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Measuring ICT capital and estimating its impact on firm productivity

Manufacturing firms versus firms in Services

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Abstract

This paper provides a comparative analysis of the impacts of information and communication technology (ICT) on firm labour productivity among firms in Manufacturing and Services, as well as among firms in different service industries. For this purpose I use a rich employer–employee panel data set of Norwegian firms covering the period 2002–2006. The analytical framework is based on different specifications of the firm–level production function. The results are consistent with ICT having a positive impact on firm labour productivity. Accounting for labour heterogeneity, i.e., for different skills of the workers, provides evidence on complementarities between ICT and the use of high-skilled employees. The results also indicate considerable differences between firms in Manufacturing and Services and between firms in different service industries with respect to productivity effects of ICT, non–ICT and human capital and with respect to the gain of joint use of ICT and high-skilled workers.

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Summary in Norwegian

Informasjons- og kommunikasjonsteknologi (IKT) brukes stadig mer både i husholdninger, næringsliv og offentlig sektor. Utviklingen i IKT-sektoren og den omfattende utbredelsen av IKT-bruk i dagliglivet er en viktig kilde til mer effektive transaksjoner både i samfunnet generelt og i næringslivet spesielt. Mange har av den grunn hevdet at vi er inne i et viktig tidsskille i den økonomiske utviklingen, og det har vært trukket paralleller til tidligere teknologiske revolusjoner som utbredelsen av elektrisitet, forbrenningsmotoren og telekommunikasjon. Påstander om en omfattende digital revolusjon underbygges med at IKT er en gjennomgripende teknologi som øker produktiviteten i en rekke sektorer i økonomien. Automatisering i industrien og innføring av elektroniske tjenester i varehandel, bank- og forsikringssektoren er viktige eksempler på dette.

Det har blitt gjennomført flere empiriske studier på virksomhetsnivå for å avdekke mulige sammenhenger mellom total faktorproduktivitet (TFP) eller arbeidskraftsproduktivitet på den ene side og IKT-intensitet på den annen side (se, for eksempel, Black og Lynch, 2001, Bresnahan mfl., 2002, Brynjolfsson og Hitt, 2003, og Hempell, 2005). Disse studiene tyder på at IKT-investeringer bidrar til økt produktivitetsvekst dersom det utføres en rekke komplementære investeringer i tilknytning til IKT-investeringene (se OECD, 2003). Dette er især investeringer rettet mot organisasjonsmessige innovasjoner og prosessinnovasjoner, samt investeringer som bidrar til utvikling av nye produkter. Dessuten tyder disse studiene på at vellykket implementering av IKT i produksjonsprosessen forutsetter tilgang på høyt kvalifisert arbeidskraft.

Halvorsen (2006) som studerer produktivitetsutviklingen i norsk økonomi for perioden 1981-2003, finner at produktivitetsveksten i private tjenesteytende næringer var mye høyere på 1990-tallet enn på 1980-tallet (2,8 % mot 1,4 % i gjennomsnitt årlig vekst, henholdsvis). Mye av denne veksten stammet fra siste femårsperiode, med gjennomsnitt årlig vekst på 3,3 % for perioden 1996-2000. Den sterke veksten fortsatt i 2001-2003 (3,4 %). Gitt at teknologisk utvikling var en av de sentrale faktorene bak den beregnede TFP-veksten, gir disse tallene en støtte for velkjente oppfatninger om at moderne løsninger innenfor distribusjon og bruk av IKT på 1990-tallet aktivt har bidratt til å endre produksjonsprosessene og har ført til produktivitetsveksten i denne næringen.

Denne studien belyser hvilken effekt IKT-bruk har på arbeidsproduktivitet i norske foretak og hvorvidt denne effekten er komplementær med bruk av høyt kvalifisert arbeidskraft. Den inneholder en komparativ analyse av betydningen av IKT for produktiviteten i forskjellige næringer med et spesielt fokus på tjenesteytende næringer. Hovedfunnene kan sammenfattes som følger:

Det er en positiv sammenheng mellom IKT-bruk og produktivitet i næringslivet: I alle modellspesifikasjoner får jeg positiv og statistisk signifikant estimat for koeffisienten foran IKT-variabelen, noe som viser at IKT har positiv virkning på foretakenes arbeidsproduktivitet.

