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Dynamic Decomposition of Total Factor Productivity Change in the EU Food, Beverages, and Tobacco Industry: The Effect of R&D

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Abstract. The main objective of this paper is to generate measures of TFP change for the food, beverages, and tobacco industry in the EU. Explicitly taking into account the fact that some of the inputs used in the industry are fixed in the short run, the generated measures of TFP change reflects the dynamic nature of the problem. The second objective is to analyse TFP change into its components and explicitly examine the effect of Research and Development (R&D) effort on TFP growth. Data are collected from EU KLEMS and the OECD Structural Analysis database. The data contain country-level information on output volume, input prices and capital stock, as well as R&D expenditure for the food, beverages, and tobacco industry for the 15 "old" EU Member States. They cover the 1970-2005 but most series contain gaps. The results show that for the period under consideration TFP in the industry grew on average at an annual rate of almost 2%. TFP growth was much faster in the 1970s and 1980s, with a considerable slowdown in the 1990s. This growth is driven primarily by growth in output and secondly by the reduction in labour input. Expenditure on R&D has a positive but relatively small effect on TFP.

Keywords: TFP change, Food Industry, R&D.

1. Introduction

A global, market-driven economy imposes greater competitive pressure on firm decision makers as they balance the trade-off between exploiting the full productive potential of their systems and technologies, and adopting innovations. Both avenues can lead to enhanced profitability. Sustaining competitiveness over the long run involves attention to growth prospects in both levels; innovations are needed to keep pushing the competitive envelope, and efficiency gains are needed to ensure that implemented technologies can succeed. The ability of an industry to be competitive supports the growth potential of firms.

A definition of competitiveness at the industry level focuses on the growth in returns to factors employed. While many factors influence competitiveness at the industry level, a high rate of Total Factor Productivity (TFP) growth is an indicator that the industry will be able to generate rents and therefore attract production factors in order to continue its operations.

The main objective of this paper is to generate measures of TFP change for the food, beverages, and tobacco industry in the EU. Explicitly taking into account the fact that some of the inputs used in the industry are fixed in the short run, the generated measures of TFP change reflect the dynamic nature of the of the problem. A second objective is to analyze TFP change into its components and specifically examine the effect of Research and Development (R&D) effort on TFP growth.

Policy makers in the EU and its Member States are paying increasing attention to structural change feeling that that this is happening so slowly as not to cause a serious threat in the foreseeable future. Baily and Gersbach[1] generate fairly highly productivity growth rates, but Traill[2] claims that these rates will be difficult to sustain in the long run in an open economy. Governments' role could be to help firms adapt to best international practice in the utilization of technology and in management.

Studies investigating the productivity change in the aggregate in US food processing sector report some negative productivity growth during some years. For example, negative productivity growth in the aggregate food sector is reported by Heien[3] during the ten of the years between 1958 and 1977, by Chan-

Kang, Buccola, and Kerkvliet[4] during five of the years between 1963 and 1992, and by Morrison[5] during seven of the years between 1966 and 1991. Analysis of the average TFP growth without ranking the plants finds negative productivity growth in the food industry during the six out of the twenty-three years between 1973 and 1995. The average productivity growth in the food industry of 0.9 percent is slightly higher than the estimate of 0.82 percent average productivity growth rate in the U.S. processes food sector between 1963 and 1992 by Chan-Kang, Buccola, and Kerkvliet[4], and 0.78 percent growth between 1065 and 1991 by Morrison[5]. Celikkol, Stefanou and Pompelli[6] report TFP decomposition results which show that the scale effect offers a more significant contribution to the TFP growth than the technical change for the plants that are in the lowest and the highest TFP quartile groups in all food industry. Scale effect dominance over the technical change effect indicates that plants in the industry extract scale efficiencies over technical gains.

Upon reviewing the empirical research on economic growth in contrast to the stylized facts of growth modeling, Easterly and Levine[7] find that the facts do not support models with diminishing returns, constant returns to scale, some fixed factor of production, or an emphasis on factor accumulation. However, empirical work does not yet decisively distinguish among the different theoretical conceptions of TFP growth. They recommend that economists should devote more effort toward modeling and quantifying TFP.

