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Decomposing productivity growth allowing efficiency gains and price-induced technical progress

Alfons Oude Lansink

Wageningen University, Wageningen, Netherlands

Elvira Silva

University of Porto, Portugal

Spiro Stefanou

Pennsylvania State University, University Park, PA, USA

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Summary

Time- and firm-specific output technical efficiency measures are generated within a price-induced technological change framework. The firm-specific production frontier incorporates past prices as an argument encouraging innovation and a time trend to account for exogenous technical change. The theoretical model is used to decompose total factor productivity into a scale effect, an efficiency change effect and a technological change effect. Input bias arising from exogenous technical change and price-induced innovation is investigated using a multiple-input measure of biased technical change. The empirical focus is on Dutch pot-plant firms during the period 1979–1995 using the maximum entropy estimation method.

Keywords: inter-firm efficiency, price-induced technical change, bias in technical change, maximum entropy

JEL classification: Q12, D24

1. Introduction

Identifying and estimating the components of productivity growth provides insight into the impact of technology exploitation and technical change as firms evolve over time. Investigation of the technology typically centres on the exploitation of scale economies, with more recent studies addressing the role of efficiency gains from using a given technology (e.g. Färe *et al.*, 1994; Kumbhakar, 1997). Technical change often focuses on exogenous change (e.g. Kumbhakar and Heshmati, 1996). However, in the presence of technical efficiency gains, identifying and estimating how firms catch up to the new efficient frontier and the role of induced innovation are important forces to disentangle.

The objectives of this paper are threefold. First, time- and firm-specific output technical efficiency measures are generated within a price-induced technological change framework. Technological change is similar in nature to any investment process as it requires time and adjustment that is not instantaneous. Consequently, current and past prices can only induce technological change in the future and current technological change depends on past prices. The current technology reflects technology choices, which are influenced by past prices. A time trend is also included in the firm-specific frontier to account for exogenous technical change. The second objective of this paper is to decompose total factor productivity (TFP) growth into a scale effect, an efficiency change effect and a technological change effect. A price-induced technical change effect and an exogenous technical change effect constitute the technological change effect. The final objective addresses the primal measures of input bias arising from price-induced innovation and exogenous technical change. Input bias measures are generated for each firm at each time period.

The empirical focus of this paper is on specialised Dutch pot-plant firms as a case study. The Dutch glasshouse industry faced substantial energy price increases as a result of the two oil crises, and this led firms to substitute mineral gas for oil and to adopt energy-saving technologies. The large dependence of the Dutch glasshouse industry on energy makes this sector an interesting case to analyse technical efficiency and the components of TFP growth within the price-induced technical change framework, and to evaluate the impact of prices on the direction of technical change.

The importance of the role of relative prices as an inducement mechanism of technological innovation was originally suggested by Hicks (1932), who argued that technical progress is not labour-saving by nature. It is the relative cheapening of capital that induces the development of capital-using production techniques. The role of relative prices as an inducement mechanism has been further stressed by Rothbarth (1946) and Habbakuk (1962) in a comparative analysis of US and British industries. The theory of induced innovation has been enriched by numerous contributions, including those of Hayami and Ruttan (1971), Binswanger (1974) and Verspagen (1992), among others.

A key historical direction of the theory of induced innovation addresses the impact of prices on the direction of technological change (e.g. Hayami and Ruttan, 1971). The empirical analysis of that issue has been implemented by including (output and input) prices in the production function specification that act as shifting variables on the production frontier. Consequently, within this framework prices have both the role of signalling scarcity and the role of inducing technical change by acting as a driving force to develop new technologies (Paris, 1993; Paris and Caputo, 1995; Celikkol and Stefanou, 1999).

The distinguishing feature of the model used in this paper is that firm-specific production frontiers and time- and firm-specific efficiency parameters permit identification of intra- and inter-firm technical efficiency measures as well as an inter-firm catch-up component. Intra-firm technical efficiency involves computing a firm's efficiency degree over time taking the firm-specific production frontier as the reference frontier. Inter-firm technical efficiency for a firm involves choosing the 'best practice frontier' at each time period among the set of comparable firms and then evaluating the firm's technical efficiency relative to that frontier. The inter-firm catch-up component for a given time period may incorporate differences in technology across firms arising from differences in the rate of innovation adoption by firms in a specific industry, or input quality differences, or both. Oude Lansink *et al.* (2001) initially suggested the notions of intra-firm efficiency and inter-firm catch-up. However, their approach did not account for the role of prices in technical change.

The estimation of a firm-specific production frontier can be an ill-posed problem when the number of time periods in the panel data set is not large enough, implying the number of parameters to be estimated exceeds the number of data points. If the problem is ill-posed, traditional estimation methods (e.g. least squares, maximum likelihood) may fail to determine a unique solution, unless parametric assumptions (e.g. all slope parameters are equal for all firms whereas the intercept term is firm-specific) or prior information is used to generate a well-posed problem. Oude Lansink (2000) estimated a dual system of input demand and output supply equations and showed that firm-specific intercepts of the input demand and output supply equations generate a production function that is firm specific in slope parameters and intercept terms. However, the production frontier that is derived in this way is firm specific to a limited degree, as firm specificity follows from only four intercepts (39 other parameters are equal for all firms). Moreover, the method used by Oude Lansink (2000) does not allow for estimating intra-firm efficiency and inter-firm catch-up separately. In this paper, the maximum entropy formalism is used to estimate firm-specific production frontiers and time- and firm-specific efficiency parameters. The maximum entropy formalism reveals a powerful tool to estimate a production frontier that is fully firm specific, i.e. in the intercept and all slope parameters (Golan *et al.*, 1996).

The theoretical model used to derive the inter- and intra-firm efficiency measures and the catch-up component is presented in the next section, followed by the decomposition of the TFP growth and measures of input bias in Section 3. The data used in this paper are obtained from a stratified sample of Dutch glasshouse firms over the time period 1979–1995 and are the focus of Section 4. The empirical model and the maximum entropy estimation procedure are presented in Section 5. Finally, the empirical results and conclusions are presented in the last two sections of the paper.