Tilgang på høyt kvalifisert arbeidskraft er viktig for vellykket bruk av IKT: Hva foretakene får ut av IKT-investeringer er sterkt knyttet til den arbeidskraften de har. Foretakene er avhengig av personale som kan bruke utstyret. Denne studien viser at det forekommer positive samspilleffekter mellom IKT-bruk og bruk av ansatte med høy utdannelse. Det eksisterer således en viktig forbindelse mellom IKT-bruk og humankapital.

Det er stor variasjon i virkninger for forskjellige næringer: Det er foretakene i *Forretningsmessig tjenesteyting og Varehandel* som viser seg å være mest kapitalintensive når det gjelder IKT-kapital i årene 2002-2006. Samtidig er den høyeste veksten i IKT-kapitaltjenester i samme periode observert for T*ransport og Hotell-*

og restaurant næringene. Disse tallene gir en støtte for konklusjonene i Halvorsen (2006). Effekten av IKT på foretakenes arbeidsproduktivitet viser seg å være høyere for foretakene i Tjenesteyting enn for foretakene i Industri. Den sterkeste effekten er observert for *Databehandlingsvirksomhet og Telekommunikasjon*. Deretter følger foretakene i *Varehandel, Transport og post og Konsulentvirksomhet*. Samspilleffekter mellom bruk av IKT kapital og bruk av ansatte med høy utdannelse viser seg imidlertid å være viktigere i Industri enn i Tjenesteyting.

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1. Introduction

Information and communication technology (ICT) is one of the most dynamic areas of investment as well as a very pervasive technology. The possible benefits of ICT use for a firm include among others savings of inputs, general cost reductions and greater flexibility of the production process. The use of ICT can lead to productivity gains both directly, e.g., through reduced production time, and indirectly, e.g., through improved communication possibilities among employees and reduced co-ordination costs. This technology may also stimulate the innovation activity in the firm leading to higher product quality and creating of new products. These innovation-enabling characteristics make ICT a potentially important driver of productivity growth (see, e.g., OECD, 2003).

One of the first attempts to estimate the role of IT assets on productivity at the firm-level was made by Brynjolfsson and Hitt (1995). Since then a broad variety of empirical studies has emerged exploring the impacts of ICT on the firm productivity[1]. Most of these studies employ a production function framework to estimate the elasticity of output with respect to ICT capital, controlling for the amount of other inputs. While, the quantitative results from these studies vary substantially, they all find evidence on positive impact of ICT on firm productivity. However, the data limitations in most of these studies have not allowed comparing the effect of ICT on productivity among different industrial sectors.[2]

The main aim of this paper is to explore the impacts of ICT on firm labour productivity and provide a comparative analysis of these impacts among different industries in Norway. The differences between firms in Manufacturing and Services, as well as differences between firms from different service sectors are the main focus of the current paper for three main reasons. First, ICT investments have been most intensive in the service sector (see, e.g., OECD, 2000a). Second, the service sector has experienced rapid changes over the last decades, especially in such industries as Retail trade, Wholesale trade and business–related services.[3] Finally, business–related services have been important drivers of economic growth over the last decades in industrialised countries (OECD, 2000b).

Both economic theory and empirical evidence suggest that there is a key link between the skill level of the workforce and economic performance.[4] Availability of skilled workforce is also important for the successful use of ICT (Bresnahan et al., 2002). The study on ICT and economic growth for 13 countries (see OECD, 2003) demonstrated that the use of ICT contributes to improved business performance, but only when it is complemented by other investments and actions at the firm level, such as changes in the organisation of work and changes in workers' skills (see also Caroli and Van Reenen, 1999 and Bresnahan et al., 2002). Hence, ignoring differences in workers' skills might lead to overstating the true impacts of ICT on production. This paper explores how accounting for heterogeneity in the workforce influences the relation between different inputs and firm productivity. Moreover, it explores the existence of complementarities between ICT and human capital in different industries.

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[1] See, for example, recent studies by Atrostic and Nguyen (2002), Biscourp et al. (2002), Black and Lynch (2001), Bresnahan et al. (2002), Brynjolfsson and Hitt (2003), Greenan et al. (2001), Hempell (2003, 2005).

