Computerisation, productivity and skill structure: evidence for France using firm level data

Pierre Biscourp*, Bruno Crépon*, Thomas Heckel*, Nicolas Riedinger*

Preliminary version

Abstract

The continuous innovation process experienced by the information technology industries over the last decades, has caused the price of computer power to decrease dramatically. This has led many firms to invest massively in increasingly efficient computers. This paper is an attempt to assess the impact of this phenomenon (often termed “computerisation”) on both labour productivity and the relative demand for skill. Unlike most studies dealing with the technological bias issue, most of which rest on the estimation of factor demand equations, we evaluate the complementarities between computers, skilled and unskilled labour, by estimating both a production function and a relative labour demand equation. This allows us to study how the productivity of labour as well as the skill structure are affected in the short-run by an increase in the stock of computers and in the long-run by a decrease in their price. Using a panel of more than 5000 firms followed over the period 1994-1997, we find that the effects of computerisation have been significant on both labour productivity and the skill structure. The large magnitude of our estimates suggests that we also capture the impact of other unobserved factors closely correlated with computer investment.

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* INSEE timbre G231
15 Boulevard Gabriel PERI
BP100 92244 MALAKOFF CEDEX
nicolas.riedinger@insee.fr

Introduction

For several decades, firms have benefited from the continuous technical progress achieved by the producers of computers, as constant increases in the data processing power have been obtained together with drastic price reductions for a given quality level. This has led many firms to invest massively in increasingly efficient computers.
The improvement in the quality of computers has raised the issue of measuring their prices in a way allowing for sensible comparisons over time. For this purpose the so-called hedonic price method has been used in several countries to estimate quality-adjusted price indices (Griliches, 1971). Studies usisng these prices point to a strong decrease in the price of computer power, at an average annual rate of around -15% (see Oliner and Sichel (2000) for the United States and Crepon and Heckel (2000) for France). This evolution has been interpreted by some as paralleling the so-called "Moore's Law", which asserts that the data processing capacity of semi-conductors has doubled every four year for more than twenty years (Gordon, 2001). The decline in the price of computer power may therefore be viewed as driven exogenously by technical innovations. In this study we attempt to assess empirically the effects of this shock to the technological environment of firms, on the production processes they choose to implement and in particular on their demand for labour.

The availability of cheaper computer power has led to a wider diffusion of computers within firms, generating a possibly substantial impact on productivity. It has been argued that this mechanism has been the main force driving labour productivity up in the United States. Oliner & Sichel (2000) shows that under the set of assumptions of the classical growth accounting framework, labour productivity has increased on average by 2.6% per year in the United States during the second half of the 1990s, and that 1 percentage point of this average growth rate can be attributed to information technology capital deepening (including hardware, software and communication equipment). The picture however looks somewhat different for France. Applying a similar methodology to French data spanning the period 1987-1998, Crépon an Heckel (2000) find an average labour productivity growth rate of 1.7% and a contribution of the hardware diffusion to this growth rate of 0.3 percentage point. The use of individual data allows us to conduct further the inquiry, in relaxing and checking some of the assumptions needed to evaluate computer contribution at the macro-level. The first issue we tackle in this study is thus the relationship between price decline, computer use and labour productivity.

The accumulation of computers should also affect the relative use of the other inputs due to substitution effects. In particular, we ask how the combination between skilled and unskilled labour has changed as a result of the diffusion of computers. Complementarities with computers may indeed differ from one category of skill to the other. According to the skill-biased technical change story, the increasing use of computers should benefit the skilled workers at the expense of the unskilled, presumed more substituable with computers. Many empirical studies have looked into this issue, with a view to explaining the downward shift on the relative demand for unskilled labour that all developed countries have experienced during the last decades. There is indeed strong macro-economic evidence that, since at least the beginning of the 1980s, the gap between the relative demand for and the relative supply of skills has widened. This tendency has led to increasing inequalities in the United Sates and in continental Europe, following however quite different patterns. The United States have experienced a strong increase in the wage dispersion whereas in most European countries the most visible effect has been a rise in the unemployment of the unskilled (Krugman, 1994). In France, the relative remuneration of skilled and unskilled labour has remained stable while the employment structure has been twisted at the expense of the unskilled during the last two decades: skilled workers including business heads, senior executives and intermediate occupations, who made up 20% of the work force in 1976, represent 35% in 1998. Skill-biased technical change is one possible explanation for these labour markets outcomes.[1] Testing this hypothesis empirically is the second goal of this paper.

Our main contribution in the abundant literature available is to simultaneously consider both issues presented above, by assessing the impact of the decline in the price of computers on the skill mix of firms, using the production function directly as well as labour demand equations. The former approach brings additional information as it requires less stringent technological assumptions than the latter. Studies on the skill biased technical change typically rely on the estimation of factor demand equations. More precisely, they focus on the impact of a marginal

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[1] An alternative potential culprit pointed by economists is the impact of international trade, which would affect the specialization of countries. However, most studies (see e.g. Machin and Van Reenen (1998) for international evidence) have shown that most of the shift in relative labour demand has occurred within, rather than between, industries. That suggests that the international trade explanation is not the relevant one at least in its most simple accceptance.

increase in the stock of computers on the skill intensity of the firm. We provide a complementary point of view. Using the production function approach, we estimate the short run technological complementarities between computer capital on the one hand, categories of skill on the other hand. We then compare these results with those obtained by the labour demand approach. This allows us to investigate whether firms have adjusted their relative level of skills in accordance with the corresponding complementarities with computers.

The production function approach also leads us to address the question of the impact of computer accumulation on labour productivity. Paralleling the above strategy, we ask whether the actual behaviour of firms in terms of computer investment is consistent with their estimated technological characteristics. More precisely, we test whether firms adjust their stocks of computer stocks to a level matching their estimated returns to computers.

Finally, our structural approach allows us to assess the macro-economic implications of our results with regard to both issues.

Our main conclusion is that computerisation strongly affects labour productivity as well as the skill structure of firms. More precisely, we find evidence for high returns to computer capital which should have induced strong productivity gains in the short-run. At the macro-economic level, the accumulation of computer capital should be responsible for a labour productivity increase of about 1.3 percentage point per year. This contribution represents a much larger impact than the usual evaluations computed using the growth accounting framework (such as the one found in Crépon and Heckel (2000)). This is due to the fact that the elasticities of production to computer capital are found to be much higher than their cost shares. We discuss the meaning of these excess returns to computers. Moreover, our results suggest that the fall in the prices of computers should imply in the long-run large gains in labour productivity, yet to be observed.

Our findings also support the technological bias story. The accumulation of computers should explain a large part of the shift in the aggregate relative labour demand for skill in the past decade. However, firms seem not to have fully adjusted their levels of skills with regard to the complementarities and substitution effects with computers. Finally, our results also suggest that the fall in the prices of computers should imply in the long-run changes in the skill structure. However, the lack of precision of our estimates does not allow to provide an accurate figure on this issue.

This paper is organized as follows. In the first section, we define two sets of parameters of interest relevant to the two issues addressed. We derive explicit expessions for these parameters, given assumptions on the technology. We comment on the particular cases of the Cobb-Douglas and of the Translog production functions. We present the data in the second section. The third and last section is devoted to the results of our estimations and to the discussion of their significance.

Assessing the economic effects of computerisation

In this section we address two issues from a theoretical point of view:

- How does computerisation affect labour productivity ?
- How does computerisation affect the productive combination of inputs and in particular the relative demand for skill ?

For this purpose, we use a standard microeconomic framework where the accumulation of computer capital is viewed as the result of the price decrease experienced by information technologies. We define in this framework a set of parameters enabling us to capture these effects and test their significance. Both issues are investigated from two points of view corresponding respectively to the short-run and the long-run analysis:

- What is the effect of a marginal rise in the stock of computers ?
- What is the effect of a marginal fall in the price of computers ?

Every time the nature of complementarities between inputs is to be investigated, the usual Cobb-Douglas technology appears too restrictive, which leads us to retain the more flexible Translog specification. We give the expressions of all the parameters of interest using a set of technological assumptions based on the primal (i.e. from the technology of production), regardless of input prices. This allows us to investigate the optimality of the firms' behaviour given the observed equilibrium prices.

Impact of computerisation on labour productivity

Short-run effects

In order to assess the impact of computerisation on productivity, we consider a production function f involving three inputs, namely labour (l), computer capital (k_c) and an aggregate of other forms of capital (k_o). We denote respectively the quantities and the prices of inputs as x_l, x_{kc}, x_{ko} and p_l, p_{kc}, p_{ko}. Log-differentiating the production function enables us to grasp formally the relationship between the growth of the quantities of inputs and that of production :

$$d\ln(y) = e_l d\ln(x_l) + e_{kc} d\ln(x_{kc}) + e_{ko} d\ln(x_{ko}) \qquad [1]$$

where $e_i = x_i f_i / f$ denote by definition the elasticities of production to the quantities of inputs. Since we are interested in labour productivity, we re-write the previous equation in the following way:

$$d\ln\left(y/x_l\right) = e_{kc} d\ln\left(x_{kc}/x_l\right) + e_{ko} d\ln\left(x_{ko}/x_l\right) + (q-1) d\ln\left(x_l\right) \qquad [2]$$

We use this equation in the empirical section to evaluate the short-run effect of computer accumulation on labour productivity, abstracting from scale effects: a 1% rise in the stock of computer capital increases labour productivity by e_{kc}%. This measure captures a short-run effect insofar as quantities of labour and other capital are held constant.