2. Theoretical model

2.1. Intra-firm efficiency

The notion of intra-firm output technical efficiency implies that each firm has a firm-specific production frontier. Intra-firm output technical efficiency measure is modelled as a time- and firm-specific scaling parameter and estimated using a primal specification of the firm's profit maximisation problem. This study employs the primal specification rather than the dual value function, as output technical efficiency can be computed directly from the firm-specific production frontier.

The firm-specific production frontier is modelled as

$$Y_{ht} = U_{ht} \cdot F_h(X_{ht}, \bar{w}_t, t) + e_{ht} \tag{1}$$

where Y_{ht} is firm h's observed output level at time period t; $U_{ht} \in [0, 1]$ is a firm- and time-specific scaling parameter representing firm h's output technical inefficiency at time t; $F_h(\cdot)$ is the firm-specific frontier function for firm h; X_{ht} is an observed $n \times 1$-vector of inputs for firm h at time t; $\bar{w}_t$ is a vector of past input prices acting as a shift parameter of the technology frontier; t is a time trend accounting for exogenous technical change; and e_{ht} is an error term accounting for random events such as exceptional weather circumstances or pests.[1] By including time and input prices in the production function specification, exogenous technical change and price-induced innovation, respectively, are separated from technical inefficiency.

Intra-firm technical efficiency involves computing a firm's technical efficiency degree over time taking the firm-specific production frontier as the reference frontier. Hence, intra-firm efficiency reflects the utilisation of resources within the firm and provides information on the firm's perception of its production potential. This efficiency measure concentrates on the managerial and engineering problems of attaining the maximum output possible given the set of inputs. Hence, this efficiency measure reflects human capital factors such as experience, education and managerial capability.

Given the production specification in (1), firm h's intra-firm efficiency at time t is determined as the ratio of actual output to the frontier output at time t:

$$\lambda_{ht}^{I} = \frac{U_{ht} \cdot F_h(X_{ht}, \bar{w}_t, t)}{F_h(X_{ht}, \bar{w}_t, t)} = U_{ht}. \tag{2}$$

A coherent system of n input demand equations at time period t can be derived by using firm h's first-order conditions for profit maximisation:

$$\frac{U_{ht}\partial F(\cdot)}{\partial X_{hit}} = c_{it}, \qquad i = 1, \ldots, n \tag{3}$$

where c_{it} is the ratio of the price of the input i to the output price at time t.

2.2. Inter-firm efficiency

Inter-firm technical efficiency involves choosing the 'best practice frontier' at each time period among the set of comparable firms and then evaluating the

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[1] The theory of induced innovation does not imply that technical change possesses a wholly induced character. Technical change also reflects the progress of general science (scientific innovation) and technology. Consequently, a time trend is also included as an argument of the firm-specific production frontier to account for the impact of scientific innovation on the production technology.

firm's technical efficiency degree relative to that frontier. Consequently, inter-firm efficiency reveals a particular firm's performance relative to the 'best available technology' in the industry.

Let us assume firm *j* belongs to the set of comparable firms for firm *h*. Given the observed input bundle for firm *h*, X_{ht}, and inserting it in firm *j's* production frontier yields the maximum output level firm *j* could obtain if this firm were using the same input bundle as firm *h*, $F_j(X_{ht}, \bar{w}_t, t)$. Given firm *h*'s set of comparable firms at time period *t*, the 'best practice frontier' for firm *h* at time *t*, $F^*_{ht}(\cdot)$, is determined as the technology yielding maximum obtainable output given the input vector X_{ht}:

$$F^*_{ht}(X_{ht}, \bar{w}_t, t) = \max_j \{F_j(X_{ht}, \bar{w}_t, t)\}. \tag{4}$$

The 'best-practice' technology for a firm in (4) is similar to the concept of the best-practice or frontier production function for an entire industry proposed by Førsund and Hjalmarsson (1987).

Once the 'best practice frontier' is identified, firm *h*'s inter-firm efficiency at time *t* (λ_{ht}) is determined as the ratio of firm *h*'s actual output at time *t* to the maximum obtainable output at time *t* in the reference group:

$$\lambda_{ht} = \frac{U_{ht} F_h(X_{ht}, \bar{w}_t, t)}{F^*_{ht}(X_{ht}, \bar{w}_t, t)}. \tag{5}$$

The inter-firm efficiency measure shows the potential for an increase in firm *h*'s output if this firm were using the best-practice technology.

2.3. Inter-firm catch-up

Intra-firm and inter-firm technical efficiency measures are related by an inter-firm catch-up component measuring the relative performance of the firms within the industry. The inter-firm catch-up component reflects the gap between a firm's production potential and the 'best available technology' in the industry. This gap may be due to several reasons such as input quality differences (e.g. managerial capability, experience, education) and differences in the adoption rate of innovations across firms. Another explanation may be differences in composition of vintages of capital (Førsund and Jansen, 1977; Førsund and Hjalmarsson, 1987; Førsund *et al.*, 1996). Embodied technological progress leads to different vintages of capital, implying that capacity of a recent vintage is more efficient than that of an older vintage (Førsund and Hjalmarsson, 1987). Inertia in the capital structure, embodied technological progress and different expansion rates of firms result in different holdings of capital goods across firms (Førsund and Hjalmarsson, 1987).

Given the 'best practice frontier' for firm *h* in (4), the inter-firm catch-up component at time *t* is given by

$$\lambda^C_{ht} = \frac{F_h(X_{ht}, \bar{w}_t, t)}{F^*_{ht}(X_{ht}, \bar{w}_t, t)}. \tag{6}$$

The inter-firm efficiency measure in (5) is equal to the product of the intra-firm efficiency in (2) and the catch-up component in (6), $\lambda_{ht} = \lambda^I_{ht} \cdot \lambda^C_{ht}$.