Once capital and its sluggish adjustment are taken explicitly into account, the decomposition of TFP growth takes on additional components. Luh and Stefanou[8] define these decompositions that account for both static and disequilibrium effects, find in the capital adjustment is a significant aspect to overall productivity measurement. These dynamic contributions to growth are important to identify as they have different policy implications. Investment and R&D policy at national levels are frequent instruments used by policy makers to encourage industrial development.

The remainder of this paper is organized as follows. The next section presents a theoretical model of dynamic behavior from an intertemporal cost-minimization perspective. This section also contains the decomposition of TFP growth into various components using the theoretical model. The econometric technique used for the estimation is described in section 3, and an application to the EU food, beverages, and tobacco industry follows in section 4. Finally, section 5 provides some concluding comments.

2. Dynamic decomposition of TFP

We start by assuming that the objective of the Decision Making Unit is to minimize the discounted sum of future production costs over an infinite horizon, subject to the equation of motion for the quasi–fixed factors, pre–specified production targets, and the production technology. We assume that the decisions makers form static expectations on the set of real prices and the sequence of production targets**1**. More precisely, the decision maker solves the problem:

$$\begin{aligned} J(w,c,K,y,\Omega) &= \min_{x,I>0} \int_t^{\infty} e^{-rs}\left[w'x(s)+cK(s)\right]ds \\ \text{subject to:}\quad \dot{K}(s) &= I(s)-\delta K(s), \quad K(0)=K_0>0, \quad K(s)>0 \\ y(s) &= F\left[x(s),K(s),\dot{K}(s),\Omega(s)\right], \quad \text{for all} \quad s\in[t,\infty) \end{aligned} \tag{1}$$

1 Price expectations are static in the sense that *relative* prices observed in each base period are assumed to persist indefinitely (Epstein and Denny[9]). As the base period changes, expectations are altered and previously decisions are no longer optimal. Only that part of the decision corresponding to each base period is actually implemented. As such, this model formulation reflects the behavioural assumption that Decision Making Units revise price expectations without anticipating revision. In commodity production (historically), input prices tend to move in a less volatile manner than output prices. With this study focusing on the cost minimization framework, output prices are not an issue and the relative importance of relative input price movements is downgraded.

where w is vector of variable input prices; x and K are vectors of variable inputs and quasi-fixed inputs, respectively; c is the vector of rental prices of quasi-fixed inputs; I and $\dot{K}$ are gross and net rates of investment, respectively; r is the constant discount rate; δ is a constant depreciation rate; $y(s)$ is a sequence of production targets over the planning horizon starting at time t; $\Omega(s)$ represents arguments that influence technological progress; and, $F(x(s), K(s), \dot{K}(s), \Omega(s))$ is the single output production function satisfying the regularity conditions. The inclusion of net investment $\dot{K}$ in the production function reflects the internal cost associated with adjusting quasi-fixed factors in terms of foregone output. The production function, $F(x(s), K(s), \dot{K}(s), \Omega(s))$, possesses the following properties:

1. it is continuous and twice-continuously differentiable,
2. it is finite, nonnegative, real valued and single valued for all nonnegative and finite x, K, $\dot{K}$ and Ω,
3. it is strictly increasing and concave in x, K and Ω, and
4. it is strictly decreasing (increasing) in $\dot{K}$ when $\dot{K}$ is positive (negative) and strictly concave in $\dot{K}$.

Let the technological progress function, Ω, be determined by research and development, $RD(s)$, and the passage of time to reflect autonomous technical change, s; $\Omega(s) = (RD(s), s)$.

The intertemporal cost minimization problem in (1) implies the following Hamilton-Jacobi equation:

$$rJ(w, c, K, y, \Omega) = \min_{x, I>0} \{w'x + cK + (I - \delta K)J_k + \gamma(y - F(x, K, \dot{K}, RD, t))\} + J_t \tag{2}$$

The Hamilton-Jacobi equation links the current decisions to future possibilities. In this equation, rJ is the flow version of the long run, intertemporal cost function. It is composed of the instantaneous variable cost, the service cost of capital, instantaneous capital gain (or loss), and the shift in cost associated with the autonomous technical progress. $\gamma \geq 0$ is the Lagrange multiplier associated with the production target and is defined as the short-run, instantaneous marginal cost.