At the long-run optimum, firms choose the quantity of all inputs given prices, so that elasticities are linked to shares of inputs in total costs. This is easily seen by writing the cost minimisation program of the firm:

$$\begin{array}{ll} \min & p_l x_l + p_{kc} x_{kc} + p_{ko} x_{ko} \\ st & f\left(x_l, x_{kc}, x_{ko}\right) = y \end{array} \qquad [3]$$

and expressing the corresponding first-order conditions in the following way:

$$\pi_i = \frac{e_i}{q} \qquad [4]$$

where $q = \sum e_i$ is the elasticity of scale and $\pi_i = p_i x_i \big/ \sum p_j x_j$ are the cost shares.

The system of relationships [4] is in particular a building block of the traditional growth accounting framework. In the special case of computer capital, however, its empirical validity remains questionable. Several recent micro-econometric studies[2] point to the existence of a significant discrepancy between the right-hand side and the left-hand side of the equations. More precisely, returns to computer capital estimated from production functions turn out to be higher than the observed share of computers in the overall factor remuneration. This gap could result from production function misspecifications, from poor measurement of factor shares or from actual under-investments in computers. We will use our data to address this issue, and discuss it more at length in the empirical section.

The Cobb-Douglas production function is a natural starting point to evaluate returns to inputs:

$$\ln\left(y\right) = a_0 + \sum_i a_i \ln\left(x_i\right) \qquad [5]$$

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[2] See Lehr and Lichtenberg (1998), Stolarick (1999), Brynjolfsson and Hitt (2000).

This specification does not however allow for parameter heterogeneity across firms, as the elasticities of production to inputs are restricted to be constant:

$$e_i = a_i \qquad [6]$$

In order to compare elasticities and shares at the firm level, we complement this approach by the use of the more flexible Translog specification whose expression is:

$$\ln(y) = a_0 + \sum_i a_i \ln(x_i) + \frac{1}{2}\sum_{i,j} b_{ij} \ln(x_i)\ln(x_j); \quad b_{ij} = b_{ji} \qquad [7]$$

The Translog production function can be seen as a second-order approximation to any technology. Under this specification, returns to inputs vary across firms, depending on the quantities of inputs they use, in the following way :

$$e_i = a_i + \sum_j b_{ij} \ln(x_j) \qquad [8]$$

Long-run effects

If we consider the fall in the price of computers to be exogeneous, we may study the impact of a marginal decrease of this price on labour productivity. In order to evaluate such long-run effects, we need to examine the compensated factor demand system, which is the solution to the cost minimisation program [3]. Assuming that the returns to scale parameter q is constant, the system of factor demands can be expressed in a log-differentiated form as:

$$d\ln(x_i) = \frac{1}{q}\sum_j e_j s^A_{ij} d\ln(p_i) + \frac{1}{q} d\ln(y); \quad i \in \{l, kc, ko\} \qquad [9]$$

$$s^A_{ij} = \frac{\sum_k x_k f_k}{x_i x_j}\frac{F_{ij}}{F} \qquad [10]$$

$$F = \begin{vmatrix} 0 & f_l & f_{kc} & f_{ko} \\ f_l & f_{l,l} & f_{l,kc} & f_{l,ko} \\ f_{kc} & f_{kc,l} & f_{kc,kc} & f_{kc,ko} \\ f_{ko} & f_{ko,l} & f_{ko,kc} & f_{ko,ko} \end{vmatrix}$$

where s^A_{ij} are the *Allen-Uzawa partial Elasticities of Substitution* (AUES)[3], F is the determinant of the bordered Hessian, and F_{ij} is the co-factor of f_{ij} in F.

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[3] Note that the AUES is a *one-input-one-price* elasticity of substitution, as it measures the responsiveness of the compensated demand for one input to a change in another input price.

Equations [9] can be used in particular to compute the variation in the productivity of labour due to the change in the two forms of capital costs relative to labour cost[4] abstracting from scale effects:

$$d\ln\left(y/x_l\right) = -h_{l,kc}\, d\ln\left(p_{kc}/p_l\right) - h_{l,ko}\, d\ln\left(p_{ko}/p_l\right) + \left(1 - \frac{1}{q}\right) d\ln\left(y\right) \qquad [11]$$

$$h_{ij} = \frac{e_i s_{ij}^{A}}{q} \qquad [12]$$

where h_{ij} are the price elasticities of factor i to the cost of factor j .

In the Cobb-Douglas case, cross-AUES are restricted to be unitary. As a result, cross-price elasticities necessarily equal factor shares. In the absence of any evidence that AUES between labour and computer capital or between labour and the other forms of capital are actually close to one, this specification appears too restrictive for our purpose. We will thus favour the Translog production function in our empirical work. Under this specification, returns to inputs, AUES as well as factor demand price elasticities are not restricted to be constant across firm. All of them are firm-specific and depend on the quantities of inputs used.

Impact of computerisation on the relative demand for skill

The second prominent issue related to the increasing use made by firms of computer-based technologies has to do with its impact on the optimal combination of other inputs. Since the beginning of the 90s, a large amount of economic literature has been devoted to the impact of computerisation on the employment structure by skills of firms. According to the technological bias story, the increasing use of computers should be beneficial to the more skilled workers at the expense of the unskilled ones, the latter being presumably more substituable with computers. If this story is to be taken seriously, the decline in computer prices provides an explanation for the declining share of the unskilled in the overall work force.

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[4] Recall that the compensated factor demand is homogeneous of degree zero in prices so that only *relative* variations in input prices matter. This property is expressed formally by the following relationships :

$$\sum_j e_j s_{ij}^{A} = 0 \quad \textit{for all } i.$$

Addressing this issue, we now distinguish two categories of skills within labour in addition to the two forms of capital in the production function of the firm. This leaves us with four inputs. For the sake of simplicity, we start by studying long-run effects. We then turn to short-run effects.

Long-run effects

We may derive the relationship between the demand for skills and the price of computers by re-writing the system [9] with the four involved inputs and subtracting the two equations corresponding to the demand for skilled and unskilled labour. We then obtain the expression of the compensated demand for unskilled labour (*lu*) relative to skilled labour (*ls*) in a log-differentiated form:

$$d\ln\frac{x_{lu}}{x_{ls}} = -s^{M}_{ls,lu}d\ln\left(p_{lu}\right) + s^{M}_{lu,ls}d\ln\left(p_{ls}\right) + y_{kc}d\ln\left(p_{kc}\right) + y_{ko}d\ln\left(p_{ko}\right) \qquad [13]$$

where $s^{M}_{ij} = \frac{e_j}{q}\left(s^{A}_{ij} - s^{A}_{jj}\right)$ are the *Morishima elasticities of substitution* (MES)[5],

$y_{kc} = \frac{e_{kc}}{q}\left(s^{A}_{lu,kc} - s^{A}_{ls,kc}\right)$ and

$y_{ko} = \frac{e_{ko}}{q}\left(s^{A}_{lu,ko} - s^{A}_{ls,ko}\right)$

The elasticity Y_{kc} provides a measure of the technological bias since it represents the change in the relative demand for skills given a change in the unitary cost of computer capital, all other factor prices being held constant. Computerisation is biased in the long-run (i.e. all adjustments of inputs being fully implemented according to relative factor prices) toward skilled labour when $Y_{kc} > 0$.

In the empirical section, we look at the meaning of our estimations by considering the terms in equation [13] as the respective contributions of the inputs price variations to the change in the skill structure. Taking advantage of the fact that all elasticities sum to zero, we use the

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[5] By contrast with the AUES, the MES measures the elasticity of a two-input ratio to the price of one of the two considered inputs, as shown by equation [13]. The MES is therefore a *two-input-one-price* elasticity. Besides, unlike the AUES and the DES which will be defined below, the MES are not symmetric in general.

following transformation of [13] that relates the variation in skill structure to relative price change:

$$d\ln\frac{x_{lu}}{x_{ls}}=s^{M}_{lu,ls}d\ln\left(p_{ls}/p_{lu}\right)+y_{kc}d\ln\left(p_{kc}/p_{lu}\right)+y_{ko}d\ln\left(p_{ko}/p_{lu}\right)\qquad[14]$$

The Cobb-Douglas functional form is irrelevant to assess the presence and the magnitude of a technological bias induced by the accumulation of computers, since unitary cross-AUES imply that Y_{kc} and Y_{ko} are both zero. By contrast, cross-AUES do not equal one and differ from one firm to the other in the translog specification. In this case, Y_{kc} may therefore be considered as a measure of the skill-biased technical change at the firm level. In the empirical section, we display some features of the distribution of this parameter.

One might want to compare these estimates of Y_{kc} with direct estimates obtained from regressions of long-run relative labour demand equations of type [13]. We do not follow this approach for two reasons. To begin with, the only measures of the prices of capital goods available to us are macro-measures that lack by construction the cross-individual heterogeneity necessary to obtain the identification of equation [13]. Furthermore, there is strong evidence that large adjustment costs are present on both forms of capital as shown in appendix I. Modelling them as quasi-fixed factors and considering short-run effects may therefore be more appropriate.

