production unit shows the following properties (see e.g. Chambers, 1988):

- (t1)  $T$  is nonempty;
- (t2)  $T$  is a closed set;
- (t3)  $T$  is a convex set;
- (t4) if  $(x, z, y) \in T$ ,  $x^l \geq x$ , then  $(x^l, z, y) \in T$  (free disposability of  $x$ );
- (t5) if  $(x, z, y) \in T$ ,  $z^l \geq z$ , then  $(x, z^l, y) \in T$  (free disposability of  $z$ );
- (t6) if  $(x, z, y) \in T$ ,  $y^l \leq y$ , then  $(x, z, y^l) \in T$  (free disposability of  $y$ );
- (t7) for every finite  $x$  and  $z$ ,  $T$  is bounded from above; and
- (t8)  $(x, z, 0_m) \in T$ , but if  $y \geq 0$ ,  $(0_n, z, y) \notin T$  and  $(x, 0_n, y) \notin T$  and  $(x, z, 0_n) \notin T$  (weak essentiality).

where  $y$  denotes an  $m$ -dimensional vector of non-negative, real-valued outputs,  $x$  denotes an  $i$ -dimensional, real-valued vector of non-negative variable inputs, and  $z$  denotes an  $r$ -dimensional, real-valued vector of non-negative exogenous factors. These properties correspond to the aforementioned requirements of monotonicity and quasi-concavity of the estimated efficiency frontier.

## 7 Conclusions: The Need for Consistent and Flexible Efficiency Measurement

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Existing black box estimation tools foster incorrect and unsound efficiency estimations lacking theoretical consistency and leading to inadequate and potentially counterproductive development policy actions. The preceding discussion hence aims at highlighting the compelling need for a critical assessment of efficiency estimates with respect to the current evidence on theoretical consistency, flexibility as well as the choice of the appropriate functional form. The application of a flexible functional form as the translog specification by the majority of technical efficiency studies is adequate with respect to economic theory.<sup>47</sup> However, most applications do not adequately test for whether the estimated function has the required regularities of monotonicity and quasi-concavity, and hence run the risk of making improper policy recommendations. The researcher has to check a posteriori for the regularity of the estimated frontier which means checking these requirements for each and every data point with respect to the translog specification. If these requirements do not hold they have to be imposed a priori to estimation as briefly outlined in the text. Imposing global regularity nevertheless leads to a significant loss of functional flexibility, local imposition requires a differentiated interpretation: if theoretical consistency holds for a range of observations, this ‘consistency area’ of the estimated frontier should be determined and clearly stated to the reader. Estimated relative efficiency scores hence only hold for observations which are part of this range. Alternatively flexible functional forms – as e.g. the symmetric generalized McFadden – could be used which can be accommodated to global theoretical consistency over the whole range of observations. Furthermore one should always check for a possibility of using dual concepts such as the profit or cost function with respect to the efficiency measurement problem in question.<sup>48</sup> Hence, policy measures based on such efficiency estimates are not subject to possible inadequacy and a waste of scarce resources. Here exemplary applications already exist in the literature. The test for theoretical consistency of an arbitrary selected sample of translog production frontiers published in development relevant literature in recent years revealed the significance of this problem for daily efficiency measurement as well as policy formulation.

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<sup>47</sup> Unless there is strong a priori information on the true functional form, flexibility should be maintained as much as possible (see e.g. Lau, 1986).

<sup>48</sup> As Lau (1986, p.1558) notes: „With regard to specific applications, one can say that as far as the empirical analysis of production is concerned, the surest way to obtain a theoretically consistent representation of the technology is to make use of one of the dual concepts such as the profit function, the cost function or the revenue function.“

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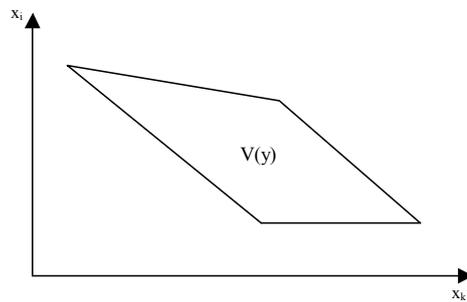
## Appendix

### A1: Properties of $F(x)$

(1a) monotonicity: if  $x' \geq x$ , then  $f(x') \geq f(x)$

(1b) quasi-concavity:  $V(y) = \{x: f(x) \geq y\}$  is a convex set where  $V(y)$  denotes the input requirement set

Figure A1: A Convex Input Requirement Set



(1c)  $f(x)$  is finite, non-negative, real valued, and single valued for all non-negative and finite  $x$ .