Based on the optimized version of the Hamilton-Jacobi equation, we can analyze TFP change into various components. The first order conditions for the minimization problem in (2) are:

$$F_x = \frac{w}{\gamma} \quad and \quad J_k = \gamma F_{\dot{K}} \tag{3}$$

Additionally, differentiation of (2) with respect to capital stock and R&D yields:

$$F_K = \frac{c - (r + \delta)J_k + \dot{J}_k}{\gamma} \quad and \quad F_{RD} = \frac{-rJ_{RD} + \dot{J}_{RD}}{\gamma} \tag{4}$$

where:

$$\dot{J}_K = \frac{dJ_K}{dt} = J_{KK}\dot{K} + J_{tK} \quad and \quad \dot{J}_{RD} = \frac{dJ_{RD}}{dt} = J_{K,RD}\dot{K} + J_{t,RD} \tag{5}$$

Next, by totally differentiating the production function, $y = F(x(s), K(s), \dot{K}(s), \Omega(s))$, with respect to time, using (3) and (4), and rearranging, we obtain:

$$\hat{y}\ \left(\equiv \frac{\dot{y}}{y}\right) = \varepsilon\left[\hat{g}_x + \hat{g}_{SS} + \hat{g}_{J_K} + \hat{g}_{\dot{K}} + \hat{g}_{RD}\right] + \hat{A} \tag{6}$$

where ε are the long-run returns to scale under dynamic adjustment and the $\hat{g}$ s are the different components of the TFP (Stefanou[10], and Luh and Stefanou[8]). Their mathematical expressions and interpretation are given in Table 1. The details of the derivation of (6) are given in Appendix A.

Defining total factor productivity growth as the difference between output growth and input growth (variable input growth plus investment growth) – noting that capital, in the current period, is not a choice variable for the decision maker – we obtain:

$$\begin{aligned} T\hat{F}P &= \hat{y} - \hat{g}_x + \hat{g}_{\dot{K}} \\ &= \varepsilon\left[\hat{g}_{SS} + \hat{g}_{J_K} + \hat{g}_{RD}\right] + (\varepsilon - 1)\left[\hat{g}_x + \hat{g}_{\dot{K}}\right] + \hat{A} \end{aligned} \tag{6}$$

The last equation decomposes TFP change into five components:

- Steady state capital growth $\varepsilon\left[\hat{g}_{SS}\right]$
- Changes in the shadow cost of capital stock $\varepsilon\left[\hat{g}_{J_K}\right]$
- R&D $\varepsilon\left[\hat{g}_{RD}\right]$
- Scale $(\varepsilon - 1)\left[\hat{g}_x + \hat{g}_{\dot{K}}\right]$
- Exogenous technical change $\hat{A}$

The effect of autonomous technological progress, however, can only be obtained residually:

$$\hat{A} = \hat{y} - \varepsilon\left[\hat{g}_x + \hat{g}_{\dot{K}} + g_{SS} + \hat{g}_{J_K} + \hat{g}_{RD}\right] \tag{7}$$