Short-run effects

Let us consider the short-run program of the firm which consists in minimizing the cost of variable inputs (labour) given the stocks of quasi-fixed inputs (capital), conditional on the level of production:

$$\begin{aligned}&\min\ p_{lu}x_{lu}+p_{ls}x_{ls}\\&st\quad f\left(x_{lu},x_{ls},x_{kc},x_{ko}\right)=y\end{aligned}$$

The associated short-run compensated relative demand for unskilled labour can be expressed in a log-differentiated form as[6]:

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[6] This equation is obtained in practice by inverting the two last equations of system of [9] concerning ($d\ln x_{kc}$,$d\ln x_{ko}$) to derive expressions of ($d\ln p_{kc}$,$d\ln p_{ko}$). These expressions can then be used with the two first equations of system [9] in order to express ($dln(x_{lu})$,$dln(x_{ls})$) as a function of labor costs and capital stocks.

$$d \ln \frac{x_{lu}}{x_{ls}} = s^{D}_{lu,ls} d \ln \frac{p_{ls}}{p_{lu}} + j_{kc} d \ln \frac{x_{kc}}{y} + j_{ko} d \ln \frac{x_{ko}}{y} + \left(j_{kc} + j_{ko}\right)\left(1 - 1/q\right) d \ln y \qquad [15]$$

where $s^{D}_{ij} = -\frac{f_i f_j \left(x_i f_i + x_j f_j\right)}{x_i x_j \left(f_{ii} f_j^2 - 2 f_{ij} f_i f_j + f_{jj} f_i^2\right)}$ are the *direct elasticities of substitution* (DES)[7],

$$j_{kc} = \frac{e_{kc} s^{A}_{ko,ko} \left(s^{A}_{lu,kc} - s^{A}_{ls,kc}\right) - e_{ko} s^{A}_{kc,kc} \left(s^{A}_{lu,ko} - s^{A}_{ls,ko}\right)}{e_{kc} \left(s^{A}_{kc,kc} s^{A}_{ko,ko} - \left(s^{A}_{kc,ko}\right)^2\right)} = \frac{q \left(s^{A}_{ko,ko} y_{kc} - s^{A}_{kc,ko} y_{ko}\right)}{e_{kc} \left(s^{A}_{kc,kc} s^{A}_{ko,ko} - \left(s^{A}_{kc,ko}\right)^2\right)}$$

$$j_{ko} = \frac{e_{ko} s^{A}_{kc,kc} \left(s^{A}_{lu,ko} - s^{A}_{ls,ko}\right) - e_{kc} s^{A}_{ki,ko} \left(s^{A}_{lu,kc} - s^{A}_{ls,kc}\right)}{e_{ko} \left(s^{A}_{ko,ko} s^{A}_{kc,kc} - \left(s^{A}_{kc,ko}\right)^2\right)} = \frac{q \left(s^{A}_{kc,kc} y_{ko} - s^{A}_{kc,ko} y_{kc}\right)}{e_{ko} \left(s^{A}_{ko,ko} s^{A}_{kc,kc} - \left(s^{A}_{kc,ko}\right)^2\right)}$$

The elasticity j_{kc} can be interpreted as a short-run measure of technological bias since it represents the change in the relative demand for skills in response to a change in the quantity of computers, relative wage, quantities of other capital goods and output being held constant. Computerisation is then biased toward skilled labour in the short-run when $j_{kc} < 0$.

In the empirical section, we therefore focus on the two terms of [15] corresponding to capital accumulation and use them to weight up the contribution of capital accumulation to the change in the skill structure.

As for the long-run effects, these parameters are equal to zero under the Cobb-Douglas specification, whereas they are firm-specific in the case of the translog. We present in the empirical section distributions across firms of j_{kc} ands j_{ko} computed from the estimation of a Translog production function. They will be compared to the direct estimates obtained from the short-run relative demand for skills [15]. The empirical studies we are aware of on the topic of technological bias rely on such short-run relative labour demand estimations.[8] Most micro-econometric studies find a positive correlation between skill intensity and computer use.[9] We believe that this correlation provides only half of the relevant evidence. Indeed, it is by no means to be taken for granted that such correlations reflect the true technological complementarities rather than the managers' beliefs about these complementarities. Only the

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[7] Equation [15] involves the DES between the two forms of labour. This elasticity measures the percentage change in ratio of inputs divided by the percentage change in the relative prices of inputs, quantities of other inputs and output remaining constant.

[8] The precise specification of the relative labour demand may vary across studies. In most of them, labour demand equations are derived from a Translog cost function. This approach leads to a relationship involving cost shares instead of logarithms of the two forms of labour as in equation [15].

[9] See e.g. Caroli and Van Reenen (1999), Doms, Dunne and Troske (1997), Dunne, Haltiwanger and Troske (1996), Greenan, Mairesse and Topiol-Bensaid (1998), Haskel and Heden (1999), Kaiser (1998) and Machin (1996).

comparison with "primal" estimates can allow to disentangle this problem. To our knowledge, only Bresnahan, Brynjolfsson and Hitt (2000) and Caroli and Van Reenen (2000) have investigated so far the existence of complementarities between skills and computers using a production function framework. These papers do not however make explicit the relationship between the technology they postulate and the demand for skills.

Moreover, approaches based on the short-run labour demand may be misleading if their results are used to infer conclusions on the long-run effects of the fall in computers price. Indeed, the notions of short-run technological bias and long-run technological bias we have defined do not in general coincide. To make this point clear, let us express the long-run elasticities Y_{kc} and Y_{ko} as functions of the short-run ones j_{kc} and j_{ko}:

$$y_{kc} = q\left(e_{kc} s^{A}_{kc,kc} j_{kc} + e_{ko} s^{A}_{kc,ko} j_{ko}\right)$$
$$y_{ko} = q\left(e_{kc} s^{A}_{kc,ko} j_{kc} + e_{ko} s^{A}_{ko,ko} j_{ko}\right)$$

If Y_{kc} and j_{kc} are opposite in sign, long and short-run technological biases take place in the same direction. Since $e_{kc} s^{A}_{kc,kc} < 0$, Y_{kc} is a decreasing function of j_{kc}. However, it may be that Y_{kc} and j_{kc} have the same sign because of the long-run substitution effects between the two forms of capital. Under the (quite reasonable) assumption that the two forms of capital are not p-complements (i.e. that $s^{A}_{kc,ko}$ is nonnegative), a simple sufficient condition for Y_{kc} to be positive is that j_{kc} is negative and j_{ko} is positive, i.e. that short-run bias concerning the two forms of capital work in the opposite direction.

We summarize in table 1 the set of the parameters defined in this section as well as the methodology we will employ to evaluate them.

Table 1

Parameters of interest	Methodology	
	Primal approach	Dual approach
Returns to : - labour e_l - computer capital e_{kc} - other capital e_{ko}	Estimation of : - a three-inputs Cobb-Douglas PF. - a three-inputs Translog PF.	Computation of firm-specific cost shares.
Price-elasticities of labour to: - computer capital $h_{l,kc}$ - other capital $h_{l,ko}$	Estimation of a three-inputs Translog PF.	–
Long-run skill demand elasticity to : - computer capital cost Y_{kc} - other capital cost Y_{ko}	Estimation of a four-inputs Translog PF.	–
Short-run skill demand elasticity to : - computer stock j_{kc} - other capital stock j_{ko}	Estimation of a four-inputs Translog PF.	Estimation of a short-run relative labour demand.

The data

Two sources of tax data have enabled us to build a very comprehensive database, which provides us with measures of the firm’s computer stock as well as the skill composition of its workforce. The computation of capital stocks, obviously critical in this kind of study and often subject to large measurement errors, is carried out on the basis of stocks of fixed assets reported in the tax returns of companies subject to the “normal real profits” regime (BRN). This is an obvious advantage compared to most previous studies, based on proxies for actual IT stocks, such as computerisation dummies. Our data allow us to construct a quantitative measure of the extent of computerisation at the firm level. The BRN source provides also the yearly average number of employees as well as value-added. The data on labour cost and employment by skill is compiled using the DADS (annual declarations of social data made by firms).

Measuring capital stocks

The BRN source provides the balance sheet as well as the profit and loss account, for all firms subject to the BRN. However detailed fixed assets accounts distinguishing IT stocks from others capital goods are only available for a sample of around 30 000 firms distributed roughly equally between the manufacturing and the service industries, over the period 1989-1998. For this reason, only this sample may be used in our study. This section presents in more detail the construction of our measures of both capital stocks.

Information technology

The stock of computer capital appears in the company accounts under the item "office equipment, furniture and computer equipment", which includes in addition to computers, other office equipment such as typewriters and telephone handsets, as well as furniture. In order to obtain a stock of computers, we first use national account data to assess the share of computers in the overall item . We then introduce a correction to take account of the fact that the fixed assets are valued in company accounts at historic (acquisition) cost . The more standard "perpetual inventory" method, which is usually preferred, was not used in this case because it deals with investment flows and requires the use of sufficiently long series that were not available to us.

Series of prices for computer investment are needed for the construction of capital series. The measurement of prices in the computer equipment has been the subject of substantial work aimed at taking into account the improvement in product quality so that the measured volume should properly reflect the increase in the services provided by computer equipment. For this purpose the so-called hedonic price method is used (Griliches, 1971). INSEE has been compiling this type of index for France only since 1990 (Moreau, 1991). This index is not markedly different from the American price index calculated, using similar methods, by the Bureau of Economic Analysis (BEA), at least until 1995. We have therefore constructed a composite index drawing on the results obtained by the BEA, which has compiled this type of index since the mid-1970s. As a result, the price of investment in IT equipment fell by almost 13.7% a year over the period 1977-1999.

Other capital goods

The transformation of the other assets available from the tax returns data at the historical cost into volumes, is carried out using the same method. The eight types of capital goods (construction, buildings, general and technical installations, transport equipment, reusable packaging) are then aggregated into a single Divisia index.

