ICTs and time-span in technical efficiency gains. A stochastic frontier approach over a panel of Italian manufacturing firms

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Abstract

This paper, in contrast to much of the existing literature, which focuses on the impact of Information and Communication Technologies (ICT) on labour productivity, assesses the relationship between ICTs investments and Technical Efficiency (TE) using a stochastic frontier approach. We use a large panel dataset of Italian manufacturing firms over the period 1995-2006 and confirm prior findings of the existing literature on ICT and productivity. In addition, we test on which extend the ICT investments influence the distance of the firm from the production frontier; that is, how ICT's adoption influences the closing of the firm efficiency gap. We also test how long the effects of ICT investments on technical efficiency last. We find that ICT returns on TE are influenced by some firm's characteristics, most of them idiosyncratic, such as management practices, labour organization, research and development.

Keywords: ICT; stochastic frontier; technical efficiency; manufacturing firms

JEL: D24, L25, L63, O33

1. Introduction

After a long debate on the returns of investment in information and communication technology (ICT) there is now general agreement that ICT positively contributes to economic growth both at micro and macroeconomic levels. This debate has been largely based on the productivity paradox, which started soon after Robert Solow's (1987) statement: "You can see the computer age everywhere but in the productivity statistics".

The related empirical literature studies both the relationship between ICT investments and labour productivity and ICT investments and total factor productivity (TFP). Few attempts have been made to also study the relationship between ICT investments and technical efficiency (TE) at firm level. The importance of this relationship arises from the fact that the productivity growth is mainly the result of technical and efficiency changes. Hence, it is important to verify the effect that ICTs have both on productivity and TE.

In this paper the Cobb-Douglas and Translog production functions are used to explore ICT investments impact on firm distance from the 'best practice technique'. We utilize the stochastic frontier model introduced by Battese and Coelli (1995). This methodology has the benefit that it uses a one-stage procedure to estimates both productivity and (in)efficiency. The paper adds to the existing literature in four ways. Firstly, ICT capital and high-skilled workers are considered as inputs in the firm's production function. Secondly, ICT investments are considered as a factor able to directly influence TE. Thirdly, we investigate the length of the positive impact of ICT on firm efficiency. Finally, we postulate that ICT effects on firm efficiency depend on some complementary idiosyncratic factors (such as management practices, research and development investments and other firm' characteristics) that are able to boost ICT returns.

The analysis is conducted using a balanced and an unbalanced panel data of Italian manufacturing firms taken from four consecutive waves provided by Mediocredito Centrale-Capitalia-Unicredit (hereafter MCU) for the period 1995-2006.

The results provide evidence on the above hypotheses showing that ICT investments have a positive effect both on productivity and TE of Italian manufacturing firms, when ICT is considered as a general purpose factor and as a firm specific factor, and that firms get benefits from ICT investments for a nine year period.

To explain the time-span in the impact of ICT on technical efficiency we postulate that investment in ICTs increases productivity according to some firms' heterogeneous characteristics. The paper measures the length of this impact, when accompanied by changes in management practices, complementary innovations and market competition. We demonstrate that firms that make changes in their organizational structure, that invest in research and development, that are open to international markets exploit in a better manner their ICT investments, improving their efficiency.

The remainder of the work is structured as follows: the second section analyses the relevant literature at firm level. The third section presents the relationship between productivity and TE. The fourth section introduces the economic hypotheses and the stochastic frontier model. The fifth section describes the source of the data and the variables used. Results and discussion are presented in the sixth section together with some robustness checks, while the last section offers some concluding remarks.

2. Literature Review

During the last few decades the information and communication technologies have been at the centre of the debate on their contribution to economic growth and long-lasting impact on productivity growth. This is a debate that at the macroeconomic level is still going on with different points of view and results (Brynjolfsson and McAfee, 2011; Baily et al., 2013; Byrne et al., 2013; Gordon, 2013), while at the microeconomic level the studies are going deeper and deeper in measuring the diversified effects that ICTs have on firm performance and organization.

At the microeconomic level, the relationship between ICT investment, productivity and technical efficiency has been analysed for different countries and periods of time. The analysis is usually conducted with parametric and non-parametric methodologies that use different estimation techniques: OLS, IV, logit, stochastic frontier, and data envelopment analysis. In order to verify the impact of ICTs on productivity and TE this work utilize the stochastic frontier model introduced by Battese and Coelli (1995). This methodology has the benefit that it uses a one-stage procedure to estimates both productivity and (in)efficiency.

Shao and Lin (2001, 2002), using both a stochastic and deterministic frontier production function on a panel data of United States firms, show that ICT has a significant positive effect on TE and hence contributes to productivity growth. Becchetti et al. (2003) evaluate the impact of investments in software, hardware and telecommunications of small and medium-sized Italian manufacturing firms on a series of intermediate variables and on productivity. In order to evaluate whether current ICT investments are able to affect firm efficiency, they use a Cobb-Douglas stochastic frontier approach. Their results show that investments in telecommunications positively affect the creation of new products and processes, while software investment increases the demand for skilled workers, average labour productivity and proximity to the optimal production frontier.

Mouelhi (2009), using a stochastic frontier approach on a panel data of Tunisian manufacturing firms, investigates whether the adoption of ICT impacts on the efficiency in factors use. The results show a positive return on ICT capital. Tunisian firms that have a relatively intensive use of ICT are on average 5 percent more efficient than those that do not. Mouelhi's results also suggest that benefits from investment in ICT require complementary investments and changes in human capital.

Yuhn and Kwon (2010) investigate the link between IT and productivity growth in South Korea using the Brynjolfsson and Hitt's (2000) proposition that IT affect firm efficiency through new organizational and working practices. They follow Battese and Coelli (1992, 1995) in specifying the error term that measures technical efficiency. Using a panel data of Korean information technology-producing and using firms they find that 80 percent of the TFP firm's growth during the period 1990–2000 was due to technological change, 5 percent to scale economies and 15 percent to improvements in technical efficiency, mainly deriving from organizational and managerial changes required by IT investments.

Finally, Castiglione (2012), using both a Cobb-Douglas and a Translog production stochastic frontier, estimates the impact of ICT on TE in the Italian manufacturing firms over the period 1995–2003. The results show that ICT investments positively and significantly affected firms' TE. Castiglione states that since the mean efficiency of the Italian manufacturing firms is 0.49 this implies that output could be theoretically increased. Castiglione concludes that ICT investments and other factors might contribute to increase productivity and technical efficiency.

To take a step further along these findings a distinction between ICT and non-ICT capital should be introduced in the stochastic frontier analysis together with high-skilled and low-skilled labour. In this respect we make a research advance. In fact, while the relationship between ICT investments and firm productivity is a straightforward extension of the basic model of the production function that includes ICT and skilled labour as separate types of capital and labour, the inclusion of ICT investments as an additional input that affects firm efficiency is not a trivial problem.

In addition to the above aspects, some other factors should also be considered in this context. For example, Brynjolfsson and Hitt (1996) show that the impact of ICT investments on productivity varies between firms. They find that some firms use ICTs in a more productive way compared to others. The cause could be ascribed to two different factors: idiosyncratic characteristics due to the rigidity of the cost structure and specific characteristics of organisational structure, such as strategy and management techniques. Dedrick et al. (2003) find that management experience and complementary investments explain part of the variation in

ICT pay-offs. In a subsequent paper Brynjolfsson and Hitt (2003) demonstrate that computer investment generates firm's output growth in the first year of instalment, while increasing output growth accrues over the years of service. They postulate that the increasing contribution of computers to productivity growth over the years (between 3 and 7 years) is mainly due to a broader set of assets that complement computers and make them work better over the computer's life-span. The present research is also an attempt to find those factors that give an explanation to the time-span of this impact.