### A2: Negative Semi-Definiteness of a Matrix

Any symmetric matrix  $\mathbf{M} \in \mathbb{R}^n \times \mathbb{R}^n$  is negative semi-definite (nsd) if and only if

$$\mathbf{Q}(\mathbf{M}, \mathbf{Z}) = \mathbf{Z}'\mathbf{M}\mathbf{Z} \leq 0 \quad (\text{A1})$$

for arbitrary  $\mathbf{Z} \in \mathbb{R}^n$ .

The  $\mathbf{Q}(\mathbf{M}, \mathbf{Z})$  is referred to as the quadratic form of the symmetric matrix  $\mathbf{M}$ .

If  $\mathbf{Q}(\mathbf{M}, \mathbf{Z}) < 0$ ,  $\mathbf{M}$  is called 'negative definite'.

**Lemma A1.**  $\mathbf{Q}(\mathbf{M}, \mathbf{Z})$  is nsd only if

- a. its principal minors (i.e. determinants) alternate in sign starting with a negative number,
- b. its principal submatrices are nsd, and
- c. the diagonal elements of  $\mathbf{M}(m_{ij})$  are nonpositive (i.e.  $m_{ij} < 0$ ).
- d.  $\mathbf{Q}(\mathbf{M}, \mathbf{Z})$  of the rank  $> 3 \times 3$  is nsd if for all eigenvalues  $e$  of  $\mathbf{Q}$ :  $e \leq 0$ .

### A3: Eigenvalues of a K x K Square Matrix

Let  $\mathbf{A}$  be a linear transformation represented by a matrix  $\mathbf{A}$ . If there is a vector  $\mathbf{X} \in \mathbb{R}^n \neq 0$  such that

$$\mathbf{A} \mathbf{X} = \mathbf{e} \mathbf{X} \quad (\text{A2})$$

for some scalar  $\mathbf{e}$ , then  $\mathbf{e}$  is called the *eigenvalue* of  $\mathbf{A}$  with corresponding (right) *eigenvector*  $\mathbf{X}$ :

$$(\mathbf{A} - \mathbf{e} \mathbf{I}) \mathbf{X} = 0 \quad (\text{A3})$$

where  $\mathbf{I}$  is the *identity matrix*. As shown by Cramer's rule, a linear system of equations has nontrivial solutions if the determinant vanishes, so the solutions of equation (A3) are simply given by:

$$\det(\mathbf{A} - \mathbf{e} \mathbf{I}) = 0 \quad (\text{A4})$$

Equation (A4) is known as the *characteristic equation* of  $\mathbf{A}$  and the left-hand side is known as the *characteristic polynomial*. For e.g. if  $k = 2$ , i.e. a 2x2-matrix, the eigenvalues are determined by

$$\mathbf{e} \pm = \frac{1}{2} [(a_{11} + a_{22}) \pm \sqrt{4a_{12}a_{21} + (a_{11} - a_{22})^2}] \quad (\text{A5})$$

which arises as the solutions of the *characteristic equation*:

$$x^2 - x(a_{11} + a_{22}) + (a_{11}a_{22} - a_{12}a_{21}) = 0 \quad (\text{A6})$$

Table A1: Numerical Details of Regularity Tests Performed – Example I

(29 observations out of 100 are published in: Coelli et al., 2003).

(Note: **bold**, not consistent with economic theory)