Measuring firm level employment by skill

The DADS is an employee level tax source of information. Each employer must provide for each employee an individual declaration which contains in particular:

- the occupational category
- the yearly remuneration
- the associated amount of labour tax
- the number of hours worked

The occupational categories available are aggregated into two categories of skills including respectively:

- office and manual workers,
- business heads, senior executives and intermediate occupations.

We aggregate the exhaustive employee level file, available over the period 1994-1997 into a firm level dataset. We compute an average hourly labour cost at the firm level for the two categories of skill. As the exhaustive DADS applies to all employees within all French firms, it allows both an accurate measurement of the structure of employment and labour cost by skill at the firm level, and a sufficiently close matching with the BRN source.

Merging the comprehensive DADS firm-level dataset with the BRN source leaves us with a balanced panel over the period 1994-1997 of about 5500 firms distributed roughly equally between the manufacturing and the service industries. This merged dataset is used to asses the impact of computerisation on labour productivity and on the relative demand for skill within firms. However, when the distinction between skills is not needed but a longer or different time period is of interest, we will use the data set stemming from the BRN source (covering the period 1989-1998) before the merge with the DADS source[10].

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[10] Note that in the data set merged with the DADS labour is measured in number of hours, whereas in the data set before merge labour is measured in mean number of employees.

Estimation results

This section presents the empirical implementation of the twofold strategy suggested in the first section. As far as labour productivity is concerned, our method consists in obtaining estimates of the parameters of interest from the production function. We then assess their consistency with the model of optimizing behaviour and discuss their order of magnitude when compared to macro-economic evolutions. Addressing this first issue, we only distinguish three inputs: labour, computer capital and other forms of capital. We start by estimating a Cobb-Douglas production function under various sets of identifying restrictions in order to assess the magnitude of the returns to computer capital. We then estimate the more flexible Translog specification. This serves three purposes:

- it provides a test of the robustness of the results obtained under the Cobb-Douglas specification,
- it allows to overcome the limitations of the Cobb-Douglas function as far as elasticities heterogeneity is concerned,
- it allows us to investigate more closely the consistency of the estimated returns to computer capital with patterns of behaviour consistent with firm optimization.

We close this first sub-section by commenting the orders of magnitude obtained for the parameters of interest.

For the second part addressing the issue of the technological bias, we distinguish further between two skill levels within labour. We are then left with four inputs: unskilled and skilled labour, computer and other forms of capital. We first assess the possibilities of substitution using a Translog production function. The results are then confronted to those obtained from the relative labour demand equation. We finally discuss the macro-economic meaning of our results.

Estimating the returns to computer accumulation

Assuming parameter homogeneity: the Cobb-Douglas production function

Average values across firms for the elasticities of production to the quantity of labour, to the stocks of computer capital and to the stocks of the the other forms of capital can be directly obtained in estimating the Cobb-Douglas production function (equation [5] with three inputs:

labour, computer stock and other capital goods). Under this specification, returns to inputs are indeed the estimated coefficients as shown in equation [6].

We estimate this production function using a balanced panel of 5531 firms over the period 1994-1997 with four usual panel data estimators (see table 2). Recall that the between estimator is subject to a large bias of unobserved heterogeneity, as the unobserved determinants of computer capital accumulation such as organisation or research and development activity, are likely to be positively correlated with production. The between estimate of the coefficient on the stock of computers is therefore expected to be biased upwards. Conversely, eliminating this unobserved heterogeneity by identifying the parameters of interest within the intra-individual dimension (within estimator, first differences or long differences) should lead to a decrease in the estimated coefficient.

Table 2

	Between	Within	First differences	Long differences
Log. of hours (e_l)	0,66 (0,012)	0,58 (0,017)	0,45 (0,022)	0,70 (0,026)
Log. of computer stock (e_{kc})	0,20 (0,008)	0,06 (0,007)	0,07 (0,009)	0,05 (0,011)
Log of other capital stock (e_{ko})	0,09 (0,007)	0,10 (0,010)	0,10 (0,016)	0,10 (0,015)
Returns to scale (?)	0.95	0.74	0.62	0.85
Number of firms: 5531 / Estimation period: 1994-1997				
Standard errors in parenthesis				

Table 2 shows that controlling for unobserved heterogeneity indeed induces a sharp decrease in the estimated returns to computer capital: the between estimate of the elasticity is 0.20, as opposed to values ranging from 0.05 to 0.07 in the intra-individual dimension. This difference is likely to reflect a strong correlation between unobserved fixed effects and computer capital.

These results point to the large size of the biases induced by the presence of unobserved heterogeneity. Controlling for fixed effect, however is no sufficient protection against biased estimates, as simultaneity and measurement errors are also likely to affect the OLS estimates, even so, or more so in the intra-individual dimension. In particular, measurement errors are known to induce large downward biases with first-difference estimators. This bias is however expected to decrease as the length of the difference increases (long differences), or in deviations to the individual average (within estimator). Indeed, the coefficient on labour estimated in first differences (0.4) appears to be much lower than those obtained by using within (0.6) or long difference (0.7) estimators. The same is true concerning the elasticity to scale (0.6 againt 0.7 and 0.8). This might reflect significant measurement errors on firm employment. As this downward bias appears to be most severe on labour, measurement errors should also be largest on the stock of labour. Measurement errors may however account for only part of this bias. One would in particular expect larger measurement errors on the stocks of capital[11].

An alternative explanation for the sizeable discrepancy observed on the coefficient on labour between the first-difference and the long difference estimators, consists in emphasizing the bias of simultaneity: a shock increasing productivity (for instance the implementation of a technological innovation), i.e. increasing the level of output for a given quantity of inputs, may also improve the competitivity of the firm and shift factor demands upwards, all the more so in the short run for those inputs least costly to adjust (in our case labour). For all factors, this theoretically generates an upwards bias on the elasticity, all the more so when the length of the difference is longer. This is another possible explanation for the larger coefficient on labour obtained with long differences compared to first differences.

Whatever the main source of bias involved for the elasticity of production to labour, a remarkable feature of the previous estimations is the stability of the estimated elasticities with respect to capital stocks, after controlling for individual effects. This suggests that the main source of bias on these coefficients, specifically for the stock of computers, is the bias of unobserved heterogeneity. What is more, comparing estimates based on first differences and long differences, bearing in mind the effects of simultaneity, shows that simultaneity biases on the stock of computers are unlikely to be large. This leaves us with an estimated return to computers ranging from 0.05 to 0.07.

Let us assess the robustness of this result across size, industries and time. Our dataset allows us to carry out estimations on sliding samples over the period 1989-1998. We display the within estimator (table 3). Results are however very similar when we use first and long differences. The estimated returns to computers are stable through time, around 0.05. This result is close to the value obtained from the previous estimation[12] (table 2). The estimation

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[11] Note that we also get a great discrepancy between first and long differences when labour inputs is not measured with the number of hours worked but with the number of employees. The use of hours may generate larger measurement errors but does not therefore provide a sufficient explanation for the gap between the two estimators.

[12] Notice that the results concerning the period 1994-1997 do not exactly coincide with the results in table 2 since labour is measured with number of employees in table 3 since we need data not only on the period 1994-1997, but for the whole period 1989-1998.

also points to a slight increase in this coefficient from 1989 to 1998, which may be interpreted as a small upwards trend in returns to computers over the period.

Table 3

	Within estimator by subperiod						
	89-92	90-93	91-94	92-95	93-96	94-97	95-98
Log. of hours (e_l)	0,61 (0,012)	0,60 (0,011)	0,57 (0,010)	0,48 (0,008)	0,47 (0,008)	0,62 (0,017)	0,61 (0,021)
Log. of computer stock (e_{kc})	0,03 (0,004)	0,04 (0,004)	0,05 (0,004)	0,05 (0,003)	0,06 (0,004)	0,05 (0,007)	0,06 (0,008)
Log of other capital stock (e_{ko})	0,09 (0,007)	0,08 (0,007)	0,08 (0,007)	0,11 (0,006)	0,10 (0,006)	0,09 (0,010)	0,08 (0,010)
Returns to scale (θ)	0,73	0,72	0,70	0,64	0,63	0,76	0,75
Number of firms	10250	10953	12831	16680	17138	6167	6106
Standard errors in parenthesis							

Returns to computers appear to be highest for large firms (more than 250 employees), at around 0.09 (table 14 in appendix). They are also relatively large for small firms (less than 50 employees), at around 0.05. A smaller value of around 0.02 is however obtained for firms between 50 and 100 employees. This heterogeneity across size-groups makes caution necessary when it comes to interpreting our results.

It is finally worth noting that distinguishing between manufacturing and service industries does not yield significantly different results as far as returns to computers are concerned (see table 15 in appendix).

Table 4

	GMM estimators	
	Model in levels instrumented by lagged first-differences	Model in first-differences instrumented by lagged levels
Log. of hours (e_l)	0,90 (0,066)	0,31 (0,239)
Log. of computer stock (e_{kc})	0,08 (0,054)	-0,09 (0,077)
Log of other capital stock (e_{ko})	0,07 (0,037)	0,54 (0,160)
Sargan statistics	23,30	65,80
Degrees of freedom	18,00	12,00
P-value	0,18	0,00
Number of firms	4491	5142
Estimation period	1994-1997	1995-1997
Standard errors in parenthesis		

In order to deal with all sources of bias, and check in particular for the possible presence of simultaneity, we implement two standard General Method of the Moments (GMM) estimators: we successively estimate the model in levels instrumented by lagged differences of the explanatory variables under the assumption of constant correlation between regressors and individual effects (Arellano and Bover, 1995), and the first-differenced model instrumented by lagged levels (Arellano and Bond, 1991). The Sargan test leads to favour the model in levels istrumented by lagged first differences (table 4). The estimated returns to computers do not differ significantly from our previous estimates. However the poor precision of these estimators points to the weakness of the instruments we use to explain the decision to invest in computers.