Table 1: Definition of the components of dynamic productivity decomposition

Symbol	Expression	Description
	Impact of scale effect	
$(\varepsilon - 1)\left(\hat{g}_x + \hat{g}_{\dot{K}}\right)$	$(\varepsilon - 1)\left[\sum_i \frac{w_i \dot{x}_i}{rJ}\hat{x}_i + \frac{J_K \dot{K}}{rJ}\hat{\dot{K}}\right]$	- The proportional growth of the variable inputs and net physical investment demand
	Impact of changing shadow costs of the capital	
$\varepsilon \cdot \hat{g}_{J_K}$	$\varepsilon \cdot \frac{\left[J_{KK}\dot{K} + J_{tK}\right]K}{rJ}\dot{K}$	- The proportional changes in the endogenously determined marginal values of quasi-fixed factor stocks
	Impact of changing steady state capital stock	
$\varepsilon \cdot \hat{g}_{SS}$	$\varepsilon \cdot \frac{\left[c - (r+\delta)J_K\right]K}{rJ}\hat{K}$	- The proportional growth in quasi-fixed factor levels at the long-run equilibrium
	Impact of technological progress	
$\varepsilon \cdot \hat{g}_{RD}$	$\varepsilon \cdot \left[\frac{-rJ_{RD}RD}{rJ}R\hat{D} + \frac{J_{RD}RD}{rJ}\hat{J}_{RD}\right]$	- Technological progress arising from R&D effort
$\hat{A}$	$\frac{1}{y}\frac{dF}{dt}$	- Technological progress arising from autonomous sources

3. Econometric estimation

The dynamic dual approach involves specifying the functional form of J in terms of its arguments. With a single quasi-fixed input of capital stock, the value function taking the quadratic functional form and assuming symmetry of the parameters where $\alpha^{ij} = \alpha^{ji}$ can be specified as:

$$J = \alpha^0 + P' \cdot \begin{pmatrix} \alpha^w \\ \alpha^c \\ \alpha^K \\ \alpha^y \\ \alpha^{RD} \\ \alpha^t \end{pmatrix} + \frac{1}{2} P' \cdot \begin{bmatrix} a^{ww} & a^{wc} & a^{wK} & \alpha^{wy} & \alpha^{wRD} & \alpha^{wt} \\ & a^{cc} & a^{cK} & \alpha^{cy} & \alpha^{cRD} & \alpha^{ct} \\ & & a^{KK} & \alpha^{Ky} & \alpha^{KRD} & \alpha^{Kt} \\ & (symmetric) & & \alpha^{yy} & \alpha^{yRD} & \alpha^{yt} \\ & & & & \alpha^{RDRD} & \alpha^{RDt} \\ & & & & & \alpha^{tt} \end{bmatrix} \cdot P \tag{8}$$

where $P' = (w' \quad c' \quad K' \quad y \quad RD \quad t)$.

By the intertemporal version of Shephard's lemma, we can generate factor demands by differentiating the optimized Hamilton-Jacobi equation,

$$rJ(w,c,K,y,RD,t) = \{w'x^* + cK + (I^* - \delta K)J_k\} + J_t \tag{9}$$

with respect to c to yield net investment demand:

$$rJ_c = c + J_{kc}\dot{K}^* + J_{tc} \tag{10}$$

and with respect to w to yield variable factor demand:

$$rJ_w = x^* + J_{Kw}\dot{K}^* + J_{tw} \tag{11}$$

After rearranging, we obtain the system:

$$\begin{aligned} w'x + cK &= rJ - \dot{K}J_K - J_t \\ \dot{K}^* &= J_{Kc}{}^{-1}\left[rJ_c - c - J_{tc}\right] \\ x^* &= rJ_w - J_{Kw}\dot{K} - J_{tw} \end{aligned} \tag{12}$$

All coefficient parameters for the system of equations implied by the dynamic model can be estimated after appending a linear disturbance vector with mean vector zero and variance-covariance matrix Σ. Joint estimation of the system provides parameter estimates of the behavioral value function represented by equation (8). Further, the net investment equation does conform to the linear accelerator, $\dot{K} = M\left(K - K^*\right)$, where K^* is the long-run equilibrium capital stock which depends on *(w, c, K, y, RD, t)* and $M = r - \left(\alpha^{cK}\right)^{-1}$ is the adjustment rate towards the long–run equilibrium. The maintained model is recursive in the endogenous variable of net investment demand, serving as an explanatory variable in the variable input demand equations.

4. Application

4.1. Data and Estimation

The model developed above is applied to a panel of industry–level data from the 15 "old" Member States of EU. The empirical analysis is applied at the ISIC 2 digit level for the category of manufacturing of food products, beverages, and tobacco. However, for most countries that are studied the proportion of manufacturing of tobacco to the entire sector is very small.