Atzeni and Carboni (2001), in explaining the importance of ICTs adoption, apply a growth accounting methodology to calculate the total factor productivity residual over the period 1989-1997. This residual is then regressed on a number of variables including an estimate of ICT investments and their complements. Addressing the analysis to territorial disparities, the authors find that the impact of ICT on productivity is significant and helps to explain the difference in firm performance between the North and South of Italy. Bugamelli and Pagano (2004) find strong evidence in favour of complementarity between ICT, human capital and reorganisation of production.

Hall et al. (2013) in a recent work analyse the role of ICT and R&D investments on both innovation and productivity performance in an unbalanced panel of Italian manufacturing firms. They have investigated the interaction of the percentage of skilled workers with the two variables and found that skills significantly interact with R&D and produce a positive effect on firm's innovative performance, while the interaction of skills with ICT do no affect it. They conclude that the share of white-collars is complementary to R&D but not with ICT in innovating.

In the previous works the importance of the complementary factors that ICT require to have greater effects on productivity are shown. However, no attempt has been made to test the effects on TE of the ICT and its complementary factors. Very often the introduction of new managerial and work organization along with ICTs is done to boost productivity, without taking into account its effects on technical efficiency, thus underestimating the contribution of ICT to firm performance.

3. Productivity and Technical Efficiency

The firm production frontier specifies the maximum output achievable by employing a combination of inputs. The distance between the production frontier and the actual output is regarded as its technical inefficiency. Thus, a firm operates below the frontier when it is technically inefficient and on the production frontier when it is technically efficient (Farrell, 1957). In production theory, productivity and TE are two related concepts, even though they represent two different performance measures. In fact, a firm may be technically efficient and may still be able to improve its productivity by exploiting scale economies, and by introducing new technologies (for a detailed discussion see Coelli et al., 1998). Therefore, an important relationship exists between productivity and TE. Leaving aside scale economies, productivity growth is the effect of the change in TE and the shift in the production frontier; thus, TE is one important factor in a firm's productivity, the other being technological change (Chen and McGinnis, 2007).

TE is concerned with the maximization of output for a given set of resource inputs and indicates how far the firm can increase its output without requiring further resources. A technically inefficient firm could produce the same output with less of at least one input or could use the same inputs to produce more of at least one output.

One way to represent TE is illustrated in Figure 1 in which labour and capital have been considered as the only inputs in the production process. Given two inputs and one output, the efficient frontier, or the 'best practice' production function, may be represented by the isoquant that shows the minimum combination of inputs, given the state of the technology that can produce a given level of output. Technical change may be represented either by an upward shift in the production frontier or by a downward shift of the isoquant. In Figure 1, technical change is represented by investments in ICT; the first isoquant q_{nict} regards those firms which do not invest in ICT, whilst the second involves firms investing in ICT. With the new, lower isoquant, all firms, for each level of output, may use fewer inputs. A firm, using the two inputs labour and capital, to produce the output level q, is technically inefficient if it produces it at point *A* as compared to the frontier firm, which operates at point *B* if it does not invest in ICT and at point C if it does invest in ICT. Hence, the distance *AB* can be regarded as the firm's technical inefficiencies, while the distance *BC* can be regarded as technical progress. In fact, a firm operating at point *A* is inefficient because technically it could produce the same level of output using less input: moving to point *B* or, introducing ICTs, moving to point *C*. Hence firm inefficiency may be divided into two parts: technical inefficiency (from *A* to *B*) and the additional inefficiency due to the ICT *gap* (from *B* to C). Consequently, the inefficiency of a firm that does not invest in ICT depends on how far the firm is from its equilibrium point, that is, from a condition of fully utilizing its current technology, and on the adoption of the new technologies (Infante, 1990). In this work we also consider the additional efficiency that is present for firms that do invest in ICT.

4. Economic Hypotheses and Empirical Approach

The purpose of this work is to find out whether ICT investments significantly affect the firm distance from the optimal production frontier. The impact of ICT investments on efficiency at firm level will be estimated by using the stochastic frontier approach for panel data. In this case the inefficiency effects (Battese and Coelli, 1995) are expressed as an explicit function of a vector of firm-specific variables and a random error. This approach has been recognised (Wang and Schmidt, 2002) to be better than the two-stage estimation which inconsistently assumes the independence of the inefficiency effects. The two-stage estimation procedure is unlikely to provide estimates which are as efficient as those that could be obtained using a single-stage estimation procedure.

In the past twenty years the demand for skilled workers has increased. According to Arvanitis (2004) many factors have contributed to this increase; however, most authors think that this effect is attributable primarily to skill-based technical change. The increase in demand for labour has led many authors to relate skill-biased technical change to the largest and most widespread new technologies of the past years (Bresnahan et al., 2002). In this way, ICT and human capital build a 'complementary system' of activities (Bresnahan et al., 2002; Milgrom and Roberts, 1990). Given this strong complementarity between ICT and human capital, we also take into account the higher level of education of a firm's employed workers, as a proxy of high-skilled labour.

ICT capital and high-skilled labour can be considered as separate production factors by themselves in measuring productivity and TE, in order to investigate ICT's marginal products. Henceforth, our empirical analysis is focused on testing the following hypotheses:

Hypothesis 1: ICT capital and high-skilled labour improve production process - i.e., productivity rises.

Hypothesis 2: ICT investments impact on production process efficiency - i.e., technical efficiency rises.

Hypothesis 3: ICT investments also influence TE through its long-lasting impact - i.e. inefficiency decreases for a long time-span.

Hypothesis 4: ICT investments returns on TE depend on some idiosyncratic characteristics - i.e. new management practices, complementary innovation and other firm' characteristics.

In order to test the first hypothesis the stochastic frontier production function (Cobb-Douglas and Translog) is used. Considering also raw materials as an input, the Cobb-Douglas production function takes the following form:

$$Y_{it} = \alpha Kict_{it}^{\beta_1} Knict_{it}^{\beta_2} HighSkill_{it}^{\beta_3} LowSkill_{it}^{\beta_4} RM_{it}^{\beta_5} e^{v_{it}-u_{it}}$$

After taking the natural logarithm and adding a set of dummy variables the above equation becomes:

$$\ln(Y_{it}) = \beta_0 + \beta_1 \ln Kict_{it} + \beta_2 \ln Knict_{it} + \beta_3 \ln HighSkill_{it} + \beta_4 \ln LowSkill_{it} + \beta_5 \ln RM_{it} + \\ + \sum_{j=6}^{8} \beta_j * Pav_i + \sum_{t=9}^{12} \beta_t * D_t + + v_{it} - u_{it} \quad (1)$$

Where Y_{it} is the real output of the i^{th} firm at time t (*i=1,2,...,N* and *t=1,2,3,4*); *Kict* and *Knict* are, respectively, the ICT and non ICT capital, *HighSkill* and *LowSkill* are, respectively, the high-skilled and low-skilled labour, *RM* the raw materials and *Pav* and *D* are, respectively, the dummy variables for Pavitt sectors[1] and time period t[2]. Pavitt dummies are added because the estimation of the production function assumes that firms share a single technology, while we can fairly hypothesize that firms that operate in different sectors use different production technologies since they use ICT differently.

The random error v_i is assumed to be independent and identically distributed (i.i.d.) with zero mean and constant variance $N(0,\sigma_v^2)$, while the residual component u_i of technical inefficiency represents the effects of events incurred by the firm. This technical inefficiency is

[1] In the Pavitt taxonomy the sectors are classified in the following way: supplier dominated (Pavitt 1), scale intensive (Pavitt 2), specialised supplier (Pavitt 3), and science based (Pavitt 4). This taxonomy finds its roots in the sources of the innovation, in the needs of users and in the appropriability capacity present in each sectors. Even if it is very broad this taxonomy permits, nevertheless, to see the ways through which a firm, a region build their technological basis. In fact, each sector of region may adopt and use ICT in a different, idiosyncratic way (Ciarli and Rabellotti, 2007).