STUDY I)	MONOTONICITY First Derivatives ( $\partial Y/\partial X_i > 0$ )			DIMINISHING MARGINAL PRODUCTIVITY Second Derivatives ( $\partial^2 Y/\partial X_i^2 < 0$ )			QUASI-CONCAVITY Eigenvalues of Bordered Hessian Matrix ( $E_i \leq 0$ )			
	OBSER- VATION	Input 1	Input 2	Input 3	Input 1	Input 2	Input 3	E1	E2	E3
1	<b>-1.84754</b>	0.58990	<b>-2.59457</b>	<b>0.22570</b>	<b>0.01926</b>	<b>0.39209</b>	-3.02224	<b>0.24501</b>	-0.05969	<b>3.47398</b>
2	<b>-2.17213</b>	0.78076	<b>-2.61924</b>	<b>0.26702</b>	<b>0.00928</b>	<b>0.35379</b>	-3.26903	<b>0.23136</b>	-0.06178	<b>3.72954</b>
3	<b>-2.74557</b>	1.01085	<b>-1.94628</b>	<b>0.47594</b>	<b>0.00098</b>	<b>0.21323</b>	-3.24755	<b>3.80617</b>	-0.07251	<b>0.20403</b>
4	<b>-2.19812</b>	0.87986	<b>-1.88668</b>	<b>0.34195</b>	<b>0.00159</b>	<b>0.22891</b>	-2.81420	<b>3.25890</b>	-0.06505	<b>0.19279</b>
5	<b>-2.25597</b>	0.96989	<b>-2.53331</b>	<b>0.26812</b>	<b>0.00478</b>	<b>0.31446</b>	-3.31149	<b>0.20301</b>	-0.06409	<b>3.75994</b>
6	<b>-2.55064</b>	0.92864	<b>-1.97482</b>	<b>0.41010</b>	<b>0.00112</b>	<b>0.22256</b>	-3.11709	<b>3.61761</b>	-0.06550	<b>0.19875</b>
7	<b>-2.09167</b>	0.66468	<b>-2.96120</b>	<b>0.25701</b>	<b>0.02313</b>	<b>0.45193</b>	-3.43726	<b>0.28341</b>	-0.06892	<b>3.95483</b>
8	<b>-2.04785</b>	0.75025	<b>-2.47882</b>	<b>0.30053</b>	<b>0.01558</b>	<b>0.37532</b>	-3.07196	<b>0.29427</b>	-0.08149	<b>3.55060</b>
9	<b>-2.1103</b>	0.86619	<b>-2.15782</b>	<b>0.31882</b>	<b>0.00540</b>	<b>0.29467</b>	-2.92139	<b>0.23897</b>	-0.07554	<b>3.37686</b>
10	<b>-2.1478</b>	0.87721	<b>-2.47727</b>	<b>0.26748</b>	<b>0.00665</b>	<b>0.32590</b>	-3.17810	<b>0.21724</b>	-0.06482	<b>3.62572</b>
11	<b>-1.61834</b>	0.32424	<b>-2.27169</b>	<b>0.18924</b>	<b>0.01683</b>	<b>0.32440</b>	-2.62911	<b>0.20027</b>	-0.04159	<b>3.00090</b>
12	<b>-2.09274</b>	0.60855	<b>-2.76053</b>	<b>0.24312</b>	<b>0.01380</b>	<b>0.38344</b>	-3.29483	<b>0.23298</b>	-0.05378	<b>3.75598</b>
13	<b>-1.84929</b>	0.69421	<b>-2.07875</b>	<b>0.27999</b>	<b>0.00995</b>	<b>0.30312</b>	-2.66788	<b>0.24846</b>	-0.07146	<b>3.08394</b>
14	<b>-1.71767</b>	0.44741	<b>-2.75319</b>	<b>0.20587</b>	<b>0.03333</b>	<b>0.45307</b>	-3.04356	<b>0.26569</b>	-0.05917	<b>3.52931</b>
15	<b>-2.23325</b>	0.75167	<b>-2.96880</b>	<b>0.26167</b>	<b>0.01517</b>	<b>0.41833</b>	-3.54744	<b>0.25509</b>	-0.06382	<b>4.05134</b>
16	<b>-2.12400</b>	0.62927	<b>-1.92061</b>	<b>0.35525</b>	<b>0.00655</b>	<b>0.22699</b>	-2.73363	<b>3.14771</b>	-0.07044	<b>0.24515</b>
17	<b>-2.14986</b>	0.95218	<b>-2.68034</b>	<b>0.27325</b>	<b>0.01163</b>	<b>0.37911</b>	-3.33043	<b>0.25432</b>	-0.07861	<b>3.81871</b>
18	<b>-2.29498</b>	0.80839	<b>-2.34501</b>	<b>0.33263</b>	<b>0.00604</b>	<b>0.30822</b>	-3.15330	<b>0.24665</b>	-0.06948	<b>3.62301</b>
19	<b>-1.73083</b>	0.46499	<b>-2.69489</b>	<b>0.22880</b>	<b>0.03761</b>	<b>0.45918</b>	-3.00175	<b>0.30451</b>	-0.07077	<b>3.49360</b>
20	<b>-2.26671</b>	0.79229	<b>-2.72111</b>	<b>0.27286</b>	<b>0.00891</b>	<b>0.36085</b>	-3.40158	<b>0.23194</b>	-0.06063	<b>3.87290</b>
21	<b>-2.67506</b>	0.95063	<b>-2.28727</b>	<b>0.40663</b>	<b>0.00187</b>	<b>0.26736</b>	-3.39838	<b>3.91348</b>	-0.07144	<b>0.23221</b>
22	<b>-2.52266</b>	1.13992	<b>-2.41417</b>	<b>0.34050</b>	<b>0.00164</b>	<b>0.29645</b>	-3.43210	<b>3.93255</b>	-0.07406	<b>0.21219</b>
23	<b>-2.50714</b>	0.97349	<b>-2.40742</b>	<b>0.35750</b>	<b>0.00275</b>	<b>0.30423</b>	-3.36878	<b>3.86936</b>	-0.07241	<b>0.23631</b>
24	<b>-2.38268</b>	0.88368	<b>-2.75109</b>	<b>0.32506</b>	<b>0.00931</b>	<b>0.39033</b>	-3.49529	<b>0.28414</b>	-0.07909	<b>4.01495</b>
25	<b>-3.33296</b>	1.73031	<b>-1.80445</b>	<b>0.72829</b>	<b>0.01381</b>	<b>0.18690</b>	-3.76358	<b>4.62343</b>	-0.12655	<b>0.19571</b>
26	<b>-4.15291</b>	2.16032	<b>-2.20138</b>	<b>0.81234</b>	<b>0.02203</b>	<b>0.22269</b>	-4.70622	<b>5.69418</b>	-0.12625	<b>0.19535</b>
27	<b>-3.33596</b>	1.60037	<b>-1.70537</b>	<b>0.66031</b>	<b>0.01457</b>	<b>0.16270</b>	-3.70554	<b>4.48581</b>	-0.09353	<b>0.15083</b>
28	<b>-2.29084</b>	1.31247	<b>-2.74066</b>	<b>0.31359</b>	<b>0.00365</b>	<b>0.42868</b>	-3.53898	<b>0.29163</b>	-0.10274	<b>4.09602</b>
29	<b>-2.61776</b>	1.36709	<b>-2.91457</b>	<b>0.33706</b>	<b>0.00197</b>	<b>0.40885</b>	-3.87485	<b>0.26900</b>	-0.09219	<b>4.44592</b>