The data for the application come primarily from EU KLEMS[11], while some missing series are taken from the OECD Structural Analysis database. EU KLEMS provides harmonized series for most EU countries that go back to 1970. It collects data which are provided by national statistical agencies in each Member State. For some countries the variable on capital stock is not available. In these cases and whenever comparable data were available from OECD, the amount of capital was constructed using the Perpetual Inventory Model. Data on private R&D expenditure come from the OECD databases, but, also at this level of aggregation, the series has missing observations.

In the specification of the value function in (8) the value added, measured in constant 1995 prices is used instead of y. Since the value of materials is already subtracted from the value of output, the only remaining variable input is labor. The price of labor for every year and country is derived by dividing of (deflated) total labor compensation by the total number of hours worked in the industry. Similarly, the price of capital is derived by dividing capital compensation by the amount of capital stock. Business enterprise expenditures in the industry are used as a gross measure of R&D effort. Summary statistics for the major variables are presented in Table 2.

Table 2: Summary statistics for the variables of the model.

Variable	Obs	Mean	Std. Dev.	Min	Max
y -- value added (millions of Euros)	540	9286.3	10453.6	128.9	40377.6
L -- labor (millions of hours worked)	540	482.9	500.8	5.4	2319.4
w -- wages (Euros per hour worked)	540	11.0	5.6	1.4	26.3
K -- capital stock (millions of Euros)	438	17721.8	16919.2	254.5	64128.5
c -- rental price of capital (%)	438	17.4	5.5	5.1	33.3
R&D -- expenditure (millions of Euros)	310	108.7	110.7	6.8	488.2

The system of equations in (12) is estimated using nonlinear Seemingly Unrelated Regressions (SUR). The interest rate, r, was set equal to 5%. Because the dataset is incomplete regarding R&D expenditure, two models are estimated: one ignoring the effect of R&D and one accounting for it.

4.2. Results

The parameter estimates for the models with and without R&D expenditures are presented in Appendix B[2]. Most parameter estimates are significant at the critical 5% level. Using these estimates we can measure and decompose TFP change rates.

The different components of TFP growth from the model that does not account for the effect of R&D for different periods covered by the data are presented in Table 3[3]. On average TFP grew at rate of 2.11%.

[2] Prior to estimation the data were normalized so that some problems of numerical stability are avoided.
[3] The numbers presented in this table are weighted averages of the different components of TFP growth rates for each country, with the deflated values of output used as weights.

The TFP growth is driven primarily by growth in output and secondly by the reduction in labor input. TFP growth was much faster in the 1970s and 1980s, with a considerable slowdown in the 1990s.

As mentioned above, the net investment equation in the model conforms to the linear accelerator model. The estimate of the accelerator parameter, M, for the model is 0.13, indicating that, on average, firms adjust towards the long-run equilibrium at a rate of 13%. Finally, the industry operates at the decreasing returns to scale part of the technology, with the long-run scale elasticity estimated at 0.94.

Table 3: TFP growth decomposition without accounting for R&D (%).

	$\hat{y}$	$\hat{g}_x$	$\hat{g}_{\dot{K}}$	$T\hat{F}P$	$\varepsilon \cdot \hat{g}_{ss}$	$\varepsilon \cdot \hat{g}_{J_K}$	scale	$\hat{A}$
1971-1975	2.01	-0.72	-0.68	3.41	2.21	-1.50	0.12	2.57
1976-1980	1.72	-1.05	-0.17	2.93	1.30	-1.13	0.12	2.64
1981-1985	0.90	-1.44	0.13	2.21	1.19	-0.63	0.04	1.62
1986-1990	2.30	-0.22	-0.49	3.00	1.84	-0.98	-0.02	2.15
1991-1995	1.35	-0.67	-0.01	2.04	1.54	-1.25	0.00	1.75
1996-2000	0.16	-0.21	-0.18	0.55	1.38	-1.11	0.06	0.22
2001-2005	0.30	-0.88	0.35	0.83	1.71	-0.88	0.12	-0.12
1971-1980	2.17	-0.64	-0.12	2.94	1.64	-1.28	0.08	2.50
1981-1990	1.59	-0.89	-0.20	2.68	1.53	-0.82	0.01	1.96
1991-2000	0.95	-0.41	-0.05	1.41	1.50	-1.22	0.05	1.08
2001-2005	0.30	-0.88	0.35	0.83	1.71	-0.88	0.12	-0.12
1971-2005	1.27	-0.70	-0.13	2.11	1.56	-1.05	0.02	1.58