[2] Today, most of the empirical studies are based on different survey data that often restrict conclusions to one of the sectors, e.g. Manufacturing or Services, or to the whole economy in general without sector specification.

[3] The study of productivity and wealth growth in Norway in 1981–2003 (see Halvorsen, 2006) documents the rapid labour productivity growth in the service sector at the end of 90th – beginning of new century (in average 3.3 % in 1996–2000 and 3.4 % in 2001–2003 against 1.4 % in the 80th). ICT use is mentioned as one of factors of such a rapid growth in the service sector.

[4] This idea was first formalised by Nelson and Phelps (1966), who showed that educated workers had a comparative advantage in innovation, imitation and implementation of new technologies.

For these purposes, I construct a measure of ICT capital and apply different quantitative approaches to the estimation of the firm–level production function using Norwegian unbalanced employer-employee panel data for the period 2002–2006. The ideal measure capturing the economic contribution of capital inputs in a production theory context is flow of capital services. Building this variable from raw data entails non–trivial assumptions regarding: the measurement of the investment flows in the different assets and the aggregation over vintages of a given type of asset. Since 2002, Statistics Norway has collected micro level information on investment expenditures on ICT, i.e., on purchased hardware and purchased and own account software. This type of information has the clear benefit of providing a direct measure of investment that can be quite easily used in a production function context. The existence of detailed information on ICT flows over consecutive time periods allows building measures of ICT stocks following the perpetual inventory method – PIM – (see, for example, Bloom et al., 2005 and Hempell, 2005). However, estimating capital stocks using PIM implies specific assumptions regarding the starting point of the PIM recursion and investment depreciation and growth rates that introduces a degree of measurement error in the estimates of stocks, especially when the time series is short.[5] This paper provides some discussion on different issues related to ICT capital construction.

Beyond analysing the methodological and empirical issues, the study also aims to present evidence on the so far hardly explored productivity impacts of ICT use on Norwegian businesses. The structure of the rest of the paper is as follows. Section 2 describes the modelling framework. Section 3 presents the data and provides some descriptive statistics on ICT measures. Section 4 presents the empirical results, and Section 5 concludes.

[5] This problem is partially offset for IT assets, as they typically have a very high depreciation rate (about 30 %).

2. Modelling framework

A natural starting point for the analysis is a productivity model that accounts for ICT capital. Following Hempell (2005), I use the traditional Cobb-Douglas production function with labour and two types of capital as inputs:

$$(1) \qquad Y_{it} = F(A_{it}, K_{it}, ICT_{it}, L_{it}) = A_{it} K_{it}^{\alpha_1} ICT_{it}^{\alpha_2} L_{it}^{\alpha_3} \quad .$$

Here Y_{it} is output of firm i in period t, measured as value added in constant prices[6], K_{it} and ICT_{it} are the corresponding amounts of conventional (non–ICT) and ICT capital inputs in constant prices, L_{it} is the labour input measured as man hours, and A_{it} is the technical level term. The parameters α_1, α_2 and α_3 correspond to output elasticities of two types of capital and labour. Taking logarithms on both sides of (1) yields:

$$(2) \qquad y_{it} = \beta_0 + \alpha_1 k_{it} + \alpha_2 ict_{it} + \alpha_3 l_{it} + \beta_1 X_{it} + v_i + \zeta_{it},$$

where the small letters denote the logarithm of the corresponding variables and the technical level term is expressed as:

$$\ln(A_{it}) = \beta_0 + \beta_1 X_{it} + v_i + \zeta_{it}.$$

Here X_{it} is a vector of different firm characteristics such as firm age, location and industry, and time dummies; β_1 is a vector with the corresponding coefficients; v_i is a firm–specific term that captures different non–observed time-invariant firm characteristics affecting productivity (i.e., management ability, organisational capital, etc.); and the error term ζ_{it}, which comprises measurement errors and firm–specific productivity shocks, is assumed to be white noise.[7]

Model (2) can be further extended in different ways. First, since one of the dimensions of the data is the time–series dimension, the error term ζ_{it} may be serially correlated, e.g.:

$$(3) \qquad \zeta_{it} = \rho \zeta_{i,t-1} + \varepsilon_{it},$$

where serial correlation is represented by an AR(1) process, $|\rho| < 1$, and ε_{it} are *i.i.d.* with mean 0 and variance σ_ε^2. This serial correlation may occur, if, for example, the effects from productivity shocks are only partially captured by industry and location control variables. For the estimation of equation (2) in this case, we need subtract $\rho y_{i,t-1}$ from both sides of (2):

[6] Some studies use gross output or total sales as the measure of output. The main reason for using of value added and not gross production as the measure of output is that many firms in the population under study belong to Wholesale trade and Retail trade. For these industries the data on intermediate inputs consist of a very large part of purchases of trading goods that makes these data incomparable with the intermediate inputs of other industries. When using value added instead of gross production the intermediates do not have to be included in the production function.