[2] The four periods are: 1995–1997, 1998–2000, 2001–2003 and 2004–2006.

assumed to be non-negative random variable of independently (but not identically distributed) truncated normal distributions. The underlying normal distribution is assumed to be $N(\mu_i, \sigma_\mu^2)$. The truncated normal distribution of u_i stipulates technical inefficiency be non-negative only and dependent on some firm-specific characteristics. TE is predicted using the conditional expectations of $\exp(-U_i)$, given the composed error term of the stochastic frontier.

Technical efficiency equals one only if a firm has an inefficiency effect equal to zero; otherwise it is less than one. If U_i is equal to zero, this means that there is no inefficiency in production, the firm is technically efficient and produces its maximum potential output. Conversely, when U_i takes values less than zero this implies that there is inefficiency in the firm's production and it produces less than its maximum possible output given the technology. The magnitude of U_i specifies the 'efficiency gap', that is how far a given firm's output is from its potential output. In order to compute TE it is, therefore, necessary to estimate potential output, which can be done by the econometric estimation of the production function stochastic frontier.

The Cobb-Douglas production frontier imposes some restrictions on the production function, such as fixed returns to scale and unitary elasticity of substitution. In order to test if the Cobb-Douglas production function is an adequate representation of the data we also estimate the Translog functional form.

The Translog stochastic production frontier with five inputs (ICT capital, non-ICT capital, high-skilled labour, low-skilled labour and raw materials) can be specified as:

$$\begin{aligned}\ln(Y_{it}) = \beta_0 + \sum_\gamma \beta_\gamma \ln X_{\gamma it} + \frac{1}{2}\sum_\gamma \beta_\gamma (\ln X_{\gamma it})^2 + \sum_{\gamma \neq h}\sum_h \beta_{\gamma h} \ln X_{\gamma it} \ln X_{hit} + \\ + \sum_\varphi \alpha_\varphi Pav_{\varphi i} + \sum_\eta \alpha_\eta D_{\eta t} + v_{it} - u_{it}\end{aligned} \tag{2}$$

In the inefficiency equation, in both cases (Cobb-Douglas and Translog production frontier), in addition to factors traditionally considered in the literature, we consider ICT investments at time *t, t-1* and *t-2*. Henceforth, the inefficient equation is specified as:

$$u_{it} = \alpha_0 + \delta_1 ICT_{i,t} + \delta_2 ICT_{i,t-1} + \delta_3 ICT_{i,t-2} + \sum_{\gamma} \delta_{\gamma} * \chi_{i,t} + \varepsilon_{it} \qquad (3)$$

where ICT is the investments in information and communication technology and $\chi_{i,t}$ is a vector of six additional explicative variables. *Age* indicates the age of the firm; *group* indicates a firm is affiliated to corporate firms; *size* is firm's size: *small* if the firm has 10-50 employees, *medium* if the firm has 51–250 employees; *large* if the firm has more than 250 employees; following common practice, we insert three dummies for the fourth Italian territorial *Area*; *Pav*, and *D* indicate, respectively, the dummy variables for Pavitt sectors and time.

Therefore, in this model, if the coefficient estimates for δ_1 is significantly negative, there is an empirical evidence to confirm that ICT has a favourable total effect on technical efficiency, while if δ_2 , and δ_3 are significantly negative, there is an empirical evidence of the relationship between ICT and TE also with lagged periods of time.

Shao and Lin (2001) pointed out the possible problem of spurious correlation since the ICT variable appears in the model twice (as capital and labour in the production frontier and as investments in the inefficiency equation). However, the only two sources of spurious correlation are a common trend present in both the dependent and one or more of the independent variables and the transformation of the mutually uncorrelated variables. Since these two cases are not present in our model spurious correlation does not apply.

5. Data and descriptive statistics

The empirical analysis is based on a large unbalanced (18,601 observations) and a balanced

(189 observations per survey) panel data sample of Italian manufacturing firms over the 1995–2006 period, constructed from the four consecutive waves of the 'Survey on Manufacturing Firms' conducted by Mediocredito-Capitalia-Unicredit[3].

The MCU surveys have been published every three years since 1968. The survey provides a great deal of information about production and financial indicators of Italian manufacturing firms. In the tenth (X) survey (2003–2006), the database considers a stratified sample of 5,137 firms, according to industry, geographical and dimensional distribution for firms from 11 to 500 employees. The survey is conducted by census for firms with more than 500 employees. The database contains information from questionnaires regarding the individual firm's structure and behaviour, three years of balance sheet data, additional data on employees, age of the firm, sales revenue, etc. Information related to ICT investments has been present since 1995, it is given on a three-year basis (1995–1997, 1998–2000, 2001–2003 and 2004–2006), while total annual investments are provided.

Table 1 summarizes the number of observations in the surveys and the number of firms that invested in ICTs. The seventh survey reports on 4,497 firms, the eight survey 4,680, while the ninth one 3,452 firms and 5,137 firms are present in the tenth survey. To merge the four different waves the variable "fiscal code" was used. The number of firms that are simultaneously present in all the four waves is 189. The definitions of the variables used are summarised in Table 2, while Table 3 reports some descriptive statistics of the main variables for the unbalanced panel.

In this analysis, the proxy used for the real output is the firms' sales proceeds. For the construction of ICT and non-ICT capital we have used three different methods, taking into account that the MCU surveys report the total ICT investments in the three years period and to check if the results are influenced by the applied method.

The first methodology is the perpetual inventory method (other works apply a similar

[3] The XI survey is also available. However, since this late survey has been re-modulated, there is not the firm code that permits to connect this survey with the previous ones.

methodology: e.g. Giuri et al., 2008). In order to construct the ICT capital stock, it was assumed that the ICT investments are distributed in a similar way as the total annual investments over the three years. For example, if the total investment for a firm is €30 million in 2004, €30 million in 2005 and €40 million in 2006, it is then assumed that the ICT investments are distributed in the same way, i.e., 30 percent is attributed to 2004, another 30 percent to 2005 and the final 40 percent to 2006. Then, to obtain the ICT capital stock, the perpetual inventory method was applied according to the following equation:

$$Kict_t = Iict_t + (1 - \delta)Kict_{t-1}$$

where δ is the investment depreciation rate and $Kict$ is the ICT capital stock at the end of the previous period. Following Oliner and Sichel (2000), it is assumed that δ is equal to 25 percent[4]. The first step is to divide the investment over twelve years, next the value from 1995-97 was converted into euro and all values deflated. In using the perpetual inventory method some assumptions on the initial value should be made. In the first case, it is assumed that the ICT capital in 1994 is equal to zero, consequently the ICT capital stock in 1995 is equal to the value of investment in the same period. In the second case, the same procedure as in Hall and Mairesse (1995) for the case of R&D capital stock construction was applied (hereafter we call this method HM). The benchmark for ICT capital stock at the beginning of the observation period (1995) is calculated as if it is the result of an infinite ICT investment series, with a fixed pre-sample growth rate g of 3 percent[5] and a depreciation rate δ of 25 percent, specified as the following:

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[4] Parisi et al. (2002) assume that the depreciation rate is equal to 15 percent but the estimated results are no different from the estimate with a depreciation rate equal to 25 percent.