Identifying the magnitude of intra-firm inefficiency and the catch-up component is important. The intra-firm efficiency concentrates on the utilisation of resources within the firm whereas the catch-up component measures the relative performance of the firms within the industry. The distinguishing feature of the model is that time- and firm-specific technical efficiency measures are generated for each firm at each time period.[2]

3. Decomposing TFP growth and bias in technological change

The relation between actual output and the 'best practice frontier' for firm h at time t is given as follows:

$$Y_{ht} = \lambda^I_{ht} F_h(X_{ht}, \bar{w}_t, t). \tag{7}$$

Following the standard approach of decomposing TFP growth, totally differentiating (7) and dropping the subscripts h and t yields[3]

$$\mathrm{d}Y = \lambda^I \sum_{i=1}^{n} F_{X_i} \mathrm{d}X_i + \lambda^I F_{\bar{w}} \mathrm{d}\bar{w} + \lambda^I F_t \mathrm{d}t + F(\cdot)\mathrm{d}\lambda^I. \tag{8}$$

Dividing (8) through by $F(\cdot)$ and dt and rearranging yields

$$\hat{Y}\frac{Y}{F(\cdot)} = \lambda^I \left[\sum_{i=1}^{n} F_{X_i} X_i \hat{X}_i + F_{\bar{w}} \bar{w}\hat{\bar{w}} + F_t\right] \frac{1}{F(\cdot)} + \frac{\mathrm{d}\lambda^I}{\mathrm{d}t} \tag{9}$$

where the circumflex indicates proportional growth rates (i.e. $\hat{Y} = \dot{Y}/Y$), and some further reorganising and recognising that $\lambda^I = Y/F(\cdot)$ leads to rewriting (9) as

$$\hat{Y}\lambda^I = \lambda^I \left[\sum_{i=1}^{n} \frac{F_{X_i} X_i}{F(\cdot)} \hat{X}_i + \hat{W} + \hat{A}\right] + \frac{\mathrm{d}\lambda^I}{\mathrm{d}t} \tag{10}$$

where $\hat{W} = F_{\bar{w}}\bar{w}\hat{\bar{w}}/F(\cdot)$ and $\hat{A} = F_t/F(\cdot)$ represent the proportional shift in the firm-specific frontier technology as a result of price-induced technological change and exogenous technological change, respectively. Defining $TF = \sum_{i=1}^{n} F_{X_i} X_i$ and multiplying and dividing through by TF leads to (10) being rewritten as

$$\hat{Y} = \frac{TF}{F(\cdot)} \left[\sum_{i=1}^{n} \frac{F_{X_i} X_i}{TF} \hat{X}_i\right] + \hat{W} + \hat{A} + \hat{\lambda}^I \tag{11}$$

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[2] For other types of time- and firm-varying specification, see Kumbhakar and Heshmati (1995). Some studies using firm-specific (but time invariant) technical inefficiency are Pitt and Lee (1981), Schmidt and Sickles (1984), Kumbhakar (1987, 1988), Battese and Coelli (1988) and Atkinson and Cornwell (1993). Several other studies use time-varying technical inefficiency measures to investigate the behaviour of technical efficiency over time (Cornwell *et al*., 1990; Kumbhakar, 1990; Battese and Coelli, 1992).

[3] Only one input price is considered in the firm-specific production frontier, because in the empirical application the past price of energy is taken as the shift parameter of the production frontier.

where the ratio $TF/F(\cdot)$ is the sum of all production elasticities and measures returns to scale of the frontier technology. Denoting the Divisia index

$$\hat{F}_X = \sum_{i=1}^{n} \frac{F_{X_i} X_i}{TF} \hat{X}_i$$

and inserting this expression into (11) leads to proportional actual output growth being written as

$$\hat{Y} = \frac{TF}{F(\cdot)} \hat{F}_X + \hat{W} + \hat{A} + \hat{\lambda}^I \tag{12}$$

where $(TF/F(\cdot))\hat{F}_X$ is the frontier technology scale effect (input growth), $\hat{W}$ is the price-induced technological change effect, $\hat{A}$ is the exogenous technological change effect and $\hat{\lambda}^I$ is the intra-firm efficiency change effect.

Total factor productivity growth ($T\hat{F}P$) is defined as the residual growth in output, not accounted for by the growth in variable and fixed factors:

$$T\hat{F}P = \hat{Y} - \hat{F}_X. \tag{13}$$

Inserting (12) in (13) results in the TFP growth decomposition:

$$T\hat{F}P = \left(\frac{TF}{F(\cdot)} - 1 \right) \hat{F}_X + \hat{W} + \hat{A} + \hat{\lambda}^I. \tag{14}$$

TFP growth is decomposed into a scale effect, a technological change effect and an efficiency change effect.

The Hicksian theory of induced innovation implies that an increase in the price of one factor relative to other factor prices induces a sequence of technical changes reducing the use of that factor relative to the use of other input factors. Historical evidence reveals that technological development facilitates the substitution of relatively abundant (cheap) factors for relatively scarce (expensive) factors of production. Consequently, technological change can affect input productivities and factor use differentially, leading to the distinction between neutral and biased technological change.

Using the concept of Hicks neutrality, Binswanger (1974, 1978) proposes a definition of input bias in terms of factor cost shares. This definition has the advantage of leading to a single measure of bias for each factor in the multiple-input case.[4]

Multiple-input measures of input bias arising from exogenous technical change and price-induced innovation are derived following Binswanger (1974, 1978). The measure of bias in price-induced technological change for

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[4] The original definitions of neutral and biased technological change are formulated in terms of the marginal rate of technical substitution (Hicks, 1963). The Hicksian definition of bias requires pairwise comparisons of all inputs' marginal products leading to $n-1$ measures of bias for each factor in the n-factor case. Thus, in a multiple-input production process it is not clear whether technological change is overall using or saving in each input. Antle (1984) proposes a multiple-input measure of biased technical change based on the profit-maximising cost shares derived from the profit function.

input i and firm h at time t is defined as

$$BI_i^h(X_{ht}, \bar{w}_t, t) = \sum_{j \neq i} s_j BI_{ij}^h \tag{15}$$

where s_j is the cost share of factor j and

$$BI_{ij}^h(X_{ht}, \bar{w}_t, t) = \frac{\partial \left[\dfrac{\partial F_h(\cdot)}{\partial X_i} \Big/ \dfrac{\partial F_h(\cdot)}{\partial X_j} \right]}{\partial \bar{w}}. \tag{16}$$

BI_{ij}^h measures the impact of the energy past price on the marginal rate of technical substitution between input factors i and j for firm h at time t. BI_i^h indicates that if, on average, the marginal product of factor i is increasing (decreasing) relative to all others, then $BI_i^h > 0$ (<0) and price-induced technological change is overall factor-i using (saving). If price-induced technological change is neutral (that is, if all $BI_{ij}^h = 0$), then all $BI_i^h = 0$.