[7] This model can be easily transformed such that labour productivity is the dependent variable. If we subtract l from both sides of (2) we get: $y_{it} - l_{it} = \beta_0 + \alpha_1(k_{it} - l_{it}) + \alpha_2(ict_{it} - l_{it}) + (\alpha_1 + \alpha_2 + \alpha_3 - 1) l_{it} + \beta_1 X_{it} + v_i + \zeta_{it}$. I will use the main specification for the estimation, i.e., model (2).

(2a)
$$y_{it} - \rho y_{i,t-1} = \beta_0(1-\rho) + \alpha_1(k_{it} - \rho k_{i,t-1}) + \alpha_2(ict_{it} - \rho ict_{i,t-1}) + \alpha_3(l_{it} - \rho l_{i,t-1}) + \beta_1(X_{it} - \rho X_{i,t-1}) + \nu_i(1-\rho) + \varepsilon_{it},$$

then we get the model with an *i.i.d.* error term.[8]

Another extension of model (2) allows for heterogeneous labour input. Both economic theory and empirical evidence suggest that there is a key link between the skill level of the workforce and economic performance. Hence, omitting heterogeneity in the quality of labour may lead to overstating the productivity of ICT capital. To account for this bias, I decompose a firm's workforce into employees who are high-skilled (with at least 13 years of education[9]) and low skilled (with less than 13 years of education). Letting N_h and N_l denote the corresponding amounts of man hours (with total amount of man hours $N= N_h +N_l$) and θ denote the productivity differential of high-skilled workers compared to low skilled workers, effective labour input L_{it} is specified as:

(4)
$$L_{it} = N_{l,it} + (1+\theta)N_{h,it} = N_{it}(1+\theta h_{it}).$$

Here $h_{it} = N_{h,it} / N_{it}$ denotes the share of hours worked by high-skilled workers in the firm. Taking logarithm of (4) and inserting it in (2) yields:

(2b)
$$y_{it} = \beta_0 + \alpha_1 k_{it} + \alpha_2 ict_{it} + \alpha_3 n_{it} + \alpha_4 h_{it} + \beta_1 X_{it} + \nu_i + \zeta_{it},$$

where the approximation follows from $\ln(1+\theta h_{it}) \approx \theta h_{it}$ and $\alpha_4 = \alpha_3\theta$.[10] The inclusion of skill–shares in the production function estimations as in (2b) in order to control for heterogeneity of labour quality is a very common approach in the literature (see, for example, Lehr and Lichtenberg, 1999, Caroli and Reenen, 2001, Bresnahan et al., 2002, and Hempell, 2005).

Several recent studies claim that differences in the skills of the workforce are also important for the usage of ICT capital. For example, the study on ICT and Economic Growth for 13 countries (see OECD, 2003) demonstrated that the use of ICT contributes to improved business performance, but only when it is complemented by other investments and actions at the firm level, such as changes in the organisation of work and changes in workers' skills (see also Caroli and Van Reenen, 1999 and Bresnahan et al., 2002). To test for complementarity between ICT capital and skill composition in the firm the model (2b) can be extended in the following way:

(2c)
$$y_{it} = \beta_0 + \alpha_1 k_{it} + \alpha_2 ict_{it} + \alpha_3 n_{it} + \alpha_4 h_{it} + \alpha_5 ict_{it} \times h_{it} + \beta_1 X_{it} + \nu_i + \zeta_{it}.$$

If the coefficient of the interaction term $ict \times h$ is positive then we can conclude that the intensity of ICT use and skills are complements and that productivity of ICT is increasing with the share of highly educated employees.