Next, R&D is included in the specification. To capture the effect of R&D that possibly spreads over several periods, the following specification of the RD variable is used:

$$RD_t = 0.1 \cdot (\mathrm{R\ \&\ D})_{t-1} + 0.4 \cdot (\mathrm{R\ \&\ D})_{t-2} + 0.4 \cdot (\mathrm{R\ \&\ D})_{t-3} + 0.1 \cdot (\mathrm{R\ \&\ D})_{t-4} \qquad (11)$$

where $(\mathrm{R\ \&\ D})_t$ is R&D expenditure in the food manufacturing industry in year t[4]. The parameter estimates are presented in Appendix B. The different components of TFP growth for different periods covered by the data are presented in Table 4.

TFP grew on average at rate of 1.82%, but, TFP growth rates appear now to be larger in the 1970's and 1980's with a faster slowdown later. The linear accelerator parameter M is estimated at 14%. The scale elasticity estimate is 1.12.

As expected, the inclusion of R&D in the specification captures some of the effect of the autonomous technological progress. Differences between the numbers reported in Tables 3 and 4, however, could also be attributed in part to the different set of observations used for the estimation of the two models. This is due to the missing R&D series for some countries, as well as the observations that are lost due to use of lagged values during the creation of the RD variable.

[4] The rationale behind using such a specification for R&D is that the outcome of R&D has a very small impact on production the period expenditures on R&D are realized. Its effect becomes progressively more important as innovations are integrated in the production process and fades out as these innovations become obsolete. Different specifications were used, but the results obtained are very similar to the ones reported here.

Table 4: TFP growth decomposition accounting for R&D (%).

	$\hat{y}$	$\hat{g}_x$	$\hat{g}_{\dot{K}}$	$T\hat{F}P$	$\varepsilon \cdot \hat{g}_{ss}$	$\varepsilon \cdot \hat{g}_{J_K}$	$\varepsilon \cdot \hat{g}_{RD}$	scale	$\hat{A}$
1971-1975	-	-	-	-	-	-	-	-	-
1976-1980	2.10	-0.61	-0.53	3.24	1.13	-0.79	0.00	0.23	2.66
1981-1985	1.00	-1.38	0.13	2.26	0.89	-0.43	0.00	0.10	1.70
1986-1990	2.31	-0.16	-0.04	2.51	1.19	-0.60	0.27	-0.04	1.69
1991-1995	1.42	-0.46	-0.03	1.91	0.86	-0.65	0.49	-0.02	1.22
1996-2000	0.31	-0.10	-0.43	0.84	0.82	-0.55	0.29	-0.02	0.30
2001-2005	0.29	-0.77	0.31	0.75	0.77	-0.39	0.67	0.12	-0.43
1971-1980	2.10	-0.61	-0.53	3.24	1.13	-0.79	0.00	0.23	2.66
1981-1990	1.65	-0.83	0.00	2.49	1.05	-0.53	0.15	0.04	1.77
1991-2000	0.96	-0.26	-0.26	1.48	0.85	-0.60	0.37	-0.01	0.87
2001-2005	0.29	-0.77	0.31	0.75	0.77	-0.39	0.67	0.12	-0.43
1971-2005	1.07	-0.62	-0.13	1.82	0.92	-0.54	0.32	0.07	1.06

Both models suggest that the major driving force of TFP growth in the EU food, beverages, and tobacco industry is the growth in value added. The slowdown in value added growth in the late 1990s and early 2000s drove TFP growth down. As Europe appears to be reaching a level of saturation in food products, further growth in TFP is expected to occur only by reduction in input use.