Allowing for parameter heterogeneity: the Translog specification

Estimating a more flexible production function than the Cobb-Douglas provides a way of testing the robustness of the previous results, in particular the assumption of parameter homogeneity across firms. Let us assume the Translog specification given in equation [7] with three inputs: labour, computer stock and other capital goods. As shown in equation [8], returns to inputs are allowed to differ from one firm to another since they depend on the relative use of these inputs under this specification[13]. We proceed as follows:

- we start by estimating the parameters a_i and b_{ij} from the Translog function [7].
- we then compute the following firm-specific paramaters:
    - the returns to factors e_i using the estimates a_i and b_{ij} and [8]
    - the AUES using the formula [10]
    - the elasticities of the demand for labour with respect to all factor prices using the formula [9]
- we summarize the results by giving fractiles of these parameters distributions across firms (10%, 25%, 50%, 75% and 90%); standard errors of these fractiles are computed by bootstrap.

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[13] Notice that if none of the second-order coefficients turn out to be significant, the Cobb-Douglas specification provides an appropriate description of the technology, and the parameter homogeneity assumption makes sense.

We focus on returns to factors as well as price elasticities because their interpretation is more straightforward as shown in the previous section[14]. Moreover, within, first and long differences provide very similar results (table 17 in appendix). We therefore focus once again on the within estimator (see table 5). Note however that the GMM method yields much more imprecise results, pointing again to the difficulty encountered when trying to instrument the stocks of factors. The estimates do not differ significantly from the within estimates.

The results obtained for the returns to inputs appear to be consistent with the ones obtained from the Cobb-Douglas production function: returns to computers range from 0.05 to 0.08 and the elasticity to scale is concentrated around 0.8.

Table 5

Parameters of interest	Quantiles of the parameters of interest based on the Within estimator				
	10%	25%	50%	75%	90%
e_l	0,50 (0,026)	0,54 (0,022)	0,58 (0,021)	0,62 (0,023)	0,66 (0,027)
e_{kc}	0,04 (0,009)	0,05 (0,009)	0,07 (0,009)	0,08 (0,011)	0,10 (0,013)
e_{ko}	0,06 (0,017)	0,09 (0,013)	0,13 (0,013)	0,17 (0,018)	0,20 (0,023)
q	0,71 (0,032)	0,74 (0,024)	0,78 (0,021)	0,82 (0,025)	0,86 (0,033)
$h_{l,l}$	-0,73 (0,224)	-0,61 (0,131)	-0,55 (0,103)	-0,51 (0,112)	-0,17 (0,220)
$h_{l,kc}$	0,13 (0,089)	0,17 (0,050)	0,18 (0,054)	0,21 (0,067)	0,24 (0,108)
$h_{l,ko}$	0,14 (0,162)	0,34 (0,081)	0,37 (0,069)	0,41 (0,086)	0,49 (0,142)
Number of firms: 5531 / Period of estimation: 1994-1997					
Standard errors in parenthesis					

Contrary to the Cobb-Douglas specification, the Translog does not impose unitary cross-AUES. This property has important consequences when it comes to estimating the impact of the decline in the price of computers on the productivity of labour. Recall that under the Cobb-Douglas specification, the elasticity of labour demand to the cost of computer capital equals $h_{ij} = \frac{e_i}{q}$. One computes in this case a value of 0.09(=0.07/0.74) for this parameter if one retains the within estimation (table 2). In the case of the Translog, one may compute the

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[14] Median estimates of AUES as well as parameters of the translog function are reported in appendix (table 18).

same elasticity using the following formula: $h_{ij} = \frac{e_i s_{ij}^{A}}{q}$. As the AUES between labour and computers is larger than one (distributed around 2), the Translog specification leads to an estimate of the previous cross-price elasticity distributed around 0.18, therefore significantly higher than the Cobb-douglas estimate.

All in all, both the Cobb-Douglas and the Translog specifications yield consistent estimates of the return to computer accumulation in the range 0.05-0.08, depending both on the estimation method and taking into account the (reasonable) amount of parameter heterogeneity emphasized by the Translog case. However, the more flexible Translog approach leads to significantly higher results for elasticity of labour demand to the price of computers. This elasticity is concentrated in the range 0.17-0.21. We discuss in the next sub-section the quantitative macro-economic implications of these results.

Assessing the consistency of estimated returns to computers with their cost shares

If firms are price-takers on the markets for inputs and optimize correctly, the returns to stock of computers divided by returns to scale (e_{kc}/q) must equal the share of their remuneration in total costs (p_{kc}) as shown in equation [4]. We investigate the empirical validity of this prediction by computing directly the remuneration share of computers in total cost. The remuneration of each capital good is measured as the product of the corresponding user cost[15] and stock whereas labour cost is directyly available. We display fractiles of the distibutions of the inputs remuneration share (table 6) as well as of the returns to inputs divided by returns to scale (table 7).

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[15] The user cost p_i of form *i* of capital is computed from the traditional Jorgenson's formula :

$$p_i = \left(1 - \frac{(1-d)\left(1+\Delta p_i^I / p_i^I\right)}{1+r}\right) p_i^I$$

where p_i^I is the price of investment in capital *i*, *r* is the interest rate and *d* is the depreciation rate.

Table 6

	Quantiles of factor shares				
	10%	25%	50%	75%	90%
p_l	65,3%	76,9%	85,4%	92,1%	95,9%
p_{kc}	0,3%	0,4%	0,7%	1,2%	1,9%
p_{ko}	2,9%	6,7%	13,6%	22,4%	33,7%
Number of firms: 5531 / Period: 1994-1997					

Table 7

	Quantiles of theoretical factor shares based on the Within estimator				
	10%	25%	50%	75%	90%
e_l/q	0,64	0,69	0,75	0,81	0,86
e_{kc}/q	0,05	0,07	0,09	0,11	0,12
e_{ko}/q	0,07	0,12	0,17	0,21	0,25

The share of computers remuneration turn out to be about 10 times smaller than our estimates of the returns to computers divided by returns to scales (0.007 against 0.09). We find however a strong correlation across firms between these two parameters. This feature is illustrated by on figure 1 by the graph of the bivariate density of $\left(e_{kc}/q\,;p_{kc}\right)$. As far as the two other inputs are concerned, the two parameters are of the same order of magnitude (around 0.85 for labour and 0.13 for other capital goods).

Our finding of excess returns of computers with regard to their cost share is corroborated by most recent studies. At least three types of explanations come to mind.

- To begin with, it may be that the coefficient on computer capital we estimate captures something larger than returns to computers stricto sensu, as the stock of computer capital we measure is bound to be correlated with unobserved complementary inputs. Indeed, we only measure the spending on hardware which, according to the Gartner Group Report (1999), accounts for about 20 to 40% of the total IT spending, the remainder being allocated to the costs of training, support and software. Moreover, computerisation is likely to pave the way for (or to be implemented simultaneously with) various sorts of productivity enhancing workplace reorganisations. It may therefore serve as a proxy for possibly important unobserved sources of productivity gains[16].

- Alternatively, the observed gap between estimated returns and observed shares might reflect inefficiencies i.e. mistakes in profit maximization, as well as risk-aversion on the part of managers. Brynjfolsson, Bresnahan and Hitt (2000) claim that making the best of computer investment, given the necessity to implement simultaneously a whole set of complementary workplace reorganisation processes, is a tricky task liable to deter some. Managers may finally have incomplete access to the relevant information, or simply lack the technical ability to process it properly, which may lead them to under-invest.
- Finally, part of the correlation between computers and value-added could be driven by a reverse causal effect. We already mentioned that an increase in total factor productivity shifts upwards the demands for all inputs. It may also be that profit-making firms reward their employees by replacing their old machines by more recent and user-friendly ones.