Similarly, the measure of the bias arising from exogenous technical change is defined as

$$BE_i^h(X_{ht}, \bar{w}_t, t) = \sum_{j \neq i} s_j BE_{ij}^h \tag{17}$$

where

$$BE_{ij}^h(X_{ht}, \bar{w}_t, t) = \frac{\partial \left[\dfrac{\partial F_h(\cdot)}{\partial X_i} \Big/ \dfrac{\partial F_h(\cdot)}{\partial X_j} \right]}{\partial t}. \tag{18}$$

BE_{ij}^h measures the impact of exogenous technical change on the marginal rate of technical substitution between input factors i and j for firm h at time t. BE_i^h indicates that if, on average, the marginal product of factor i is increasing (decreasing) relative to all others, then $BE_i^h > 0$ (<0) and the exogenous technological change is overall factor-i using (saving). Technological change is neutral when all $BE_{ij}^h = 0$, that is, $BE_i^h = 0$ for all i.

4. Data

Intra-firm and inter-firm efficiency analysis requires data with a cross-section and time series component. Panel data on specialised pot-plant firms covering the period 1979–1995 are obtained from a stratified sample of Dutch glasshouse firms keeping accounts on behalf of the LEI-DLO accounting system. Firms typically remain in the panel for a maximum of 8 years, resulting in an incomplete panel. Firms rotate in and out the sample to avoid a selection bias that arises when firms improve their performance by their presence in the accounting system. The data set contains 904 observations on 180 firms.

One output and three variable inputs (energy, materials and services) are distinguished. Output mainly consists of pot-plants. Other outputs included are fruits, vegetables and flowers. Energy consists of gas, oil and electricity, as well as delivery of thermal energy by electricity plants. Materials consist of seeds and planting materials, pesticides, fertilisers and other materials. Services include services by contract workers and services from storage and delivery of outputs.

Fixed inputs are structures (buildings, glasshouses, land and paving), machinery and installations and labour. Labour is measured in constant prices of 1985 and is calculated as the product of quality-corrected man years and the yearly costs of labour in 1985 (LEI-DLO/CBS). Labour includes family as well as hired labour. The quality correction of labour is performed by the LEI-DLO and is necessary to aggregate labour from able-bodied adults with labour supplied by young people (e.g. young family members) or partly disabled workers. Capital in structures and machinery and installations is measured in constant 1985 prices and valued in replacement costs.

Tornqvist price indexes are calculated for output and the three composite variable inputs with prices obtained from the LEI-DLO/CBS. The price indexes vary over the years but not over the firms, implying differences in the composition of inputs and output or quality differences are reflected in the quantity (Cox and Wohlgenant, 1986). Implicit quantity indexes are generated as the ratio of value to the price index. The past price of energy is included in the firm-specific frontier function to account for price-induced technological change and is generated as a 3-year moving average of past energy prices, that is, $\bar{w}_t = (w_{t-1} + w_{t-2} + w_{t-3})/3$, where w_{t-i} is the normalised price of energy in year $t - i$.[5] The numeraire price is a Laspeyres price index of prices of variable and fixed inputs, with weights given by their share in total costs.

Average values and standard deviations of the variables that are used in this study can be found in the Appendix (Table A1).

5. Empirical model

One of the purposes of this study is to generate firm- and time-specific output technical efficiency measures in a price-induced innovation framework. As output technical efficiency can be estimated directly from the firm-specific production frontier, these measures are generated using a primal specification of the firm's profit maximisation problem.

The firm-specific frontier for each firm in the sample is assumed to follow a quadratic specification of the production frontier:

$$Y_t = U_t \cdot \left(\beta_0 + \sum_{i=1}^{7} \beta_i X_{it} + \gamma \bar{w}_t + 0.5 \sum_{i=1}^{7} \sum_{j=1}^{7} \beta_{ij} X_{it} X_{jt} + 0.5 \kappa \bar{w}_t^2 + \sum_{j=1}^{7} \gamma_j X_{jt} \bar{w}_t \right) + e_{0t} \tag{19}$$

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[5] It is widely accepted that past and current prices can only induce technological change in the future, and current technological change depends on past prices. The choice of a 3-year moving average to generate the past price of energy is based on the observation that firms use the most recent years as having the greatest information content.

where X_{it} are input quantities at time t, with $i = 1$ (energy), 2 (materials), 3 (services), 4 (structures), 5 (machinery and installations) and 6 (labour). A time trend ($i = 7$) is included in the empirical model to account for exogenous technological change in the estimation period. Price-induced technological change is incorporated by including the past price of energy, $\bar{w}_t$, in the production frontier.

Using the first-order conditions for profit maximisation, the input demand equations can be derived as

$$X_{it} = \frac{1}{\beta_{ii}} \cdot \left(\frac{c_{it}}{U_t} - \beta_i - \sum_{j=1, j \neq i}^{7} \beta_{ij} X_{jt} - \gamma_i \bar{w}_t \right) + e_{it} \tag{20}$$

for $i = 1, 2, 3$.

Estimation of firm-specific frontiers in equation (19) and the system of equations in (20) involves a large number of parameters leading to negative degrees of freedom. In this case, traditional methods cannot be used. Equation (19) and the system of equations in (20) are estimated simultaneously using the maximum entropy estimation method.

Ill-posed problems may arise when the number of unknown parameters exceeds the number of data points. In this case, traditional estimation methods cannot be used unless restrictions on a sufficient number of parameters are imposed so that the remaining ones can be estimated (Golan *et al.*, 1996; Paris and Howitt, 1998). However, these restrictions may lead to erroneous interpretations and conclusions. The maximum entropy (ME) formalism reveals a powerful tool that provides the 'best' conclusions possible based on the data at hand (Golan *et al.*, 1996: 6).