The component related to $\hat{g}_{J_k}$ reflects the internal valuation effect. As the capital stock increases, the internal demand for capital reacts. Thus, this component reflects the demand effect which dampens TFP growth. Accounting for R&D, this demand effect is lower. The component related to $\hat{g}_{ss}$ reflects the shifting in the steady state target, K*. This target shifts as prices are revised aand R&D evolves. In both scenarios this effect is TFP dampening. With R&D, the specification is absorbing some of the its contribution.

5. Concluding comments and further remarks

The growth literature focuses on technological progress as the engine of growth as measured by the TFP change in an industry is associated with technological progress. A high rate of TFP growth is an indicator that the industry will be able to generate rents and therefore attract production factors in order to continue its operations. Firms in the EU food, beverages, and tobacco industry are assumed to minimize the discounted flows of cost. For this dynamic problem Total Factor Productivity can be expressed as a function of the Hamilton-Jacobi equation. Furthermore TFP is decomposed into five components: (i)growth in quasi-fixed factor levels at the long-run equilibrium, (ii)changes in the shadow value of quasi-fixed factor stocks, (iii) technological progress arising from R&D effort, (iv)scale effect captured by changes in the for variable inputs and investment in quasi-fixed factors, and (v) autonomous technological progress.

This study finds that R&D has a positive effect on TFP growth. The dynamic components of TFP growth clearly are substantial, accounting for 25% and 21% in the models without and with R&D, respectively. In assessing technological progress, the explicit R&D effort accounts only for a small part. This suggests that there are spill–over effects from R&D that are not accounted for. It could be argued that the level of private R&D effort maybe optimal at the firm level. However, externalities exist which firms are not taking into consideration, this effort is suboptimal from the point of view of the society.

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Appendix A: Derivation of TFP growth under dynamic adjustment

Totally differentiating the production function with respect to time yields:

$$\dot{y} = F_x{}'\dot{x} + F_K{}'\dot{K} + F_{\dot{K}}{}'\ddot{K} + F_{RD}\dot{RD} + F_t \tag{A.1}$$

Creating the percentage changes leads to:

$$\hat{y}\ \left(\equiv \frac{\dot{y}}{y}\right) = \sum_i \frac{F_{x_i}\dot{x}_i}{y}\hat{x}_i + \sum_j \frac{F_{K_j}K_j}{y}\hat{K}_j + \sum_j \frac{F_{\dot{K}_j}\dot{K}_j}{y}\hat{\dot{K}}_j + \frac{F_{RD}RD}{y}\hat{RD} + \hat{A} \tag{A.2}$$

where $\hat{A} = \frac{F_t}{y}$ is the rate of change in production associated with autonomous technical change.

We can substitute for the relations of F on the RHS in (A.2) by using the first order conditions in (3) to substitute into the 1st and 3rd components and the relations in (4) to substitute into the 2nd and 4th components, which leads to:

$$\begin{aligned}\hat{y} = &\sum_i \frac{w_i\dot{x}_i}{\gamma y}\hat{x}_i + \frac{[c-(r+\delta)J_K]K}{\gamma y}\hat{K} + \frac{J_K\dot{K}}{\gamma y}\hat{\dot{K}} \\ &+ \frac{[J_{KK}\dot{K} + J_{tK}]K}{\gamma y}\dot{K} + \frac{-rJ_{RD}RD}{\gamma y}\hat{RD} + \frac{J_{RD}RD}{\gamma y}\hat{J}_{RD} + \hat{A}\end{aligned} \tag{A.3}$$

The next step is to multiply and divide all the terms on the RHS of (A.3) – except for $\hat{A}$ – by total cost (in flow terms), rJ, and some rearrange to obtain:

$$\hat{y} = \frac{rJ}{\gamma y}\left[\begin{aligned}&\sum_i \frac{w_i\dot{x}_i}{rJ}\hat{x}_i + \frac{[c-(r+\delta)J_K]K}{rJ}\hat{K} + \frac{J_K\dot{K}}{rJ}\hat{\dot{K}} \\ &\qquad + \frac{[J_{KK}\dot{K} + J_{tK}]K}{rJ}\dot{K} + \frac{-rJ_{RD}RD}{rJ}\hat{RD} + \frac{J_{RD}RD}{rJ}\hat{J}_{RD}\end{aligned}\right] + \hat{A} \tag{A.4}$$

An important feature to note is the interpretation of $rJ/\gamma y$, which is better viewed as long-run average cost, rJ/y , divided by short-run marginal cost. Stefanou[10] establishes that this is the appropriate measure for long-run returns to scale under dynamic adjustment.