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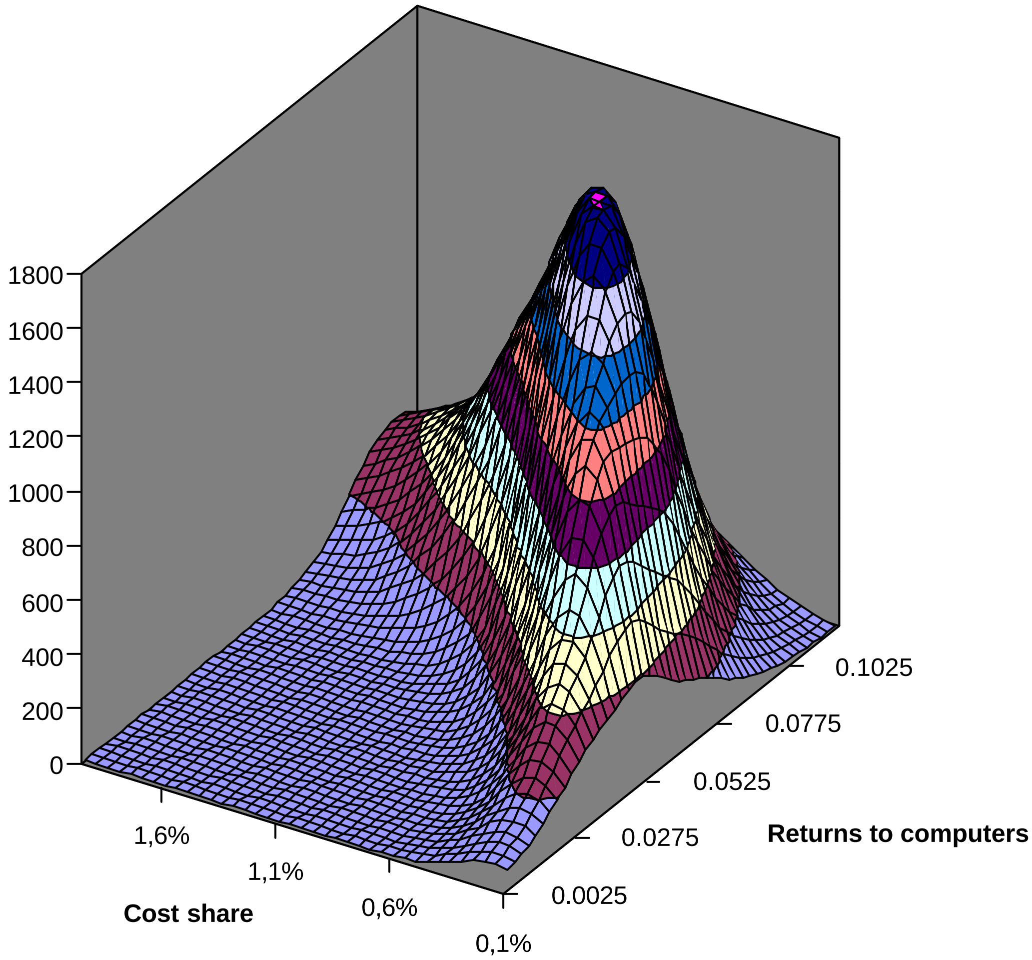
[16] See Brynjolfsson, Bresnahan and Hitt (2000) for evidence about complementarities between IT and organisational change.

Figure 1



Assessing the contribution of computerisation to the growth of labour productivity

The origin of the discrepancy between shares and elasticities matters when it comes to assessing the contribution of the accumulation of computer capital to labour productivity. In the short-run when other inputs are held constant, equation [2] shows that the contribution may simply equals $e_{kc}\Delta\log\left(x_{kc}/x_l\right)$. In the classical growth accounting framework, this quantity is computed especially under the asumption of constant returns to scale by evaluating e_{kc} as the cost share of computers. Following this methodology, Crépon and Heckel (2000) find for France that the accumulation of computer stock per head contributed for 0.3 percentage point each year to labour productivity growth which rose by 1.7% on average over the period 1987-1998. If the within estimate of e_{kc} under the Cobb-Douglas specification is to be taken seriously, we must conclude that the same variation of the computer stock per head implies a much stronger contribution of roughly 1.3 point[17] (table 8).

Table 8

	Estimate of the median elasticity	Growth rate of per head* capital stock	Contribution to labour productivity growth
Computer capital	0,07	18,50%	1,30%
Other capital	0,13	2,10%	0,30%

*mean yearly growth rate during the period 1987-1998 - Source: Crépon & Heckel (2000)

If we believe that the discrepancy between these two evaluations points to the omission of unobserved complementary inputs exhibiting high returns, we must attribute the gap of 1 percentage point (=1.3-0.3) to the accumulation of some form of material, human or organisational capital linked to computerisation. However, if the true explanation is under-investment, the contribution of computers is under-estimated by the growth accounting framework which underestimates the returns to computers.

Let us now turn to the impact of computerisation on productivity from a long-run perspective, by treating the decrease in the price of computers as the exogeneous force driving computer accumulation. As discussed in the first section, the growth of labour productivity can be decomposed, apart from scale effects, into two terms, representing the impacts of the price variations of the two forms of capital (equation [11]). We use this decomposition to evaluate the expected growth of labour productivity within French firms during the period 1987-1998. Under the assumptions that the two cross-price elasticities involved in equation [11] are uniform and equal to the their median, the contribution to the growth of labour productivity is then simply computed as the product of the relative price change by the estimate of the elasticity (table 9).

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[17] We focus here on the issue of evaluating the elasticity e_{kc}. However, the second multiplicative term involved in the contribution to growth, namely the growth rate of the volume of computer capital $\Delta\log(kc)$, may also be part of the problem, as the large order of magnitude of this growth rate mainly stems from the strong estimated decrease in the quality-adjusted prices of computers. One may argue that the perception by firms of the actual cost does not fall that fast (Greenan, L'Horty, Mairesse; 2001) or that users do not fully benefit from the quality improvements of computers.

Table 9

	Estimate of the median elasticity	Change in the relative price*	Contribution to the growth of labour productivity
Computer capital	0,14	-17,80%	2,40%
Other capital	0,19	-2,20%	0,40%
*mean yearly growth rate during the period 1987-1998 - Source: Crépon & Heckel (2000)			

According to our results, the fall in the price of computers should have implied an annual increase in labour productivity of around 2.4 percentage points while the variations in the prices of the other forms of capital have a more limited influence. The puzzle about this is that this increase appears much too strong with regard to the actual variation estimated at 1.7% during the period 1987-1998[18]. This discrepancy may cast doubt on either our estimates or the magnitude of the fall in the price of computers. We cannot however reject the possibility of under-investment in computers on the part of firms up to now, which would lead us to predict strong labour productivity gains when firms reach their long-run optimum in the future.

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[18] Notice that we should compare our contribution of 2.4% with the within evolution of labour productivity and not with its total evolution of 1.7%. Crépon and Duhautois (2001) using data on French firms over the period 1985-1995 provide however some evidence supporting the fact that labour productivity evolutions are on a large part within evolutions.

Substitutions between computer capital and skills

The empirical issue of technological bias has so far been adressed from a single point of view based on the estimation of labour demand equations, with the notable exceptions of Bresnahan, Brynjolfsson and Hitt (2000) and Caroli and Van Reenen (2000). Tackling the problem from a dual perspective is not however the only possible strategy available to identify the parameters of interest related to the issue of technological bias. In this section, we compare two alternative strategies:

- the approach based on the primal, i.e. the production function
- the approach based on the dual, i.e. labour demand equations by skills

The first approach rests on a straightforward generalization of the method presented in the previous section. Of course, in order to identify parameters of interest providing information as for the impact of computer accumulation on the composition of the workforce by skill, a necessary condition is to distinguish at least two categories of skills within the aggregate of labour used above. As shown in the section devoted to the presentation of the data, we split up total labour into "skilled" and "unskilled" workers. The relevant parameters of interest are in this section:

- the firm-specific elasticities of output to the stocks of factors
- the short DES between skilled and unskilled labour
- the short-run elasticities of the relative demand for skill to the stocks of capital
- the long-run elasticities of the relative demand for skill to all input prices.

We start by estimating these parameters using the Translog production function. We then compare these results with the ones obtained by estimating the short-run relative labour demand.

Identifying short-run and long-run measures of technological bias from production functions regressions

Distinguishing between skilled and unskilled labour restricts the size of our sample to a balanced panel of 5531 firms followed during the period 1994-1997. We estimate the Translog specification of the production function (equation [7]) with four inputs: unskilled labour, skilled labour, computer stock and other capital goods. Notice that the estimated equation is identical to the one estimated above, except that four inputs enter the production process, compared to only three previously. Again, all parameters of interest are computed using the estimated coefficients, and the method of computation is such that all parameters are firm-specific (see the first section). We display the 10%, 25%, 50%, 75% and 90% quantiles of the corresponding distributions across firms obtained from the Within estimator (table 10). The results are robust when the model is estimated in first or long differences (table 19 in appendix). We also computed Generalized Moments Methods under varied sets of identifying restrictions. Unfortunately, as far as substitutions are concerned, they lead to such imprecise estimates that we cannot infer any robust conclusion.

Table 10

Parameters of interest	Quantiles of the parameters of interest based on the Within estimator				
	10%	25%	50%	75%	90%
e_{lu}	0,22 (0,018)	0,31 (0,015)	0,38 (0,017)	0,44 (0,020)	0,49 (0,023)
e_{ls}	0,10 (0,011)	0,15 (0,011)	0,21 (0,013)	0,28 (0,018)	0,36 (0,024)
e_{kc}	0,03 (0,010)	0,04 (0,009)	0,06 (0,009)	0,08 (0,011)	0,10 (0,013)
e_{ko}	0,06 (0,016)	0,09 (0,013)	0,13 (0,014)	0,17 (0,019)	0,20 (0,024)
q	0,70 (0,032)	0,73 (0,025)	0,78 (0,022)	0,82 (0,025)	0,87 (0,032)
$s_{lu,ls}^{D}$	-1,56 (2,043)	2,26 (0,672)	2,75 (0,315)	3,74 (0,604)	6,32 (1,419)
j_{kc}	-0,71 (0,567)	-0,43 (0,190)	-0,29 (0,121)	-0,21 (0,152)	0,65 (0,482)
j_{ko}	-0,68 (0,331)	-0,07 (0,140)	0,08 (0,101)	0,28 (0,157)	0,84 (0,315)
$s_{ls,lu}^{M}$	-2,24 (2,463)	2,47 (1,300)	3,11 (0,515)	4,27 (0,989)	7,62 (2,325)
$s_{lu,ls}^{M}$	-2,07 (2,361)	2,23 (1,175)	2,82 (0,385)	3,97 (0,739)	7,20 (1,800)
y_{kc}	-0,52 (0,583)	0,25 (0,241)	0,35 (0,154)	0,52 (0,299)	1,03 (0,644)
y_{ko}	-1,24 (0,675)	-0,39 (0,277)	-0,09 (0,162)	0,18 (0,291)	1,02 (0,720)
Number of firms: 5531 / Period: 1994-1997					
Standard errors in parenthesis					

To begin with, note that the distinction between two skills within labour does not affect the conclusions about returns to inputs: returns to computers are ranging from 0.04 to 0.08 in comparison with 0.05 to 0.08 in the previous sub-section (table 5). The median of returns to other capital goods and to labour are almost identical (0.13 and 0.38+0.21=0.59 againt 0.13 and 0.58). Results appear consistent with those obtained in the previous sub-section.