[5] The growth rate of 3 percent is approximately the mean growth rate for the industrial investment during the period 1970-2007, as reported in the 2010 National Accounts of the National Institute of Statistics (ISTAT). We also apply a growth rate of 5 percent as suggested by Hall and Mairesse (1995) and the results are not significantly different (those results are available upon request).

$$Kict = \frac{ICT}{(g + \delta)}.$$

To calculate the ICT capital stock, using the second capital estimation methodology, some restrictions due to the data are taken into account. It is assumed that the ICT and non-ICT capital is distributed as the average of the same investments in the three years. In other words, if the total investment is composed of 30 percent of ICT and 70 percent of non-ICT, then the total capital is divided in the same percentage: 30 percent as proxy of ICT capital and 70 percent as proxy of non-ICT capital.

Finally, we apply the above Hall and Mairesse (1995) methodology to all periods, then the ICT capital is constructed for each year of observation. This methodology has the advantage to maintain all the observations (18,601) in the sample, giving us the possibility to introduce in the stochastic (in)efficiency determinants also the lags of ICT investments.

In the first and last method, the value of non-ICT capital stock of the firm is constructed by difference between total capital (fixed assets plus immaterial assets) and ICT capital.

The proxy for the high-skilled labour is the number of employees either with university education or with secondary high school education. For the low-skilled labour the number of employees with only primary education was used. The assumption for these proxies is that labour that use non-ICT technologies requires less education and more on the job training.

Finally, the sale revenues were deflated by the implicit price production deflators (year 2006=100) and capital, raw materials and the ICT investments were deflated by implicit investment deflator (year 2006=100).

6. Results and Discussion

In this section we first present the results of the Cobb-Douglas and Translog stochastic frontier estimations, then we examine the estimates of the frontier production functions with lags of ICT investments. Finally, we present the results of the effects of ICT on TE and its complementary factors. All the models are estimated by using the asymptotically efficient maximum likelihood method by FRONTIER 4.1[6].

The estimated results of the models specified in *equations 1–3,* are presented in Tables 4 and 5, respectively for the Cobb-Douglas and the Translog specification. Both models are estimated as a balanced panel data with 378 observations distributed over the two periods 2001–2003 and 2004–2006 (189 observations per year). The perpetual inventory method, with 25 percent rate of depreciation, applied to build the ICT capital, drastically reduces the number of observations to those of the last two surveys. The first two columns of Tables 4 and 5 present the results according to the two hypotheses for the initial value (set to zero in Model 1, and calculated as in HM in Model 2) that we have used to build the ICT capital. Model 3 displays the results for the unbalanced panel of 18,601 firms (observations) present in the four surveys, while the last two columns (Models 4 and 5) show the results for the balanced and unbalanced panel data constructed according to the HM methodology.

To test the first hypothesis, i.e. ICT capital and high-skilled labour as production factor in measuring TE, we need to use the factor elasticity. While the individual coefficients for the Cobb-Douglas model are elasticities and thus can be directly interpreted, in the case of the Translog model, the elasticities are functions of the parameters and the level of the explanatory variables, and thus the individual coefficients cannot be directly interpreted as elasticities.

[6] The FRONTIER 4.1 package uses the three steps estimation method procedure. These three steps provide a maximum likelihood estimate of the parameters of the stochastic frontier production function. The first step is an Ordinary Least Squares estimate of the function. Here all the estimators β, with the exception of the intercept β_0, are unbiased. At the second step a grid search on γ is conducted. The value for the parameters β (excepting β_0) are set to the OLS value, β_0 and σ^2 parameter are adjusted and all other parameters (μ,η and δ) are set to zero. At the last step the values in the grid search are used as starting values in an iterative procedure to obtain the maximum likelihood estimates.

Hence, for the case of the Translog model the elasticities are calculated by partial derivatives and are displayed in the same table[7].

In order to test if the Cobb-Douglas production function is an adequate representation of the data, given the specification of the Translog model, the likelihood ratio test was used. The purpose is to test the null hypothesis that the second order coefficients of the Translog frontier are simultaneously zero[8]. The null hypothesis that the Cobb-Douglas frontier is an adequate representation of the data is rejected in all models, given the specification of the Translog stochastic frontier. Then, using a likelihood ratio test, the Translog functional form is found to be a more appropriate fit for the data. For this reason we discuss in detail only the results of the estimations of the Translog production frontier.

The results of the test of the first hypothesis is presented in the upper part of Tables 4 and 5, while the test of the second hypothesis is presented in the lower part of the same table. The calculated elasticities are all positive, demonstrating that ICT capital and high-skilled labour positively contribute to increase the output as well as the other production factors. We found that the elasticities of ICT capital is higher compared to the non-ICT capital in Models 2 and 5, while it is lower in the other cases. On the other side, the elasticity of high-skilled labour, as expected, is always higher than that of the low-skilled labour, confirming that firms that have more educated workers increase their productivity more than firms where less educated workers prevail. In all the Models 1–5 the estimated elasticities are quite low. For example, in the case of balanced panel data (Model 1) the elasticities of ICT capital is equal to 0.10, the elasticities of the non-ICT capital is equal to 0.16, while 0.14 and 0.02 are, respectively, the elasticities of high-skilled and low skilled labour. These results are similar to other related papers. Bugamelli and Pagano (2004) found an elasticity of ICT capital equal to 0.04 and of other capital equal to 0.24. Shao and Lin (2001) found an elasticity of ICT investment equal to 0.05 and an elasticity

[7] The results for each parameter are available upon request.

[8] The value of the generalised likelihood-ratio statistics for testing the null hypothesis for the balanced panel data with the initial value set to zero (first column) is computed in the following way $LR = 2(353.72 + 492.62) = 1961.24$.

of capital equal to 0.23. These differences in ICT and non-ICT capital elasticity support the idea that ICTs have not yet fully influenced firms that still heavily rely on non-ICT capital.

The results of the test for the second hypothesis are reported in the lower part of Tables 4 and 5. The coefficient estimates for ICT investments, in both specifications (Cobb-Douglas and Translog), is always significantly negative with the exception of Model 1, which indicates that higher ICT investment reduces firm inefficiency.

Other control variables give the expected results. Older firms are significantly more efficient than the average. This also supports other findings (see Assefa and Matambalya, 2002) that firms become more efficient over time as a result of a growing stock of experience in the production process. Small and medium-sized firms present a differentiated performance according to the estimated results of the five models. In fact, in Models 1 and 2 that include the last two surveys observations the results show that small and medium firms have a higher efficiency with respect to large firms. However, when all the four surveys and observations are taken into account (as in Models 3-5) the small firms present a worse performance. This may be due to the fact that small firms adapted more recently to the new information technology paradigm than large firms. Firms affiliated to corporate firms and firms located in the North (north-east and north-west) and in the Centre are significantly more efficient than non-corporate and Southern firms. This is consistent with the results of Atzeni and Carboni (2001) and Becchetti et al. (2003). In other words, firms situated in the North or Centre of Italy, which are the more industrialised areas, are, on average, more efficient than firms situated in the South of Italy. Small and medium size firms and firms operating in the first three Pavitt sectors are significantly more efficient than large ones and firms operating in the fourth Pavitt sector. This may be attributed to the specific characteristics of the Italian manufacturing sector. In fact, almost all firms are of small-medium size and tend to be concentrated in the first Pavitt sector.

The test results of the third hypothesis, i.e. ICT investments also influence TE through its long-lasting impact, are presented in Table 6. To do this we estimated a frontier production function that includes lagged ICT investments related to $t-1$ and $t-2$, consequently the model collapse to a cross section using just the final period data (2004–2006).