Table A2: Numerical Details of Regularity Tests Performed – Examples II-VI

(Due to lacking data on each observation for study II) to VI) evaluated at the sample means.)

(Note: **bold**, not consistent with economic theory)

STUDY	MONOTONICITY First Derivatives ( $\partial Y/\partial X_i > 0$ )	DIMINISHING MARGINAL PRODUCTIVITY Second Derivatives ( $\partial^2 Y/\partial X_i^2 < 0$ )	QUASI-CONCAVITY Eigenvalues of Bordered Hessian Matrix ( $E_i \leq 0$ )
<b>IIA)</b>  <b>Model 1</b>	Input 1: 1115.82115 Input 2: <b>-1.17838</b> Input 3: 5.23465 Input 4: 26.37129	Input 1: -47.18914 Input 2: <b>0.00133</b> Input 3: -0.01544 Input 4: <b>0.00042</b>	E1: <b>1298.53011</b> E2: -1321.70761 E3: <b>0.01271</b> E4: -0.02751 E5: -23.99859
<b>IIB)</b>  <b>Model 2</b>	Input 1: 1015.04819 Input 2: 2.35394 Input 3: 4.39806 Input 4: 14.95299	Input 1: <b>2424.33423</b> Input 2: -0.02503 Input 3: -0.012672 Input 4: -0.01413	E1: -382.95155 E2: <b>2814.24112</b> E3: -0.00444 E4: -0.02995 E5: -6.97277
<b>IIIA)</b>  <b>Model 1</b>	Input 1: 9.92808 Input 2: <b>-2377936.216</b> Input 3: 3.62655	Input 1: <b>1.21123E-05</b> Input 2: <b>869070.6498</b> Input 3: <b>1.77912E-06</b>	E1: -9.92808 E2: <b>9.92809</b> E3: <b>6.7825E+14</b> E4: -6.7825E+14
<b>IIIB)</b>  <b>Model 2</b>	Input 1: 5.19119 Input 2: <b>-206283.4505</b> Input 3: 0.12041	Input 1: <b>2.71923E-06</b> Input 2: <b>11711.38547</b> Input 3: -3.01675E-09	E1: -5.19119 E2: <b>5.19119</b> E3: <b>3.12125E+12</b> E4: -3.12125E+12
<b>IV)</b>	Input 1: 545.51798 Input 2: 63.39966 Input 3: 210.64866 Input 4: 1.22185	Input 1: <b>325.59682</b> Input 2: -0.07723 Input 3: -2.32279 Input 4: -0.00026	E1: -473.82527 E2: <b>756.14889</b> E3: -0.61524 E4: <b>41.48851</b> E5: -0.00035