As far as the substitution parameters are concerned, the main results of this approach are the following :

- The DES between skills ($\sigma_{lu,ls}^{D}$) as well as the MES ($\sigma_{ls,lu}^{M}$ and $\sigma_{lu,ls}^{M}$) appear to be distributed around central values of about 3. Thus, the relative demand for skill responds to a shock in the relative labour cost both in the short-run and in the long-run more strongly than what the standard Cobb-Douglas specification would predict[19].
- Computerisation appears to be skill-biased both in the short-run and in the long-run: the estimated elasticity of the short-run relative demand for unskilled labour to the stock of computers φ_{kc} is negative in more than 75% of firms in our sample, significantly so for more than half of them. There is similar evidence that the elasticity of the long-run relative demand for unskilled labour to the price of computer capital Ψ_{kc} is mainly positive in the economy.
- In contrast, our results exhibit no clear feature as far as the impact of the accumulation of other forms of capital on the relative demand for skill is concerned. Indeed, the elasticities φ_{ko} and Ψ_{ko} appear to be distributed roughly symmetrically around zero.

We comment further on these orders of magnitude after presenting the estimations we obtain from the quasi-fixed relative labour demand equation.

Assessing the consistency of the production function approach with labour demand regressions

We estimate an equation of relative labour demand using specification [15]. Estimating such an equation theoretically raises two endogeneity issues, one related to wages the other to capital stocks.

To begin with, the relative wage and the level of relative employment may be determined simultaneously at the firm level. In other words the true model of factor demand by the firm may be more complex than the standard microeconomic theory assumes, in particular the assumption that the firm is price taker on the labour market may not hold. If this is indeed the

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[19] In the Cobb-Douglas specification, the DES and the MES are equal to one.

case, the OLS estimate of the DES between skilled and unskilled labour is likely to be biased in absolute value towards zero. Furthermore, the observed heterogeneity in the relative wage across firms may reflect differences in the quality mix of workers (within skill groups) rather than differences in the relative price of labour. The standard way of dealing with this problem is to use instrumental variable estimators. Appropriate instruments are however not readily available. We therefore estimate the equation both with and without the relative labour cost term. In both cases, we implicitly assume that the firm is price-taker on the labour market. However, when the relative labour cost is included as a regressor, we make the additional assumption that variations in this variable properly reflect some heterogeneity in the relative supply for skill (possibly due to regional specificities). We otherwise implicitly assume the unicity of the labour market and the perfect mobility of the workforce. In the latter case, the DES is not identifiable and the supply shocks are captured by the time dummies.

Secondly, since the stocks of capital are chosen by the firms' managers, the associated coefficients are potentially biased. However, we emphasize in appendix 1 that firms invest in computers as well as in other capital goods unfrequently and in a lumpy way. This suggests large adjustment costs on both forms of capital, implying long adjustment lags, so that this additional bias of simultaneity should be of limited magnitude.

Table 11

	Between	Within	First differences	Long differences
$s_{lu,ls}^{D}$	0,78 (0,060)	0,50 (0,029)	0,48 (0,037)	0,54 (0,048)
j_{kc}	-0,35 (0,017)	-0,03 (0,008)	-0,01 (0,009)	-0,04 (0,014)
j_{ko}	0,25 (0,014)	0,02 (0,011)	0,01 (0,014)	0,03 (0,018)
Value added	-0,08 (0,010)	-0,01 (0,014)	0,00 (0,017)	-0,01 (0,024)
Number of firms: 5388 / Estimation period: 1994-1997				
Standard errors in parenthesis				

We estimate the equation using a balanced panel of 5388 firms during the period 1994-1997[20]. We display the results obtained by taking advantage of the inter-individual variation (between) as well as the intra-individual dimension (within, long differences and first

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[20] We lost a few firms in comparison with previous estimations, namely 5531-5388=143 due to deviant values of wages.

differences) (table 11). The last three estimators eliminate the bias of unobserved heterogeneity but are still subject to biases of simultaneity as well as measurement errors to various degrees.

All estimators provide close values for the DES between skill groups, ranging from 0.5 to 0.8. However, this approach points to much smaller substitution possibilities between skill groups than was computed from the production function approach where the median value of this parameter was evaluated around 3 (table 10). Providing an answer to this inconsistency raises many deep economic and econometric issues that we recalled at the beginning of this sub-section. We are not willing to deal with this issue further here. Let us instead concentrate to the technological bias parameters of interest, noticing that the estimated coefficients on the stocks of capital are not affected by the omission of the relative wage variable (table 21 in appendix).

All estimators support the technological bias hypothesis since they provide a negative elasticity to computers. We obtain however a much smaller coefficent in absolute terms in the intra-individual dimension (within, first differences and long differences) than in the inter-individual dimension (between). The orders of magnitude of the elasticity obtained in the intra-individual dimension are also much lower than the ones found with the production function approach, which yielded values concentrated around -0.3, more consistent with the between estimation.

Before pointing to reasons explaining the difference between the production function and the labour demand approaches, notice that the short-run skill biased parameter (j_{kc}) is not precisely estimated in the production function approach so that the two estimates are not significantly different at the 5% level[21].

We must however admit that the production function approach yields larger effects. This may point to the fact that imperfect information is an essential characteristics of the managers' environment. The latter may as a result not be fully aware of the complementarities between labour and computers, and firms may consequently not have exhausted all the possibilities of substitution allowed by computerisation.

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[21] The confidence intervals are indeed respectively [-0.29 +/- 2x0.12] and [-0.03 +/- 2x0.01].

This leaves us with one robust result, the significant effect of computer accumulation on skill demand. There remains however uncertainty as far as the order of magnitude of this effect is concerned.

Using GMM estimators to protect against measurement errors and endogeneity biases points once again to the the poor instruments at hand to explain the accumulation of computers (table 22 in appendix).

Assessing the contribution of computerisation to the aggregate relative demand for skills

We now attempt to provide a rough evaluation of the shift in the aggregate relative demand for unskilled labour that one should expect from the accumumation of computer stock (short-run) as well as from the decline in the computers price. As with the previous issue of labour productivity, we focus on the evolutions in France during the period 1987-1998 described in Crépon and Heckel (2000). For the short-run, we use equation [15] where the contribution due to variations in the relative prices of the inputs is computed as the product of the elasticity by the relative price variation (table 12). To obtain a rough evaluation, we assume that the elasticities involved are uniform and equal either to:

- the within estimates of their medians under the Translog specification (table 10),
- the within estimates in the labour demand equations (table 11).

We consider both of them because they yield very different results.

Table 12

	Estimate of the elasticity	Relative price or capital productivity variation	Contribution to relative employment variation
Skilled labour	0,5 2,75	0,00%	0,00% 0,00%
Computer capital	-0,03 -0,29	16,80%	-0,50% -5,00%
Other capital	0,02 0,08	0,40%	0,01% 0,03%

As for the long-run, only estimates of skill-biased parameters are available from the production function. As the production function approach leads to high estimates of the impact of computerisation on the demand for labour, we present the estimation of the impact in the long-run with the median but also the lower bound of the 5% confidence interval, in order to provide a conservative estimate (table 13).

Table 13

	Estimate of the median elasticity	Mean yearly relative price variation	Contribution to the variation of relative
Skilled labour	2,8	0,00%	0,00%
Computer capital	0,35 0.05(=0.35-2x0.15)	-17,40%	-6,10% -0,87%
Other capital	-0,09	-1,80%	0,16%

Both short and long-run approaches lead to significant evolutions concerning the skill structure. We would even expect annual increases in the relative labour employment exceeding the observed macroeconomic trend when considering the estimates from the production function approach, since the actual variation of relative employment is around -2.7% per year over the period 1987-1998. When using more conservative estimates for the elasticities, we still get significant evolutions ranging from 0.5% to 0.9% in the short-run and in the long-run. We can therefore conclude that computerisation is skill-biased and that it is likely to matter a lot on a macro-economic level. However, as illustrated above, the order of magnitude of the evolutions linked to computerisation are still very imprecise given the large dispersion of the estimates and their poor precision.

Conclusion

This paperr provides empirical evidence that the decrease in the price of computers must have influenced labour productivity as well as the skill structure significantly in the past decade. Moreover, all the potential effects of this decrease may have yet not occurred.

However, it must not be taken for granted that incremental gains in the computer industry will be permanently skill-biased. Our results suggest that some complementary input, such as organisational change, may matter as much as computers themselves. If technological bias actually reflects an organisational bias, computerisation will become skill-neutral when associated opportunities of reorganisations are exhausted. Expliciting this link between computerisation and organisational change is therefore a pre-requisite if we want to assess the influence of future decreases in the price of computer power.