Once again we analyse the Translog specification results as in the last two columns. Results show that current ICT investments positively influence firm efficiency, while, for what concerns the influence on efficiency of the last two periods lagged ICT variables, the better result is obtained in the last column specification where both lagged variables present a negative and significant coefficient, confirming that ICT investments contribute to reduce inefficiency over a long time-span. This result slightly contrasts with other works (Brynjolfsson and Hitt, 2000; David, 1990) which assert that ICT investments need a period of between three to ten years to show their full benefits.

As a robustness check we have estimated both the Cobb-Douglas and the Translog stochastic frontier using the third method to construct the ICT capital, based on Hall and Mairesse's (1995) methodology. By using this method we maintain all the observations (18,601) in the sample, giving us the possibility to introduce in the stochastic (in)efficiency determinants also the lags of ICT investments. However, due to the high correlation between current ICT investments and its lags, we introduce the variables one at a time into the inefficiency equation. Results are reported in Table 1A in the Appendix and confirm that current ICT investments and its two lags negatively influence firm technical inefficiency in the Italian manufacturing sector.

6.1 ICT investments and firm characteristics

In order to test our fourth hypothesis we investigate if ICT returns are influenced by new management practices and other firm characteristics. Assuming that there are some heterogeneous characteristics among firms, we try to identify some factors associated with either short or long time-span between ICT investments and firm efficiency.

To this aim we have used the last three surveys, otherwise we could not sub-divide the sample in two parts as below explained, since in the resulting sample some characteristics would not be present. The result is a sample of 1,772 observations for the last two surveys. Table 7 presents some additional results of our basic model according to four firm characteristics[9].

We have split the sample according to some firm characteristics that in our opinion are able to influence the performance of different vintages of ICT investments. In all the estimations the set of other control variables remains the same as before (age, corporate firm, size, area, and Pavitt). Considering that the input variables in the production function remain the same and do not show any differences, we report in the table only the δ parameters for the ICTs.

In particular, in columns 2 and 3 we split the sample into two parts. Column two considers firms with an entrepreneurial and organisational factor (*Eo*) equal to or greater than 1, while in column three it is less than 1. The entrepreneurial and organisational variable is constructed as the ratio between the sums of entrepreneurs, managers and line managers and of blue and white-collar employees. If a firm with an *Eo* ratio greater or equal to 1 receives greater ICT returns compared to another firm with a ratio less than 1, it means that ICT investments require also organisational changes, to better exploit the ICT benefits. Our results show that firms with an *Eo* greater than 1 present a better performance of current and previous period ICT investments, while investment of two periods before do not positively influence firm efficiency. On the other side, firms with a management factor less than 1 receive a strong return from current ICT investment, while previous periods investments have a negative (or no) influence on firm performance.

[9] The results of the all models (Tables 5 and 6) estimated according to this sample are available upon request.

The changes in the previous variable (*Eo*) may be due to management and labour reorganization that are required by new information technologies, that usually require more skilled managers and less blue collars. Much of the introduction of ICT's coincides with a less intensive labour organization that passes through a phase of firm restructuring and of workers' dismissal.

In the fourth and five columns of Table 7 we check the ICTs impact on the efficiency of firms that have or not dismissed workers in the last three years of our analysis (2004–2006). Results are controversial since current ICT investments decrease firm efficiency, while the two previous periods investments positively affect efficiency. The former result may be explained by the fact that the firm's restructuring phase is not yet completed. On the other side, firms that do not dismiss workers in the current period do not get positive returns to their efficiency.

In columns 6 and 7 we divide the sample between firms that do or do not invest in R&D, since we assume that these two types of firms present different returns of ICT investments. Column 6 shows that ICT associated with R&D investments produce a strong positive impact on firm efficiency, demonstrating that firms engaged in R&D strongly utilize all the three vintages of ICT investments. In contrast, firms that do not invest in R&D receive strong returns only from current period ICT investments.

In columns 8 and 9, of the same table, we control the ICT impact on firms that are engaged in international markets and firms that operate only in the domestic market. The current and previous period ICT investments strongly and positively affect the efficiency of the former firms, while the investments of the two periods before have no impact on firm efficiency, since international competition requires the use of updated ICTs. Conversely, firms that do not export (one-third of our sample) receive a higher impact on efficiency from the current and oldest ICT investments.

As a new robustness check we have estimated our fourth hypothesis also with the unbalanced panel of 18,601 observations. The results are presented in Table 2A in the appendix, and show that firms that have an entrepreneurial and organisational factor (*Eo*) equal to or greater than 1, that dismissed workers, that invests in R&D and that export reach an higher efficiency due to the impact of current and past ICT investments.

7. Conclusions

This paper analyses the impact of ICTs on Italian manufacturing firms, both on productivity and technical efficiency, using a stochastic frontier approach. The Mediocredito-Capitalia-Unicredit (MCU) dataset that we used permits us to merge four consecutive surveys over the years 1995–2006, obtaining a firm panel with 18,601 observations. Using this large dataset we contribute to the existing literature in different ways. As far as the functional form is concerned, both the Cobb-Douglas and the more flexible Translog production function frontier were tested, since the literature, which this work refers to, generally omits testing the suitability of the Cobb-Douglas specification. The results support our choice, since the Cobb-Douglas production function was rejected in all models.

Another step further along from the previous literature is to make a distinction between ICT and non-ICT capital in the stochastic frontier analysis together with high-skilled and low-skilled labour. In this respect we make a research advance. In fact, while the relationship between ICT investments and firm productivity is a straightforward extension of the basic model of the production function that includes ICT and skilled labour as separate types of capital and labour, the inclusion of ICT investments as an additional input that affects firm efficiency is a not a trivial research question. This inclusion has some implications that we have reassumed in four linked work hypotheses.

With the first hypothesis we test to what extend the ICT capital and high-skilled workers influence firm productivity. To this purpose we have used different methods to build the ICT capital. The results are not so univocal as expected. We found that the elasticities of ICT capital is higher compared to the non-ICT capital in two out of five estimated models, while it is lower in the other cases. On the other side, the elasticity of high-skilled labour, as expected, is always higher than that of the low-skilled labour, confirming that firms that have more educated workers increase their productivity more than firms where less educated workers prevail.

With the second hypothesis we test on which extend the ICT investments influence the distance of the firm from the production frontier; that is how ICT's adoption influence the closing of the firm efficiency gap. In this case the results are univocal since the estimated coefficients for ICT investments, in both specifications (Cobb-Douglas and Translog), is always significantly negative with the exception of one model, which indicates that higher ICT investment reduces firm inefficiency. Other control variables (firm age, corporate firm, firm size, territorial area, Pavitt sectors and time) in the technical efficiency estimations give the expected results.

Given the positive answer to the second hypothesis, the main question of the third one is quite straightforward: how long do the effects of ICT investments on technical efficiency last? Results confirm that current ICT investments positively influence firm efficiency, while for the influence on efficiency of the last two periods lagged ICT variables, the better result is obtained in the unbalanced panel HM specification where both lagged variables present a negative and significant coefficient, confirming that ICT investments contribute to reduce inefficiency over a long time-span. This result slightly contrasts with other works (Brynjolfsson and Hitt, 2000; David, 1990), which assert that ICT investments need a period of between three to ten years to show their full benefits.

Finally, we investigated if ICT returns on technical efficiency are influenced by some firm's characteristics, most of them idiosyncratic, such as management practices, labour re-organization, research and development and export. We found that the impact of ICTs reduces firm inefficiency for a long time-span after their adoption, demonstrating that when firms accompany ICT adoption with some management and organizational change, they can get larger returns from ICTs. We found that firms that started their adaptation to the information technologies through new management practices (augmenting the share of entrepreneurs and managers on labour and the workers dismissal), get larger ICT benefits for firms efficiency. With these results, we have also the indirect confirmation that the ICTs represent a technical progress that is simultaneously high skill-biased and labour saving. In addition, our results show that ICT investments associated with R&D investments produce a strong positive impact on firm efficiency, demonstrating that firms engaged in R&D strongly utilize all the three vintages of ICT investments. We also checked for the ICT impact on the efficiency of firms that are engaged in international markets and firms that operate only in the domestic market. The current and previous period ICT investments strongly and positively affect the efficiency of the former firms.