When firm-specific frontiers need to be estimated, the number of parameters is usually very large, leading to negative degrees of freedom. Rewriting the production frontier in (19) in a vector form yields

$$Y_t = U_t \cdot G_t \beta + e_{0t} \tag{21}$$

where β is a $K \times 1$ vector of parameters to be estimated and G_t represents a $1 \times K$ vector of the right-hand-side variables. Estimating this model using ME econometrics requires all β_k to be expressed as the sum of the product of M probabilities and support values:

$$\beta_k = \sum_{m=1}^{M} p_{km} z_{km} \tag{22}$$

where p_{km} are probabilities and z_{km} are the corresponding support values. Support values for all parameters of the production frontiers are $[-10, -5, 0, 5, 10]$. Inspection of the average values of the variables used in the estimation shows that the average values of all inputs and prices are smaller than 10, whereas the average value of output is slightly larger than 10. Therefore, in a production function, with non-negative marginal products, it is expected *a priori* that the parameters will lie in the specified interval $[-10, 10]$. Similarly, the error terms in the frontier production function and input demand equations are expressed as the sum of the product of N probabilities (w_{itn}) and support values (v_{itn}):

$$\varepsilon_{it} = \sum_{n=1}^{N} w_{itn} v_{itn}, \qquad i = 0, 1, \ldots, 3. \tag{23}$$

Support values reflect the variation of the underlying errors and are determined using the 3σ rule, where σ is the standard deviation of the dependent variable. The 3σ rule is a special case of the Chebychev's inequality to specify a set of error bounds. Following Chebychev's inequality and given some excluded tail probability, v^{-2}, the error bounds should be proportional to the standard errors of the underlying disturbances, $\pm v\sigma$. The 3σ rule excludes at most one-ninth of the mass for $v = 3$ (Golan *et al.*, 1996: 88).

Maximum entropy estimation comprises the maximisation of the following entropy function:

$$H(p, w) = -\sum_{k=1}^{K} \sum_{m=1}^{M} p_{km} \ln(p_{km}) - \sum_{i=0}^{I} \sum_{t=1}^{T} \sum_{n=1}^{N} w_{itn} \ln(w_{itn}) \tag{24}$$

subject to the model (or consistency) constraints

$$Y_t = U_t \sum_{k=1}^{K} \sum_{m=1}^{M} p_{km} \cdot z_{km} \cdot G_{kt} + \sum_{n=1}^{N} w_{0tn} \cdot v_{0tn} \tag{25}$$

and

$$X_{it} = \frac{\sum_{k=1}^{K_i} \sum_{m=1}^{M} p_{km} \cdot z_{km} \cdot I_{ikt}}{U_t \sum_{m=1}^{M} p_{im} \cdot z_{im}} + \sum_{n=1}^{N} w_{itn} \cdot v_{itn} \tag{26}$$

where K represents the total number of parameters and K_i is the subset of K parameters in the ith variable input demand equation excluding the parameter β_{ii}. The parameter β_{ii} is reflected by the term in the denominator: $\sum_{m=1}^{M} p_{im} \cdot z_{im}$. G_{kt} is the kth variable in the production frontier at time t, and I_{ikt} is the kth variable in the ith variable input demand equation at time t. Other constraints included are the additivity constraints on the probabilities of the support values of β and the error terms

$$\begin{aligned} &\sum_{m=1}^{M} p_{km} = 1 \quad \forall k \\ &\sum_{n=1}^{N} w_{itn} = 1 \quad \forall i, t \end{aligned} \tag{27}$$

and the constraint on U_t, the specific measure of output technical efficiency:

$$0 \leq U_t \leq 1 \quad \forall t. \tag{28}$$

It should be noted that the term U_t is a point estimate that is independent of the entropy function as long as it is in the range between zero and one. The multiplicative formulation that is used here makes sure that U_t appears in the demand equations for inputs, allowing identification in the model. Specifying U_t as a distribution and estimating it in the entropy function complicates the estimation of the model and will bias U_t to the centre of the support interval.

Curvature conditions of the production frontier impose non-negative marginal products and concavity in variable and fixed inputs. Non-negative marginal products of the variable and fixed inputs are ensured by adding the following set of restrictions during estimation:

$$\beta_i + \sum_{j=1}^{7} \beta_{ij} X_j + \gamma_i \bar{w} \geq 0, \qquad i = 1, \ldots, 6. \tag{29}$$

Concavity of the production frontier in variable and fixed inputs is imposed by using the necessary condition that the diagonal elements of the matrix of second order of input quantity derivatives are negative and the sufficient but not necessary condition that the row and column off-diagonal elements are smaller in absolute terms than the absolute value of the corresponding diagonal element. This results in a set of additional restrictions that are imposed during estimation:

$$\begin{aligned} &\beta_{ii} \leq 0, \qquad i = 1, \ldots, 6 \\ &|\beta_{ij}| \leq |\beta_{ii}| \qquad \forall i, j = 1, \ldots, 6 \end{aligned} \tag{30}$$

where β_{ii}, β_{ij} are the diagonal and off-diagonal elements, respectively, of the matrix of second-order derivatives of the production frontier to input quantities.

The ME objective function is strictly concave in the interior of the additivity constraint set, implying uniqueness of the optimal solution. The existence of a unique solution is assured if the intersection of the consistency and additivity constraint set is non-empty. The ME problem provides the optimal probability vectors that can be used to form point estimates of the unknown parameter vector and the unknown disturbances (Golan *et al.*, 1996).

6. Empirical results

Inter-firm technical efficiency requires choosing the 'best practice frontier' for each firm in each time period among the set of comparable firms. The set of comparable firms for each firm h is defined as the set of firms with similar size, so that size effects do not bias efficiency measures. Size is determined on the basis of the average area covered with glass. Small firms possess an area $\leq 1/3$ of the average area. Firms with an area $>1/3$ and $\leq 4/3$ of the average area are considered medium firms. Large firms are the ones with an area $>4/3$ of the average area.[6]

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[6] The number of firms in the small, medium and large size classes is, respectively, 33, 108 and 39.