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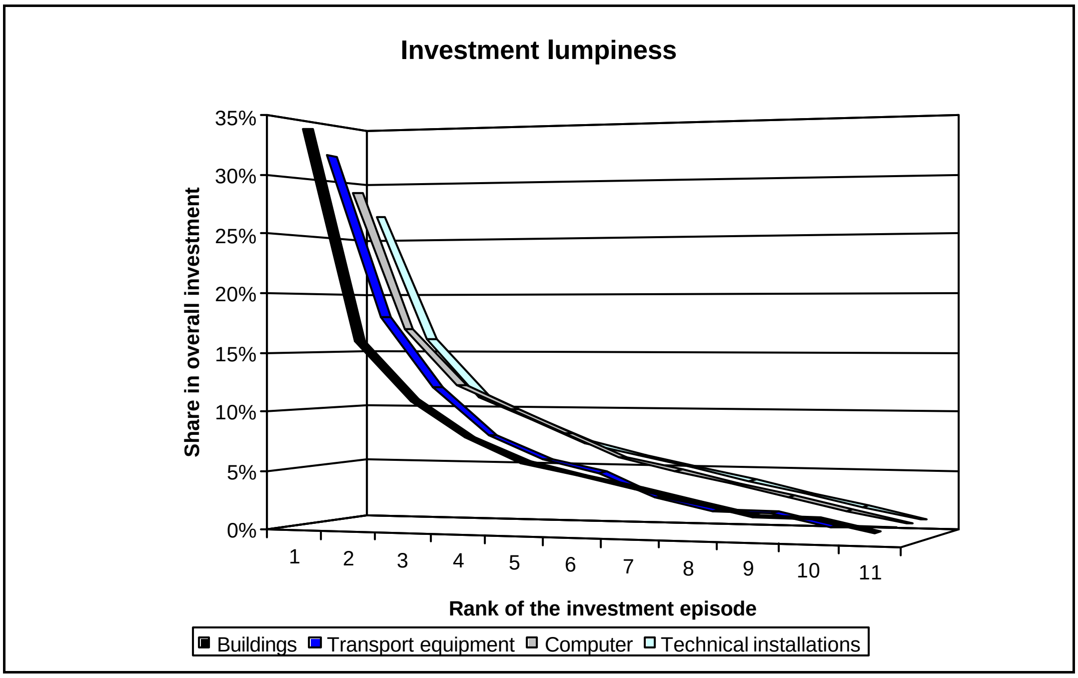
Appendix 1: Are computers a quasi-fixed factor ?

Doms and Dunne (1998) have shown that the investments of firms exhibit a high degree of lumpiness, suggesting that adjustment costs are high and non-convex. This feature provides a justification of considering capital as a quasi-fixed input in short-run demand equations. We wonder if their conclusion still holds when we distinguish computers from the other forms of capital.

We follow their method, which consists in ranking the investment episodes of a sample of surviving firms between 1986 and 1998 and computing the share of each episode (i.e. for every rank) in the total computer investment made by the firm throughout the period[22]. We then compute averages for these shares across firms. Figure 2 displays these averages for each form of capital.

For all four capital goods, the three major investment episodes account on average for more than half of the investment made over the whole period. This result suggests the existence of important non-convexities in the cost of adjusting capital stocks. Investment in computers exhibits less lumpiness than buildings and transport equipment but more than technical installations.

Figure 2



Source : Sample of firms subject to the BRN during the period 1986-1998.

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[22] We discard investments carried out in 1986 from the ranking, in order to eliminate entrants, who are likely to invest massively.

Appendix 2: Other results

- ***Cobb-Douglas production function***

Table 14 : assessing size heterogeneity

WITHIN Estimator	<50	50-100	100-250	>=250
e_l	0,52	0,58	0,64	0,63
	(0,031)	(0,040)	(0,030)	(0,032)
e_{kc}	0,05	0,02	0,06	0,09
	(0,013)	(0,016)	(0,012)	(0,012)
e_{ko}	0,08	0,14	0,07	0,13
	(0,021)	(0,024)	(0,017)	(0,017)
q	0.65	0.74	0.77	0.85
Nombre d'individus :	1486	1091	1593	1361

Number of firms : 5531 ; Period of estimation : 1994-1997

Table 15 : assessing sectoral heterogenity

WITHIN Estimator	Manufacturing	Services
e_l	0,63	0,55
	(0,025)	(0,023)
e_{kc}	0,06	0,06
	(0,010)	(0,009)
e_{ko}	0,13	0,09
	(0,019)	(0,012)
q	0.82	0.70

Number of firms : 5531 ; Period of estimation : 1994-1997

Table 16 : two measures of labour

Within Estimator	number of employees	hours
e_l	0,64	0,58
	(0,019)	(0,017)
e_{kc}	0,05	0,06
	(0,007)	(0,007)
e_{ko}	0,08	0,10
	(0,010)	(0,010)
q	0.77	0.74

Number of firms : 5531 ; Period of estimation : 1994-1997

- Three-inputs Translog production function

Table 17 : median estimates obtained fromWithin, first differences and long differences estimators

	WITHIN	FIRST DIFF	LONG DIFF
e_l	0,58	0,46	0,69
e_{kc}	0,07	0,07	0,06
e_{ko}	0,13	0,13	0,12
q	0,78	0,66	0,87
$h_{l,l}$	-0,55	-0,79	-0,44
$h_{l,kc}$	0,18	0,30	0,14
$h_{l,ko}$	0,37	0,49	0,31

Table 18 :Within estimates of the coefficients of the three-inputs Translog production function and medians of AUES based on this estimator

$$[a_l \quad a_{kc} \quad a_{ko}] = [0.58 \quad 0.07 \quad 0.13]$$

$$\begin{bmatrix} b_{l,l} & & \\ b_{l,kc} & b_{kc,kc} & \\ b_{l,ko} & b_{kc,ko} & b_{ko,ko} \end{bmatrix} = \begin{bmatrix} 0.05 & & \\ -0.02 & 0.01 & \\ -0.04 & 0.01 & 0.02 \end{bmatrix}$$

$$Median\left(\begin{bmatrix} s^{A}_{l,l} & & \\ s^{A}_{l,kc} & s^{A}_{kc,kc} & \\ s^{A}_{l,ko} & s^{A}_{kc,ko} & s^{A}_{ko,ko} \end{bmatrix}\right) = \begin{bmatrix} -0.75 & & \\ 1.96 & -14.71 & \\ 1.96 & -0.54 & -7.57 \end{bmatrix}$$

- Four-inputs Translog production function

Table 19 : median estimates obtained from Within, first differences and long differences estimators

	WITHIN	FIRST DIFF	LONG DIFF
e_{lu}	0,38	0,30	0,46
e_{ls}	0,21	0,16	0,24
e_{kc}	0,06	0,07	0,05
e_{ko}	0,13	0,13	0,12
q	0,78	0,66	0,87
$s^{D}_{lu,ls}$	2,75	2,69	2,74
j_{kc}	-0,29	-0,27	-0,36
j_{ko}	0,08	0,02	0,11
$s^{M}_{ls,lu}$	3,11	3,08	3,19
$s^{M}_{lu,ls}$	2,82	2,62	2,96
y_{kc}	0,35	0,33	0,35
y_{ko}	-0,09	0,00	-0,14

Table 20 :Within estimates of the coefficients of the three-inputs Translog production function and medians of AUES based on this estimator

$$\left[a_{lu} \quad a_{ls} \quad a_{kc} \quad a_{ko}\right] = \left[0.37 \quad 0.22 \quad 0.06 \quad 0.13\right]$$

$$\begin{bmatrix} b_{lu,lu} & & & \\ b_{lu,ls} & b_{ls,ls} & & \\ b_{lu,kc} & b_{ls,kc} & b_{kc,kc} & \\ b_{lu,ko} & b_{ls,ko} & b_{kc,ko} & b_{ko,ko} \end{bmatrix} = \begin{bmatrix} 0{,}06 & & & \\ -0{,}06 & 0{,}05 & & \\ -0{,}02 & 0{,}01 & 0{,}01 & \\ -0{,}02 & -0{,}02 & 0{,}01 & 0{,}02 \end{bmatrix}$$

$$Median\left(\begin{bmatrix} s^{A}_{lu,lu} & & & \\ s^{A}_{lu,ls} & s^{A}_{ls,ls} & & \\ s^{A}_{lu,kc} & s^{A}_{ls,kc} & s^{A}_{kc,kc} & \\ s^{A}_{lu,ko} & s^{A}_{ls,ko} & s^{A}_{kc,ko} & s^{A}_{ko,ko} \end{bmatrix}\right) = \begin{bmatrix} -3{,}20 & & & \\ 3{,}30 & -5{,}73 & & \\ 3{,}68 & -0{,}43 & -15{,}58 & \\ 1{,}73 & 2{,}29 & -1{,}01 & -7{,}45 \end{bmatrix}$$

- Short-run relative labour demand

Table 21 : with and without the wage term

Within estimator	With w_{ls}/w_{lu}	without
$s^{D}_{lu,ls}$	0,50	
	(0,029)	
j_{kc}	-0,03	-0,02
	(0,008)	(0,008)
j_{ko}	0,02	0,02
	(0,011)	(0,010)

Table 22 : two GMM estimators

	GMM LEV	GMM DIFF
$s_{lu,ls}^{D}$	-0,03	0,01
	(0,282)	(0,307)
j_{kc}	-0,14	0,30
	(0,093)	(0,190)
j_{ko}	0,19	-0,32
	(0,080)	(0,159)
Sargan	6,04	7,40
Df	6	6
p-value	0,42	0,29

Number of firms: 5388; Period of estimation: 1994-1997