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[8] This transformation decreases the sample size for each observational unit by one. Because the observation period is short (the span is only 5 years), for the estimation of this model I use the Prais–Winsten (PW) method, which allows keeping the original sample size (for the panel data version of the PW transformation see Baltagi and Li, 1991).

[9] This number of years of education corresponds to completed high school or vocational training.

[10] The first–order Taylor approximation is quite accurate if the value of θ and h are not too large. Anticipating some of the results and applying mean shares for h, the implicit product θh=0.05 is small enough (for values <0.1 the absolute error of the approximation is less than 0.005 or half a percentage point).

3. Variables construction and descriptive statistics

3.1. Data sources and variables

For the analysis, I have constructed unbalanced panels of annual firm-level data for Norwegian firms, covering the period 2002–2006. The base for the sample is the structural statistics, which are data collected by Statistics Norway. Since 2002 these data comprise information on annual investments in hardware (purchased) and software (both purchased an own account). I use this information for the construction of ICT capital. By supplementing these data with information from the accounts statistics, the Register of Employers and Employees (REE) and the National Education Database (NED), I also obtain information on output, capital and labour inputs and skill composition in the firms. Table 3.1 presents an overview of the main variables and the data sources applied in the study. A more detailed description of these data sources is provided in Appendix A.

The logarithm of value added, y, is defined as the logarithm of operating revenues minus operating expenses plus wage bills. The variable k is the logarithm of capital services, which are calculated based on the book values of a firm's tangible assets.[11] These two variables were deflated by CPI. The variable *ict* is the logarithm of ICT capital services, which are calculated from the information on the firm investments in hard- and software (the construction of ICT capital is described in detail in the next sub-section).[12] The logarithm of man hours, l, is the logarithm of the sum of all individually contracted man hours worked by employees. The variable h is the share of total number of man hours worked by high-skilled workers in the firm (high-skilled workers are those who have post-secondary education, i.e., persons who have studied for at least 13 years).

Table 3.1. Overview of variables and data sources

Variable	Interpretation	Data source(s)
Y	value added[a]	accounts statistics
K	non–ICT capital services[a,b]	accounts statistics
ICT	ICT capital services[a,b]	structural statistics
L	man hours[c]	REE
h	share of man hours worked by high-skilled employees[c]	REE, NED
Derived variables:		
y	log of value added	
k	log of capital services	
ict	log of ICT capital services	
l	log of man hours	

[a] The units of measurement are NOK in 2001 prices.
[b] The variable is measured at the beginning of the year.
[c] Man hours according to labour contracts.

3.2. Construction of ICT capital

Since 2002, Statistics Norway has collected micro level information on investment expenditures on ICT, i.e., on purchased hardware, I_{1t}, and purchased and own account software, I_{2t} and I_{3t}, respectively. As deflators for obtaining real expenditures I use the National Account price indices of corresponding investments (all

[11] All assets have been divided into two types: equipments (denoted by the superscript e) which include machinery, vehicles, tools, and transport equipments; and buildings and land (denoted by the superscript b). Then capital services $K_t = \sum_{j=e,b} (r+\delta_j)K_{jt}$, where the depreciation rates, δ_j , are 20% for equipment and 5% for buildings: see Raknerud et al. (2007). The real rate of return, r , which is calculated from the average real return on 10-year government bonds for the period 2002–2006, is 4.7% (based on the numbers from Norges Bank).

[12] It is impossible to separate completely the ICT capital services from other capital services, i.e. ICT can be a part of machinery in K_e. However, I used total expenditures on ICT for calculating the ICT capital stocks and not only the activated part of these expenditures that are reflected in the book values K_e. For example, in 2004 firms had only activated, in average, about 36% of expenditures on hardware, 31% on purchased software and 26% on own account software.

expenditures are recalculated in the 2001 prices). Further, I construct the capital stocks for each type of asset separately and then aggregate them to a total ICT capital stock.[13] Since there are time lags between the installation and the productive contribution of capital goods, I employ the capital stock at the beginning of (or at the end of the previous period) as a measure of capital input.