Finally, a word of caution should be spent on the obtained results. An endogeneity problem can arise due to the high correlation between ICT and TE. However, we could not test the simultaneity problem between ICTs and TE, because the stochastic frontier models estimated using the one-stage procedure to explain both productivity and (in)efficiency do not yet allow for checking the existence of endogeneity. Nevertheless, since in our model lagged ICT variables are introduced, we can interpret the introduction of these variables as an implicit test to control for endogeneity. This specification of the TE model confirms the existence of a significant relationship between ICT and technical efficiency. However, as De Vries and Koettler (2011) recall, "future research into more explicit methodological advances to control for endogenous factors" in the stochastic frontier approach is required.

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Table 1 - Firms in the MCU database

	Three year period 1995-1997	Three year period 1998-2000	Three year period 2001-2003	Three year period 2004-2006	All periods
Observations	4497	4680	3452	5137	189
Firms that invested in ICT	2984	3480	2111	1885	..
Firms that invested but did not show the amount	128	156	253	684	..
Firms that did not invest in ICT	975	851	591	1182	..
Firms that did not answer the question on ICT inv.	410	193	497	1386	..

Table 2 - Variables used in the analysis

Variables	*Description*
Sales revenue	Sales revenue
K	Capital (fixed assets + immaterial assets)
Kict	ICT capital
Knict	Non-ICT capital: (fixed assets + immaterial assets - Kict)
HighSkill	High-skilled Labour: number of employees with university education and high secondary school education
LowSkill	Low-skilled labour: number of employees with primary education.
ICT	Three year period ICT investments
Age	Firm's age
Group	Two dummy variables if the firm is affiliated to corporate firms
Size	Three dummy variables for firm size'. Small if the firm has 10–50 employees; medium if the firm has 51–250 employees; large if the firm has more than 250 employees
D_Area	Four dummy variables for the Italian macro areas: north-east, north-west, centre and south and islands
D_Pavitt	Four dummy variables for the sectors of activity of the firm, identified according to the Pavitt classification
D_year	Four dummy variables for time period
Eo	Entrepreneurial and organisational factor: (entrepreneurs+managers+line managers)/(white collar+blue collar)
Dismissed workers	Two dummy variables if firms dismiss or do not dismiss workers
R&D	Two dummy variables if firms invest or do not invest in research and development
Export	Two dummy variables if firms export or do not export

Table 3 - Descriptive statistics, unbalanced sample (1995-2006)

Variables	Obs	Mean	Std. Dev.	Min	Max
lnSales revenue	18601	10.71	3.44	0.00	22.32
lnKict	18601	3.53	4.42	-5.21	21.17
lnKnict	18601	3.88	4.62	-4.33	20.65
lnHighSkilled	18601	1.87	1.74	0.00	9.17
lnLowSkilled	18601	2.40	1.70	0.00	9.00
lnRM	18601	4.52	4.73	-2.77	19.25
lnICT	18601	3.08	3.89	-2.77	18.46
lnage	18601	2.92	0.90	0	7.60
D_group	18601	0.24	0.43	0	1
D_small	18601	0.66	0.47	0	1
D_medium	18601	0.25	0.43	0	1
D_area_1	18601	0.39	0.49	0	1
D_area_2	18601	0.29	0.45	0	1
D_area_3	18601	0.18	0.38	0	1
D_Pavitt_1	18601	0.49	0.50	0	1
D_Pavitt_2	18601	0.20	0.40	0	1
D_Pavitt_3	18601	0.26	0.44	0	1

Table 4:Cobb-Douglas panel frontier with ICT investments as a production factor

Variables/ Parameter	*Cobb-Douglas*				
	Model 1 Balanced PD Initial value zero	Model 2 Balanced PD HM initial value	Model 3 Unbalanced PD	Model 4 Balanced panel HM ICT capital	Model 5 Unbalanced panel HM ICT capital
Constant	10.396 (19.46)***	11.618 (83.43)***	9.155 (133.86)***	6.885 (3.55)***	8.188 (111.51)***
ICT capital	0.100 (4.90)***	0.036 (1.06)	0.018 (6.73)***	0.090 (5.69)***	0.068 (21.33)***
Non-ICT capital	0.124 (6.32)***	-1.045 (-26.89)***	0.025 (10.29)***	0.245 (6.46)***	0.089 (28.68)***
HighSkill	0.085 (1.50)	0.138 (2.18)**	0.154 (21.07)***	0.050 (0.96)	0.145 (20.97)***
LowSkill	-0.106 (-2.03)**	-0.124 (-1.93)*	-0.019 (-2.59)***	-0.023 (-4.90)***	-0.027 (-4.044)***
Raw materials	0.075 (3.51)***	0.014 (2.37)**	0.118 (47.71)***	0.083 (0.49)	0.094 (35.04)***
D_Pavitt_1	0.719 (1.45)	-0.001 (-0.10)	-0.84 (12.85)***	-1.567 (-0.128)	-0.780 (-13.16)***
D_Pavitt_2	1.215 (2.18)**	0.193 (33.08)***	-0.526 (-7.58)***	-1.170 (1.06)	-0.535 (-8.956)***
D_Pavitt_3	0.784 (1.65)*	-0.033 (1.55)	-0.767 (-11.69)***	-1.465 (-1.236)	-0.725 (-11.47)***
D_1995-1997			1.20 (33.52)***	0.320 (1.064)	1.877 (46.15)***
D_1998-2000	0.175 (0.65)	0.033 (1.59)	0.932 (28.84)***	2.284 (4.471)***	1.402 (37.89)***
D_2001-2003			8.235 (215.13)***	11.705 (18.52)***	8.752 (184.24)***
Technical Efficiency variables					
ICT Invest.	-0.071 (-1.96)***	-0.095 (-3.36)***	-0.498 (-23.22)***	-0.009 (-0.345)	-0.413 (-24.30)***
Age	0.046 (0.57)	-0.081 (-8.80)***	-1.559 (-20.77)***	-0.189 (-0.822)	-1.455 (-23.62)***
D_group	-0.391 (-2.62)***	-0.168 (-2.27)***	-5.247 (-26.37)***	-0.997 (-2.89)***	-5.019 (-37.79)***
D_small	2.317 (8.83)***	0.321 (3.59)***	3.611 (-19.72)***	4.579 (8.60)***	3.192 (17.38)***
D_medium	1.462 (6.01)***	0.008 (0.44)	-1.262 (-5.64)***	3.671 (7.35)***	-1.129 (6.878)***
D_area_1	-0.157 (-0.71)	0.074 (1.58)	-7.05 (-25.51)***	-0.687 (1.231)	-7.518 (-26.89)***
D_area_2	-0.128 (-0.59)	-0.338 (-6.98)***	-8.113 (-25.55)***	-0.784 (1.31)	-8.555 (-32.18)***
D_area_3	-0.017 (-0.07)	0.079 (5.45)***	-8.657 (-30.00)***	-0.588 (-1.153)	-9.038 (-31.23)***
D_Pavitt_1	0.632 (1.45)	0.364 (9.36)***	-12.02 (-27.85)***	-3.078 (4.009)***	-12.01 (-32.01)***
D_Pavitt_2	1.083 (2.17)***	-0.018 (-0.59)	-9.124 (-19.58)***	-2.216 (-3.144)***	-9.579 (-22.25)***
D_Pavitt_3	0.563 (1.22)	-0.083 (-3.18)***	-10.79 (-27.39)***	-3.103 (-4.473)****	-10.86 (-28.03)***
D_1995-1997	0.099 (0.32)	-3.450 (-10.04)***	-3.051 (-5.76)***	-0.178 (-0.146)	-3.459 (10.67)***
D_1998-2000			-2.830 (-6.07)***	-1.67 (-1.268)	-3.121 (11.71)***
D_2001-2003			15.257 (47.42)***	3.131 (4.259)	15.39 (53.84)***
Sigma-squared	0.791 (9.97)***	2.252 (20.67)***	22.19 (42.71)***	1.474 (3.384)***	21.60 (49.45)***
Mean Efficiency	0.603	0.767	0.503	0.532	0.512
Nr. of obs	378	378	18601	756	18601
Likelihood Ratio Tests					
Log Likelihood	-492.62	-134.697	-31587.24	-1054.7	-31201.95