The firm-specific production frontier in (19) and the system of equations in (20) are estimated simultaneously using the ME estimation method.[7] Average production elasticities and standard deviations for the three groups are found in the Appendix (Table A2). Table A2 reveals that the energy (materials) elasticity falls (increases) as the firm increases in size. The elasticity of services is greater for small firms and the same for medium and large firms. The structures elasticity is the same for medium and large firms but small firms have a marginally lower structures elasticity response. The elasticities of machinery and installations clearly suggest that larger firms have a larger production elasticity, i.e. there is a range with a factor of three separating the small and large firms. The labour elasticity falls dramatically with increasing size of the firm. However, the change from medium to large is marginally lower. Looking at small firms, the exogenous technical change effect is 50 per cent greater for the medium firms and over 100 per cent greater for the large firms.

The short-run scale measure involving the short-run input choices (three variable inputs plus labour) is below one for all groups of firms. In contrast, the returns to scale exceeds one when fixed factors are taken into account in constructing the scale elasticity measure.[8] The production elasticities estimates indicate that firms are in the decreasing returns to scale region of the short-run cost curve but in the increasing returns to scale region of the long-run cost curve. Increasing returns to scale are possible for firm-specific technologies, suggesting that firms may be on the way toward their respective long-run equilibrium. There may be some physical constraints to expansion, or firms may tend to be overcapitalised to maintain flexibility in the face of evolving competitive situations.

Intra- and inter-firm technical efficiency and catch-up measures are generated for each firm in each year over the 1979–1995 period. Average measures of those components for each group of firms and for different time periods are reported in Table 1.[9] The results indicate, on average, that the intra-firm technical efficiency component is higher than the catch-up component for all groups of firms in all time periods, implying firms are more concerned with exploring their existent production potential than adopting new technology.

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[7] Estimation was performed using GAMS (Brooke *et al.*, 1996). Regularity conditions of the production function are imposed during estimation. Concavity of the firm-specific production frontier in variable and fixed inputs is imposed by the set of restrictions in (30); consequently, the matrix of second-order derivatives of the production frontier with respect to physical inputs is negative semi-definite. Given that the ME formalism is formulated in a non-statistical context, the classical hypothesis tests cannot be performed to evaluate the statistical significance of all coefficients in the firm-specific production frontier.

[8] Specifying fixed factors in the production function raises the question of how to properly specify the scale elasticity. Stefanou (1989) takes the perspective that the scale elasticity measure should reflect the inputs that can be selected during the decision period of the model and presents the scale elasticity in the context of both dynamic and static decision making. In the presence of a static model, the short-run scale measure is the relevant measure of returns to scale.

[9] Firm- and time-specific technical efficiency measures are not reported, because of space restrictions. The results are available from the authors upon request.

Table 1. Intra- and inter-firm efficiency and catch-up component by group of firms

	Small firms			Medium firms			Large firms		
	Intra	Catch-up	Inter	Intra	Catch-up	Inter	Intra	Catch-up	Inter
1979–1980	0.899	0.640	0.571	0.893	0.519	0.458	0.840	0.647	0.543
1981–1985	0.924	0.502	0.464	0.916	0.530	0.483	0.838	0.579	0.477
1986–1990	0.960	0.679	0.649	0.911	0.486	0.441	0.868	0.568	0.485
1991–1995	0.930	0.801	0.741	0.862	0.459	0.388	0.822	0.521	0.408
1979–1995	0.934	0.643	0.599	0.903	0.503	0.451	0.849	0.569	0.474

Small firms have a higher intra-firm efficiency measure than the other two groups of firms, implying small firms can realise their production potential more readily than medium and large firms. The mean of intra-firm technical efficiency in the period 1979–1995 is 93.4 per cent, 90.3 per cent and 84.9 per cent for small, medium and large firms, respectively. The average catch-up is substantially lower than the intra-firm efficiency and is 64.3 per cent, 50.3 per cent and 56.9 per cent for small, medium and large firms, respectively. The frequency distribution (Table 2) shows that the probability mass of the intra-firm efficiency is concentrated in the upper tail of the distribution for all groups. The catch-up component is more uniformly distributed than the intra-firm efficiency; however, the range of 0.1–0.5 accounts for more than 60 per cent of the observations in all groups.

Table 2. Frequency distribution of intra- and inter-firm efficiency and catch-up by group of firms

Range	Small firms			Medium firms			Large firms		
	Intra	Catch-up	Inter	Intra	Catch-up	Inter	Intra	Catch-up	Inter
0–0.1	–	0.059	0.065	–	–	0.002	–	0.005	0.026
0.1–0.2	–	0.137	0.157	–	0.064	0.101	–	0.164	0.286
0.2–0.3	–	0.137	0.157	0.002	0.181	0.242	–	0.238	0.233
0.3–0.4	–	0.190	0.196	0.005	0.221	0.230	0.021	0.291	0.286
0.4–0.5	–	0.144	0.124	0.016	0.242	0.226	0.037	0.148	0.101
0.5–0.6	–	0.118	0.111	0.018	0.151	0.107	0.074	0.079	0.037
0.6–0.7	–	0.085	0.098	0.043	0.066	0.048	0.048	0.016	0.021
0.7–0.8	0.072	0.052	0.059	0.078	0.030	0.025	0.127	0.026	0.011
0.8–0.9	0.196	0.039	0.007	0.196	0.025	0.009	0.185	0.016	–
0.9–1.0	0.732	0.039	0.026	0.642	0.020	0.011	0.508	0.016	–

Components of TFP growth for different subperiods are presented in Table 3. The TFP growth rate ranges from an average of −1.9 per cent per

Table 3. Components of total factor productivity growth

	TFP	Exogenous	Induced	Intra efficiency	Scale
1979–1980	−0.019	0.054	0.004	−0.073	−0.004
1981–1985	0.040	0.028	0.007	0.006	−0.001
1986–1990	0.025	0.038	−0.009	0.006	−0.010
1991–1995	0.004	0.018	−0.001	−0.014	0.001

annum in the period 1979–1980 to 4.2 per cent per annum in 1981–1985.[10] The most important contribution to TFP growth is the exogenous technical change component, which has a positive impact on TFP growth in all subperiods. The exogenous technical change effect is the major determinant of the substantial growth of TFP between 1981 and 1995. Using data from the same pot-plant firms over a longer period (1975–1995), Oude Lansink (2000) found a smaller (< 1 per cent) contribution of exogenous technical change to TFP growth, but it was more stable over time. The difference may be explained by the fact that the approach used by Oude Lansink (2000) allows for a much smaller degree of flexibility in the parameters of the production frontier, both over time and across firms. The production frontier used in this paper is fully firm-specific, whereas flexibility over time is due to the fact that firms rotate in and out the sample. The important contribution of the exogenous technical change to TFP growth indicates that the progress of general science and technology has made a significant contribution during these time periods.