The (real) ICT capital stock of type *k* at the beginning of a given year *t*, ICT_{kt}, is computed by the perpetual inventory method using a constant rate of depreciation That is:

(5) $$ICT_{kt} = (1-\delta_k)ICT_{k,t-1} + I_{k,t-1},\ k = 1,2,3 \text{ and } t = 1,2,...,$$

with *k=1* for hardware, *k=2* purchased software and *k=3* for own account software capital and investments; and δ_k denoting the depreciation rate of the corresponding capital asset. Relying on available data on depreciation rates for IT–hardware and software capital from the U.S. (Fraumeni, 1997, Moulton et al., 1999), I use depreciation rates of 31.2% for IT–hardware, 55.0% for purchased software and 33.0% for own–account software.[14]

Following Hall and Mairesse (1995), the benchmark for ICT capital stock of type *k* at the beginning of the observation period for a given firm, ICT_{k1}, is calculated as if it was the result of an infinite ICT investment series, ICT_{kt}, *t=0,-1,-2,…* , with a fixed pre-sample growth rate g_k. That is:

(6)

$$ICT_{k1} = I^*_{k0} + (1-\delta_k)I^*_{k,-1} + (1-\delta_k)^2 I^*_{k,-2} + ... = \sum_{s=0}^{\infty} I^*_{ks}(1-\delta_k)^s$$
$$= I^*_{k0}\sum_{s=0}^{\infty}\left[\frac{1-\delta_k}{1+g_k}\right]^s = \frac{I^*_{k1}}{g_k+\delta_k}, with\quad I^*_{kt} = I^*_{k,t+1}/(1+g_k), t = 0,-1,-2,...,$$

(cf. equation (5) in Hall and Mairesse, 1995, which refer to construction of R&D capital stocks with a similar methodological problem).

Hall and Mairesse (1995) use the estimator $I^*_{k1} = I_{k1}$, i.e., the value of investment in asset type *k* in the first observed period. This estimator is, however, very vulnerable to measurement errors and can differ a lot from the more usual rate of investments in the firm. I instead apply a more robust estimator by setting the initial value equal to the firm's average investment value over the whole observation period:

$$I^*_{k1} = 1/T\sum_{t=1}^{T} I_{kt}\ .$$

Here *T* is the number of observations for the given firm, whereas the summation is over all *t* where data are available. This "smoothed" estimator is obviously less influenced by the volatility in the observed investment series.

[13] In most of the studies that use ICT capital the aggregation procedure is the opposite, i.e., one aggregates first over the investments in different types of assets and then construct the total ICT capital stocks (for example, see Hempell, 2005). One then, implicitly, makes an assumption of equal depreciation rates across different types of assets. Usage of this approach may potentially increase a degree of measurement error in the estimates.

[14] Some studies simply use the depreciation rate of 36% for all types of ICT assets. This value of depreciation rate reflects an average service life of 4–5 years (for example, see Eurostat, 2008). Usage of this depreciation rate for all given types of assets will be used as a simpler alternative for ICT capital stocks estimation in the sensitivity analysis in Appendix B.

Another important issue for deriving of the initial capital stocks is the assumptions about the pre-sample growth rates g_k for given types of investments. Since there are no time series available for ICT investments in Norway until 2002, I construct g_k from all available data for 2002–2006.[15] I then obtain the average annual growth rate of 24.4% for real hardware investment, of 7.9% for real purchased software capital and of 26.2% for own account software capital and apply these rates for the initial capital stock calculations.[16]

The total ICT capital services can then be calculated as:

$$ICT_t = \sum_{k=1,2,3} (r + \delta_k) ICT_{kt} \ ,$$

where the depreciation rates, δ_k , are 31.2% for IT–hardware, 55.0% for purchased software and 33.0% for own–account software, and the real rate of return, r, is 4.7% (the average real return on 10-year government bonds for the period 2002–2006).

Some firms reported a zero investment expenditures on all types of ICT assets for the whole observed period (about 13% of the firms). With the econometric specification being in logs, these firms are excluded from the empirical analysis. However, excluding these firms might lead to overstating the real output contributions of ICT. To include them in the analysis I assume the ICT stock per man hour in firms that reported zero ICT investment to be equal to the corresponding industry minimum and impute the corresponding values.