t-statistics in parenthesis. Reference group: Pavitt 4 (science based), year 2004-2006 (latter wave pattern) and area 4 (South and Islands).
*Significant at 10%; **significant at 5% and ***significant at 1%.

Table 5: Translog panel frontier with ICT investments as a production factor

Variables/ Parameter	*Translog*				
	Model 1 Balanced PD Initial value zero	Model 2 Balanced PD HM initial value	Model 3 Unbalanced PD	Model 4 Balanced panel HM ICT capital	Model 5 Unbalanced panel HM ICT capital
Constant	9.006 (24.8)***	9.524 (46.23)***	8.989 (181.54)***	4.824 (13.62)***	8.319 (121.68)***
ICT capital	*0.101*	*0.544*	*0.016*	*0.077*	*0.116*
Non-ICT capital	*0.157*	*0.232*	*0.264*	*0.099*	*0.098*
HighSkill	*0.144*	*0.028*	*0.076*	*0.190*	*0.331*
LowSkill	*0.02*	*0.026*	*0.044*	*0.122*	*0.254*
Raw materials	*0.001*	*0.001*	*0.099*	*0.07*	*0.052*
D_Pavitt_1	0.203 (1.05)	0.025 (0.22)	-0.373 (-8.44)***	-0.187 (-0.915)	-0.368 (-7.600)
D_Pavitt_2	0.449 (2.16)**	0.122 (1.09)	-0.227 (-4.87)***	-0.004 (-0.021)	-0.255 (-4.998)***
D_Pavitt_3	0.488 (2.42)***	0.129 (1.12)	-0.356 (-7.81)***	-0.145 (-0.741)	-0.343 (-6.848)***
D_1995-1997	-0.012 (-0.12)		1.950 (52.67)***	2.27 (10.497)	2.596 (55.742)***
D_1998-2000		0.037 (0.74)	1.745 (51.79)***	4.597 (24.23)	2.353 (53.641)***
D_2001-2003			8.825 (237.13)***	11.29 (17.19)***	9.377 (193.31)***
Technical Efficiency variables					
ICT Invest.	0.039 (0.30)	-0.100 (2.26)**	-0.618 (39.95)***	0.066 (1.96)**	-0.552 (-27.12)***
Age	-1.578 (-4.11)***	-0.920 (-4.66)***	-1.769 (-30.63)***	-0.871 (-5.027)***	-1.705 (-31.35)***
D_group	-1.126 (-1.13)	-0.799 (-3.57)***	-3.891 (-15.53)***	-3.194 (-6.426)***	-3.779 (-21.93)***
D_small	-3.021 (-2.62)***	-3.279 (-6.57)***	0.615 (2.09)**	4.453 (10.24)***	0.170 (0.650)
D_medium	-4.698 (-4.16)***	-6.608 (-12.27)***	-2.559 (-9.69)***	-0.321 (-1.525)	-2.735 (-11.712)***
D_area_1	-1.348 (-0.76)	0.615 (1.77)*	-8.256 (-26.38)***	-2.107 (-4.180)***	-8.853 (-25.15)***
D_area_2	-1.060 (-0.65)	1.255 (2.89)***	-9.574 (-30.49)***	-2.957 (-5.786)***	-10.116 (-28.47)***
D_area_3	0.928 (0.59)	-0.527 (-1.84)*	-10.11 (-26.99)***	-2.679 (-4.274)***	-10.532 (-29.08)***
D_Pavitt_1	-7.676 (-4.23)***	-2.771(-4.96)***	-11.21 (-29.07)***	-4.965 (-6.767)***	-11.653 (-30.49)***
D_Pavitt_2	-0.241 (-0.17)	1-065 (1.80)*	-9.016 (-21.41)***	-2.719 (-3.673)***	-9.654(-23.52)***
D_Pavitt_3	0.882 (0.89)	-0.219 (-0.37)	-9.817 (-23.24)***	-5.064 (-7.409)***	-10.162 (-25.69)***
D_1995-1997	0.28 (0.38)	0.438 (1.92)*	-3.205 (-10-82)***	-0.313 (-0.900)	-1.727 (-8.320)***
D_1998-2000			-2.768 (-11.88)***	-0.418 (-1.548)	-1.634 (-8.179)***
D_2001-2003			15.695 (44.33)***	2.227 (5.052)***	16.744 (57.86)***
Sigma-squared	7.085 (4.00)***	2.700 (8.83)***	23.821 (55.99)***	3.540 (17.01)***	23.892 (44.23)***
Mean Efficiency	0.659	0.781	0.529	0.702	0.538
Nr. of obs	378	378	18601	756	18601
Likelihood Ratio Tests					
Log Likelihood	353.72	104.19	-28814.25	-827.63	-28459.89
Test Statistics	1691.24	477.77	5545.98	3764.66	5484.12
Degree of Freed.	15	15	15	15	15
Critical Value	24.99579	24.99579	24.99579	24.99579	24.99579
Results	Reject CD	Reject CD	Reject CD	Reject CD	Reject CD

Notes: The table displays the calculated elasticities for the translog production frontier. See, also, table 4.