Observation of the sample data reveals that pot-plant firms made (and are still making) substantial investments in computerised systems during the late 1980s and beginning of the 1990s, and obtained significant savings on pesticide use by applying substrate cultivation. Also, the presence of study groups acting as a mechanism for exchanging information between firms has become increasingly important over time. The price-induced technical change effect is positive in the first and second periods and negative thereafter. The time pattern of the induced technical change effect on TFP growth seems consistent with the theory, as it may be expected that this effect is larger in the periods after the first (1974) and second (1980) world oil crises that caused substantial energy price increases. Finally, the scale effect is approximately zero in all subperiods. Inspection of the production elasticities indicates that firms operate well above the constant returns to scale region when

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[10] The observation of a wide range of TFP growth rates is not unusual when using firm level data. Bartelsman and Dhrymes (1998) find that aggregate studies of productivity mask the pattern of productivity adjustment undertaken by individual firms. Their study of individual plant data finds great heterogeneity in productivity share dynamics. In fact, they find that the reallocation of resources over time from less to more productive plants resulted in an aggregate productivity improvement of approximately 25 per cent.

Table 4. Percentage of firms with positive overall bias in price-induced technical change

	Energy	Materials	Services	Structures	Machinery and installations	Labour
1979–1980	0.221	0.283	0.177	0.593	0.221	0.451
1981–1985	0.567	0.370	0.283	0.598	0.287	0.319
1986–1990	0.559	0.539	0.392	0.555	0.331	0.351
1991–1995	0.414	0.586	0.414	0.590	0.364	0.397

both variable and fixed factors of production are taken into account.[11] The small contribution of the scale effect to TFP growth is due to small growth rates of inputs. The results from the decomposition suggest that future growth of TFP should mainly originate from exogenous technical change or from growth of input use. Firms already have a large intra-firm efficiency, thereby reducing the role of intra-firm efficiency in improving future TFP. The role of price-induced technical change in TFP growth is modest, but the results suggest that energy price increases (e.g. as a result of liberalisation of the gas market) may increase TFP in the long run.

Input bias arising from price-induced innovation and exogenous technical change are generated by calculating (15) and (17), respectively, for each input and for each firm at each time period.[12] The percentage of firms with a positive overall input bias arising from price-induced innovation is presented in Table 4. The increase and fall in the percentage of firms with an energy-using bias in the period 1979–1995 indicates that the firm's adjustments to energy price increases are not instantaneous. These results are consistent with actual developments in the Dutch glasshouse industry. Faced with substantial energy price increases after the first and second oil crises, firms in the Dutch glasshouse industry substituted mineral gas for oil and adopted energy-saving technologies such as insulation, thermal screens and forced heat circulation. For materials, the percentage of firms with positive overall bias from price-induced innovation increases over time from 28.3 to 58.6 per cent. Less than 50 per cent of the firms in the sample have a positive overall bias arising from price-induced innovation for services, machinery and installations, and labour, whereas >50 per cent of the firms show a structures-using bias in all time periods. These results indicate that, in general, energy price increases induce firms to adopt services-saving technologies, machinery and installations-saving technologies, labour-saving technologies and structures-using technologies. Furthermore, firms tend to adopt materials-using technologies in response to energy price increases.

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[11] The scale effect term takes all inputs (variable and fixed) into account through the TFP growth decomposition.

[12] Input bias measures generated for each input and each firm at each time period are not reported, because of space restrictions. The results are available from the authors upon request.

Table 5. Percentage of firms with positive overall bias in exogenous technical change

	Energy	Materials	Services	Structures	Machinery and installations	Labour
1979–1980	0.743	0.558	0.487	0.513	0.336	0.372
1981–1985	0.531	0.626	0.657	0.610	0.417	0.535
1986–1990	0.539	0.616	0.616	0.637	0.437	0.527
1991–1995	0.736	0.749	0.690	0.632	0.515	0.464

The results for the overall input bias arising from exogenous technical change are presented in Table 5. In general, the majority of the firms have an energy-, materials-, services- and structures-using bias, whereas most firms have a machinery- and installations-saving bias. Furthermore, exogenous technical change leads pot-plant firms to adopt technologies that reduce the use of machinery and installations relative to energy, materials, services and structures. In addition, the results indicate that firms tend to adopt gradually labour-saving technologies. The tendency towards adopting labour-saving technologies may be explained by the steadily rising wages in the Netherlands during most of the observation period and the general problem that glasshouse firms face in acquiring qualified and motivated personnel.