3.3. Descriptive statistics

For the years 2002–2006 I have 135848 joint-stock companies (“population”) for which total ICT capital services, i.e., hardware, purchased and own account software, other capital services and value added can be constructed. However, only half of firms were retained after merging these data with information on labour inputs in man hours and share of high-skilled workers from REE. After some data trimming the resulting unbalanced sample (‘‘full sample’’) consists of 65559 firms with a total of 210736 observations. This sample consists of firms in Mining and quarrying, Manufacturing, Construction and Services.[17] I also provide separate estimations for the Manufacturing and Service industries. The sample of firms in Manufacturing consists of 3727 firms with 14038 observations. The sample of firms in Services consists of 51816 firms with 160512 observations. These samples represent approximately 84, 88 and 81% of total man hours in the population of all joint-stock companies, all joint-stock companies in Manufacturing and all joint-stock companies in Services, respectively (the corresponding numbers based on value added are 73, 88 and 66 %).

[15] I use all available data on the firm’s ICT investments from the structural statistics in 2002–2006. Although the sample I analyze in this paper is restricted to joint-stock companies (for which the accounts statistics are available), I also utilize the out-of-sample data to calculate the total amount of ICT investments in the economy and derive the corresponding annual growth rates.

[16] Compared to well–documented U.S. data these rates are somewhat lower. Jorgenson and Stiroh (1995) calculate an average annual growth rate of 44.3% for real computer investment and of 20.2% for OCAM (office, computing, and accounting machinery) investment between 1958 and 1992 for the U.S.

[17] For industry classification I use SN2002, i.e., Mining and quarrying (NACE 10-14), Manufacturing (NACE 15-37), Construction (NACE 45), Services include Retail trade (NACE 50, 52), Wholesale trade (NACE 51), Restaurant and hotels (NACE 55), Transport and post (NACE 60-63, 64.1) and Business–related services (NACE 70-74, 64.2).

Table 3.2. Summary statistics for the different samples

					Percentiles			Per man hour	
Variable	Mean	Std. dev.	Min	Max	10%	50%	90%	Mean	Median
Full sample (210736 obs. for 65559 firms)									
Value added[a]	8294	59400	8.7	7150000	465	2017	12200	231.5	196.3
Non–ICT cap. Services[a]	871	13700	<0.1	1860000	7.4	77	808	29.0	6.9
ICT cap. Services[a]	139	1649	0	423000	<0.1	13	194	3.6	1.2
No. of employees	20	138	1	21869	2	7	29		
Share of high-skilled	21.4	29.3	0	100	0	8.2	71.2		
Manufacturing (14038 obs. for 3727 firms)									
Value added[a]	34600	143000	50.3	5580000	2715	9540	55900	226.6	204.2
Non–ICT cap. Services[a]	5320	41000	0.5	1860000	59.3	547	6268	24.3	12.0
ICT cap. Services[a]	322	1291	0	48200	2.6	49	628	1.9	1.0
No. of employees	66	193	1	5640	10	24	121		
Share of high-skilled	14.2	15.7	0	100	0	9.8	33.4		
Services[b] (160512 obs. for 51816 firms)									
Value added[a]	6469	49700	8.7	7150000	435	1743	9366	236.1	196.4
Non–ICT cap. Services[a]	607	9857	<0.1	1110000	6.4	65	629	32.8	6.6
ICT cap. Services[a]	143	1814	0	423000	0	12	197	4.2	1.4
No. of employees	17	142	1	21869	2	6	24		
Share of high-skilled	25.4	31.4	0	100	0	11.9	79.7		

[a] Measured in NOK thousands, except for values per man hour that are measured in NOK per man hour (all in 2001 prices).
[b] Services include Retail trade (NACE 50, 52), Wholesale trade (NACE 51), Restaurant and hotels (NACE 55), Transport and post (NACE 60-63, 64.1) and Business–related services (NACE 70-74, 64.2).

Table 3.2 reports summary statistics for the constructed capital services and other key variables for the defined samples (the corresponding values are reported in NOK thousands in 2001 prices). The majority of firms in the full sample are small firms with a median of 7 employees. Only about 6% of the sample consists of medium–sized and large firms with more than 50 employees.[18] The value added of the median firm in the full sample is about NOK 2017000. Its capital services are about NOK 76700 for non–ICT and about NOK 12900 for ICT. Only 8.2 % of employees in the median firm in the full sample are high-skilled. The last two columns of Table 3.2 report the mean and median of the firms' capital and output intensity for the given sample (the corresponding values are measured in NOK per man hour). If we take into account that one man year is 2086 man hours (as reported in REE for full-time full-year employee), then we can recalculate these measures in "full-time employee" terms. We then get that at the median firm, a workplace (one full-time employee) produces approximately NOK 409440 as value added during one year and that the value of the capital services for one workplace in one year is about NOK 14414 for non–ICT and about NOK 2503 for ICT capital.