Table A2 (continued):

<b>VA)</b>  <b>Model 1</b>	Input 1: 12.70210166 Input 2: 0.373871748 Input 3: 0.41408414 Input 4: 0.259400061 Input 5: 13.09440473	Input 1: -0.025869843 Input 2: -0.000461362 Input 3: -0.000776985 Input 4: -0.000434328 Input 5: -0.410269681	E1: <b>17.95294241</b> E2: <b>0.164361041</b> E3: <b>55.05044583</b> E4: -55.05405524 E5: -0.000844645 E6: -18.55066159
<b>VB)</b>  <b>Model 2</b>	Input 1: 12.73558284 Input 2: 0.118603997 Input 3: 0.466864733 Input 4: 0.234961412 Input 5: 12.70477831	Input 1: -0.028486414 Input 2: -0.00013767 Input 3: -0.000460777 Input 4: -1.89629E-05 Input 5: -0.333965667	E1: <b>17.97369508</b> E2: -18.02373131 E3: -12.19157234 E4: -0.000349844 E5: <b>12.19385827</b> E6: -0.314969346
<b>VI A)</b>  <b>Model 1993</b>	Input 1: 2483.90355 Input 2: 1.56905 Input 3: 6.03447 Input 4: <b>-0.82598</b> Input 5: 5.89932 Input 6: 9.51835	Input 1: -1973.7690 Input 2: -0.01193 Input 3: -0.00561 Input 4: <b>0.00551</b> Input 5: -0.00916 Input 6: -0.08145	E1: <b>1685.90046</b> E2: -3659.58336 E3: -18709.41058 E4: <b>18709.53378</b> E5: <b>0.00538</b> E6: -0.02303 E7: -0.32609
<b>VI B)</b>  <b>Model 1994</b>	Input 1: 2150.89636 Input 2: 6.50092 Input 3: 5.92348 Input 4: <b>-0.76074</b> Input 5: 6.47381 Input 6: 10.05337	Input 1: -1247.37124 Input 2: -1391.39286 Input 3: -0.00525 Input 4: <b>0.00422</b> Input 5: -0.01079 Input 6: -0.07681	E1: <b>24561.323</b> E2: <b>1615.8693</b> E3: <b>0.004171</b> E4: -0.02719 E5: -0.34692 E6: -2863.1868 E7: -25952.488
<b>VI C)</b>  <b>Model 1995</b>	Input 1: 1799.93649 Input 2: 7.28249 Input 3: 5.39876 Input 4: <b>-0.86076</b> Input 5: 5.83771 Input 6: 10.40969	Input 1: -1025.09236 Input 2: -0.02257 Input 3: -0.00483 Input 4: <b>0.00481</b> Input 5: -0.00929 Input 6: -0.08251	E1: <b>24112.158</b> E2: <b>1359.089</b> E3: <b>0.00469</b> E4: -0.02334 E5: -0.39265888 E6: -2384.0573 E7: -24111.985

Table A2 (continued):

<b>VI D)</b> <b>Model 1996</b>	Input 1: 1800.85281 Input 2: 9.75850 Input 3: 5.70050 Input 4: <b>-1.04981</b> Input 5: 6.06115 Input 6: 11.08452	Input 1: -1009.05752 Input 2: -0.03173 Input 3: -0.00507 Input 4: <b>0.00558</b> Input 5: -0.00879 Input 6: -0.08038	E1: <b>31260.111</b> E2: <b>1365.8201</b> E3: <b>0.00538</b> E4: -0.02140 E5: -0.41888 E6: -2374.7521 E7: -31259.922
<b>VI E)</b> <b>Model 1997</b>	Input 1: 1596.88089 Input 2: 11.44893 Input 3: 5.55262 Input 4: <b>-1.27070</b> Input 5: 5.67325 Input 6: 11.66396	Input 1: -874.60829 Input 2: -0.03836 Input 3: -0.00498 Input 4: <b>0.00693</b> Input 5: -0.00735 Input 6: -0.08345	E1: <b>33613.796</b> E2: <b>1218.5853</b> E3: <b>0.00658</b> E4: -0.01695 E5: -0.45938 E6: -2093.0165 E7: -33613.63

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