Table 6 presents the percentage of firms with an overall input bias arising from exogenous technical change larger than the bias arising from price-induced innovation. The bias attributed to exogenous technical change in (17) represents an annual rate. In comparing this rate with the price-induced bias to technical change in (15), the actual annual past (normalised) price change has been used to generate a rate of change of the price-induced bias. The price-induced bias dominates the exogenous bias if the absolute value of the rate of change of the price-induced bias is larger than the absolute value of the rate of change of the exogenous bias and vice versa. Table 6 shows that, depending on the input, between 82.9 and 99.6 per cent of the firms in the sample have an exogenous input bias larger than the

Table 6. Percentage of firms with exogenous input bias larger than induced input bias

	Energy	Materials	Services	Structures	Machinery and installations	Labour
1979–1980	0.982	0.965	0.973	0.973	0.982	0.973
1981–1985	0.890	0.921	0.921	0.957	0.965	0.933
1986–1990	0.869	0.829	0.865	0.927	0.943	0.922
1991–1995	0.979	0.962	0.992	0.996	0.987	0.987

Table 7. Percentage of firms with positive overall (induced and exogenous) input bias

	Energy	Materials	Services	Structures	Machinery and installations	Labour
1979–1980	0.699	0.496	0.442	0.531	0.301	0.354
1981–1985	0.555	0.598	0.610	0.583	0.425	0.504
1986–1990	0.486	0.563	0.604	0.629	0.412	0.518
1991–1995	0.686	0.669	0.632	0.586	0.494	0.452

induced bias in all time periods, suggesting that the exogenous bias dominates the induced bias.[13]

Table 7 presents the percentage of firms with positive input bias attributed to both induced and exogenous sources. The technological change presents a machinery- and installations-saving bias that is declining over time as nearly 50 per cent of the firms exhibit a positive overall bias for this factor during the 1991–1995 period. After 1979–1980, there is a clear pattern of technological change being materials-using, services-using and structures-using for all time periods. The input bias of the technological change concerning labour is less obvious. Approximately one-half of the firms exhibit a labour-using bias between 1981 and 1990, with over one-half of the firms presenting a pattern of labour-saving bias in the 1991–1995 period. The input bias of technological change concerning energy fluctuates from being biased toward energy use over the periods 1979–1985 and 1991–1995, with the 1986–1990 period indicating that slightly less than one-half of the firms exhibit an energy-using bias.

7. Conclusions

A theoretical model is proposed to generate time- and firm-specific efficiency measures within the price-induced technological change framework. The firm-specific production frontier incorporates energy past prices as a factor inducing innovation and a time trend to account for exogenous technical change. This approach is also used to decompose TFP growth into scale, efficiency change and technological change effects, and to investigate input bias arising from exogenous technical change and price-induced innovation.

Estimation of firm-specific production frontiers and time- and firm-specific efficiency parameters involves a large number of parameters leading to an under-identification problem. The maximum entropy formalism presents a powerful tool to address this type of ill-posed problem and is used to estimate firm-specific production frontiers and time- and firm-specific efficiency measures.

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[13] The price-induced effects are found to be negligible in the decomposition of TFP growth and in the input bias results. As the model maintains price-induced innovation and the empirical results appear to demonstrate that there are no price-induced effects, there is no need to omit the price variable.

The empirical focus of this paper is on specialised Dutch pot-plant firms in the 1979–1995 period. These firms were induced to adopt energy-saving technologies as a result of substantial energy price increases after the two oil crises. The efficiency results indicate that small firms are more able to realise their production potential than medium and large firms.

Average TFP growth rates in 1979–1995 range from −1.9 per cent per annum in 1979–1980 to 4.2 per cent per annum in 1981–1985. The major contribution to TFP growth is the exogenous technical change effect, followed by the intra-firm efficiency effect. The other two effects (price-induced technical change effect and the scale effect) on the TFP growth are negligible, in general.

The impacts of the past energy price and exogenous technical change on the direction of technological change are evaluated by generating overall input bias measures. The empirical results indicate that energy price increases induce firms to adopt energy-, services-, machinery and installations-, and labour-saving technologies, and materials- and structures-using technologies. On the other hand, exogenous technical change leads pot-plant firms to adopt technologies that reduce the use of machinery and installations, and labour, relative to energy, materials, services and structures. Furthermore, the empirical results indicate that the exogenous bias generally dominates the price-induced bias.

This paper has demonstrated that generalised maximum entropy estimation is a valuable tool in analysing TFP growth using panel data of firms, as it allows for estimating firm-specific production frontiers and imposing theoretical conditions of regularity. However, this study only included the past price of a single input, i.e. energy in the production function, whereas the theory of price-induced innovation suggests that all (relative) factor prices may play a role in technological change. Therefore, future research should focus on the effects of other input prices.

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Appendix A: Description of data and production elasticities

Table A1. Description of data

Variable	Dimension	Symbol	Period: 1979–1995 Observations: 904	
			Mean	SD
Price indexes				
Energy	base year 1985	c_1	0.739	0.206
Materials	base year 1985	c_2	1.142	0.150
Services	base year 1985	c_3	1.072	0.051
Past price energy	base year 1985	$\bar{w}$	0.704	0.162
Quantities				
Output	100,000 guilders	Y	12.728	11.759
Energy	100,000 guilders	X_1	2.246	2.076
Materials	100,000 guilders	X_2	2.949	3.300
Services	100,000 guilders	X_3	1.125	1.150
Structures	100,000 guilders	X_4	7.213	7.508
Machinery and installations	100,000 guilders	X_5	3.749	4.329
Labour	100,000 guilders	X_6	3.909	2.804
Trend	first year in sample = 1	X_7	3.335	1.901

Table A2. Average production elasticities (standard errors in parentheses)

Input	All firms	Small firms	Medium firms	Large firms
Energy	0.140	0.162	0.142	0.119
	(0.061)	(0.083)	(0.056)	(0.043)
Materials	0.255	0.242	0.254	0.270
	(0.123)	(0.128)	(0.122)	(0.122)
Services	0.093	0.105	0.090	0.093
	(0.040)	(0.053)	(0.039)	(0.029)
Structures	0.377	0.318	0.389	0.388
	(0.362)	(0.352)	(0.386)	(0.284)
Machinery and installations	0.280	0.130	0.298	0.349
	(0.251)	(0.191)	(0.253)	(0.239)
Labour	0.385	0.464	0.372	0.360
	(0.323)	(0.532)	(0.260)	(0.253)
Trend	0.033	0.019	0.033	0.044
	(0.108)	(0.161)	(0.094)	(0.093)
Past price of energy	0.094	0.092	0.109	0.053
	(0.253)	(0.548)	(0.131)	(0.097)

Corresponding author: Elvira Silva, Faculty of Economics of Porto, University of Porto, Rua Dr. Roberto Frias, 4200 Porto, Portugal. E-mail: esilva@fep.up.pt