Table 6: Panel frontier production function with lags of ICT investments

Variables/ Parameter	*Cobb-Douglas*		*Translog*	
	Cross-section Initial value zero	Cross-section HM initial value	Cross-section Initial value zero	Cross-section HM initial value
Constant	10.93 (51.02)***	10.087 (14.23)***	10.161 (14.68)***	9.243 (27.12)***
ICT capital	0.0193 (2.65)***	-0.40 (-0.78)	*0.243*	*0.071*
Non-ICT capital	0.17 (6.65)***	0.185 (5.67)***	*0.146*	*0.43*
HighSkill	0.022 (0.32)	0.098 (1.71)*	*0.119*	*0.095*
LowSkill	-0.025 (-0.423)	-0.120 (-2.37)**	*0.165*	*0.05*
Raw materials	0.056 (3.51)***	0.075 (4.25)***	*0.074*	*0.005*
D_Pavitt_1	3.515 (2.79)***	1.594 (2.33)**	-0.487 (-0.91)	0.181 (1.06)
D_Pavitt_2	2.89 (7.90)***	1.950 (1.91)*	1.542 (0.89)	0.076 (0.48)
D_Pavitt_3	1.344 (3.80)***	3.866 (0.20)	-0.555 (-1.02)	0.222 (1.37)
Technical Efficiency variables				
ICT Invest.	-0.064 (-1.69)*	-0.110 (4.11)***	-0.032 (-1.64)*	-0.033 (1.85)*
ICT Invest. (t-1)	-0.302 (-5.92)***	-0.035 (-1.05)	0.261 (4.21)**	-0.044 (-2.21)***
ICT Invest. (t-2)	0.049 (1.25)	0.030 (0.96)	-0.018 (-0.70)	-0.070 (-3.56)***
Age	0.135 (1.91)*	0.105 (1.11)	0.002 (0.03)	-0.070 (-1.15)
D_group	-0.356 (-2.16)**	-0.427 (-2.94)***	-0.405 (-3.09)***	-0.370 (-3.19)***
D_small	2.229 (9.29)**	1.985 (8.78)***	1.063 (4.04)***	-0.023 (-0.13)
D_medium	1.698 (10.55)	1.379 (6.72)***	0.700 (2.91)***	-0.143 (-0.87)***
D_area_1	0.03 (0.140)	-0.225 (-1.05)	-0.018 (-0.08)	-0.016 (-0.13)
D_area_2	-0.126 (-0.57)	-0.317 (-1.39)	-0.164 (0.74)	-0.044 (-0.33)
D_area_3	0.221 (0.930)	0.039 (0.16)	0.333 (1.46)	-0.030 (-0.22)
D_Pavitt_1	3.603 (4.41)***	1.577 (1.93)	-0.511 (-1.10)	0.526 (-1.75)*
D_Pavitt_2	2.763 (5.59)***	1.730 (1.81)*	1.452 (0.86)	0.202 (0.65)
D_Pavitt_3	1.25 (3.50)***	3.784 (0.20)	-0.533 (-1.09)	0.638 (2.13)**
Sigma-squared	0.481 (18.36)***	536.30 (9.46)***	0.256 (7.01)***	6.899 (6.94) ***
Mean Efficiency	0.501	0.702	0.570	0.796
Nr. of obs	189	189	189	189
Likelihood Ratio Tests				
Log Likelihood	-200.78	-208.85	124.08	12.31
Test Statistics			649.72	442.32
Degree of Freed.			15	15
Critical Value			24.99579	24.99579
Results			Reject CD	Reject CD

Notes: see tables 4 and 5.

Table 7: Complementarity of ICT investments

Variables	*Technical Efficiency variables*							
	EO>=01	*EO<01*	*Dismissed workers yes*	*Dismissed workers no*	*R&D yes*	*R&D no*	*Export yes*	*Export no*
ICT (t)	-0.442	-1.246	0.107	0.076	-0.346	-1.266	-1.038	-1.14
	-3.687***	-21.982***	3.032***	1.823*	-3.927***	-11.689***	-12.296***	-13.453***
ICT (t-1)	-0.975	0.114	-0.005	0.104	-0.658	0.111	-0.407	0.03
	-6.469***	2.660***	-0.016***	2.937***	-7.165***	1.697*	-4.908***	0.412
ICT (t-2)	0.326	-0.031	-0.052	-0.045	-0.149	0.111	0.183	-0.339
	5.432***	-0.768	-6.034***	-4.163***	-1.964**	1.07	1.206	-3.904***
Age	yes	yes	yes	yes	yes	yes	yes	yes
D_group	yes	yes	yes	yes	yes	yes	yes	yes
D_size	yes	yes	yes	yes	yes	yes	yes	yes
D_area	yes	yes	yes	yes	yes	yes	yes	yes
D_Pavitt	yes	yes	yes	yes	yes	yes	yes	yes
Sigma-squared	17.193	14.72	7.958	6.452	16.428	12.022	20.423	14.804
	5.883***	22.124***	16.84***	12.717***	7.487***	6.976***	16.308***	12.920***
Mean Efficiency	0.587	0.6	0.19	0.213	0.604	0.609	0.587	0.618
Nr. of obs	303	1357	1231	535	1100	608	1256	512

Notes: see table 4.

Appendix A

Table 1A: Robustness check on ICT lags

Variables	*Technical Efficiency variables*					
	Cobb-Douglas			*Translog*		
ICT Invest.	-0.413			-0.552		
	-24.30***			-27.12***		
ICT Invest. (t-1)		-0.401			-0.541	
		-22.74***			-24.99***	
ICT Invest. (t-2)			-0.420			-0.552
			24.39***			-31.29***
Sigma-squared	21.66	21.39	21.68	22.89	23.02	22.94
	49.45***	41.85***	42.34***	47.23***	53.22***	61.75***
Mean Efficiency	0.512	0.512	0.513	0.538	0.538	0.538
Nr. of obs	18601	18601	18601	18601	18601	18601
	Likelihood Ratio Tests					
Log Likelihood	-31201.95	-31201.95	-31201.95	-28459.89	-28459.89	-28459.89
Test Statistics				5484.12	5484.12	5484.12
Degree of				15	15	15
Critical Value				24.996	24.996	24.996
Results				Reject CD	Reject CD	Reject CD

Notes: see table 4.

Table 2A: Robustness check on complementarity of ICT investments

Variables	*Technical Efficiency variables*					
	EO>=1			*EO<1*		
ICT Invest.	-0.564			-0.357		
	-11.79***			-13.83***		
ICT Invest. (t-1)		-0.569			-0.367	
		-13.59***			-15.26***	
ICT Invest. (t-2)			-0.569			-0.366
			-13.88***			-14.50***
Sigma-squared	17.90	17.79	17.52	19.26	19.36	19.25
	18.84***	16.01***	18.77***	38.61***	44.43***	38.74***
Mean Efficiency	0.554	0.554	0.556	0.499	0.501	0.501
Nr. of obs	2884	2884	2884	14960	14960	14960
	Dismissed workers yes			*Dismissed workers no*		
ICT Invest.	-0.076			-0.03		
	-2.615***			-0.505		
ICT Invest. (t-1)		-0.073			-0.035	
		-2.003**			-0.560	
ICT Invest. (t-2)			-0.074			-0.015
			-2.521***			-0.279
Sigma-squared	97.68	10.33	10.33	17.34	17.21	17.19
	25.92***	30.84***	45.73***	25.06***	20.91***	24.60***
Mean Efficiency	0.616	0.615	0.615	0.588	0.590	0.588
Nr. of obs	10309	10309	10309	5121	5121	5121
	R&D yes			*R&D no*		
ICT Invest.	-0.645			-0.442		
	-24.66***			-17.61***		
ICT Invest. (t-1)		-0.646			-0.452	
		-25.58***			-17.69***	
ICT Invest. (t-2)			-0.645			-0.451
			-24.77***			-18.04***
Sigma-squared	17.87	17.81	17.75	24.82	24.72	24.96
	25.22***	25.38***	24.30***	43.62***	44.22***	41.82***
Mean Efficiency	0.566	0.566	0.566	0.542	0.545	0.543
Nr. of obs	6460	6460	6460	11650	11650	11650
	Export yes			*Export no*		
ICT Invest.	-0.537			-0.634		
	-27.87***			-18.39***		
ICT Invest. (t-1)		-0.539			-0.634	
		-27.95***			-18.30***	
ICT Invest. (t-2)			-0.535			-0.608
			29.06***			-18.00***
Sigma-squared	21.99	21.68	22.11	22.31	22.28	22.49
	38.87***	42.62***	41.46***	25.46***	25.99***	28.93***
Mean Efficiency	0.542	0.542	0.541	0.548	0.548	0.547
Nr. of obs	12675	12675	12675	5810	5810	5810
	All regressions					
Age	yes	yes	yes	yes	yes	yes
D_group	yes	yes	yes	yes	yes	yes
D_size	yes	yes	yes	yes	yes	yes
D_area	yes	yes	yes	yes	yes	yes
D_Pavitt	yes	yes	yes	yes	yes	yes

Notes: see table 4.

Figure 1: ICT Investments and Technical Efficiency