To simplify notation, we write:

$$\hat{y} = \varepsilon\left[\hat{g}_x + \hat{g}_{SS} + \hat{g}_{J_K} + \hat{g}_{\dot{K}} + \hat{g}_{RD}\right] + \hat{A} \tag{A.5}$$

where the definitions of the $\hat{g}$ s are given in Table 1. TFP change is then defined as:

$$T\hat{F}P = \hat{y} - \hat{g}_x + \hat{g}_{\dot{K}} = \varepsilon\left[\hat{g}_{SS} + \hat{g}_{J_K} + \hat{g}_{RD}\right] + (\varepsilon - 1)\left[\hat{g}_x + \hat{g}_{\dot{K}}\right] + \hat{A} \tag{A.6}$$

Appendix B: Parameter Estimates of the Dynamic Objective Function

Table B.1: Parameter estimates of the objective function without accounting for R&D.

	Coef.	Std. Err.	P>z		Coef.	Std. Err.	P>z
α^0	-23378.98	2534.457	0.000	α^K	21.556	21.56	0.000
α^w	30.43	3.075	0.000	α^{wK}	0.012	0.01	0.000
α^c	1191.65	201.296	0.000	α^{cK}	0.556	0.56	0.000
α^y	3452.51	418.255	0.000	α^{KK}	0.052	0.05	0.000
α^{ww}	-0.01	0.002	0.001	α^{yK}	1.295	1.3	0.000
α^{wc}	-0.76	0.215	0.000	α^{tK}	0.703	0.7	0.000
α^{wy}	1.01	0.207	0.000	α^t	164.097	164.1	0.073
α^{cc}	3.91	7.639	0.609	α^{wt}	0.178	0.18	0.037
α^{cy}	312.45	14.683	0.000	α^{ct}	8.711	8.71	0.446
α^{yy}	-47.8	10.402	0.000	α^{yt}	10.901	10.9	0.001
				α^{tt}	7.405	7.41	0.262

Table B.2: Parameter estimates of the objective function accounting for R&D.

	Coef.	Std. Err.	P>z		Coef.	Std. Err.	P>z
α^0	-32606.49	9765.146	0.001	α^{RDRD}	0.35	0.201	0.084
α^w	36.33	22.034	0.099	α^K	87.30	40.266	0.030
α^c	1378.02	724.736	0.057	α^{wK}	0.28	0.041	0.000
α^y	5355.06	971.411	0.000	α^{cK}	-11.26	1.037	0.000
α^{RD}	75.13	68.849	0.275	α^{KK}	-0.31	0.059	0.000
α^{ww}	-0.04	0.020	0.029	α^{yK}	12.74	1.715	0.000
α^{wc}	0.29	0.972	0.766	α^{RDK}	-0.06	0.139	0.658
α^{wy}	10.03	1.104	0.000	α^{tK}	-4.11	0.992	0.000
α^{wRD}	-0.58	0.109	0.000	α^t	-12.34	524.617	0.981
α^{cc}	-16.77	20.598	0.416	α^{wt}	2.32	0.823	0.005
α^{cy}	255.05	35.199	0.000	α^{ct}	-102.10	20.880	0.000
α^{cRD}	5.17	3.843	0.178	α^{yt}	56.86	21.478	0.008
α^{yy}	-181.48	30.537	0.000	α^{RDt}	-3.47	2.324	0.136
α^{yRD}	-0.74	3.801	0.845	α^{tt}	25.90	17.342	0.135