The structure of the two other samples differs from the full sample. The firms in Manufacturing are significantly larger both in terms of employees and value added and have also a higher capital services level for both types of capital. The firms in Services are in contrary smaller than firms in the full sample. However, the latter are more output and capital intensive (see the last two columns in Table 3.2) and have much higher share of high-skilled employees compared to the firms in full sample and especially compared to the firms in Manufacturing.

Table 3.3 shows selected descriptive statistics for the constructed ICT capital services. The share of ICT capital services in total capital services (calculated on the basis of the totals) increased from 10.4 % in 2002 to 16.9 % in 2006 with an average share being about 14.4 % in this period. That is the result of more rapid increase in the ICT capital services than in non–ICT capital services. While an average annualized growth of ICT capital services was about 18.9 % in 2002–2006, the other capital services increased in average by only 3 % during the same period. These shares and growth rates differ a lot among industries. The highest shares of ICT capital services in the total capital services are observed in Business–related

[18] Because the majority of firms are small, the median firm is more representative for the given distribution of firms and hence used for the further description.

services (NACE 70-74, 64.2), Wholesale trade (NACE 51) and Retail trade (NACE 50, 52), and the lowest are observed in Manufacturing (NACE 15-37). While the highest growth in the ICT capital services over 2002–2006 is observed in Transport and post (NACE 60-63, 64.1) and Restaurants and hotels (NACE 55), the highest growth in the other capital services occurred in Business–related services (NACE 70-74, 64.2) and Transport and post (NACE 60-63, 64.1).

Table 3.3. Descriptive statistics on ICT and other capital inputs (%), 2002–2006[a]

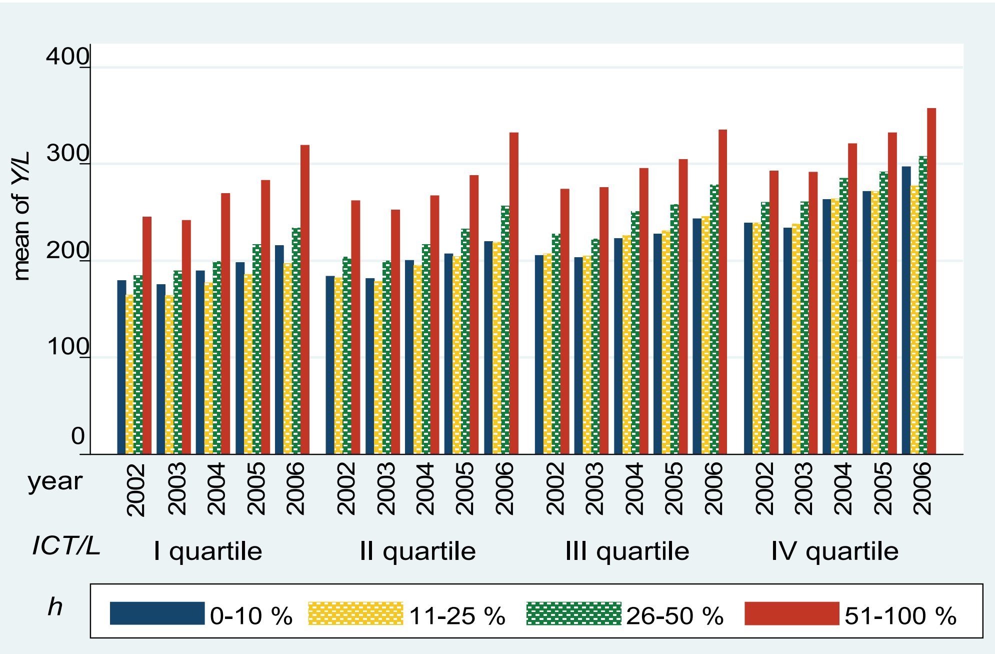
Industry (NACE digit)	Share of ICT capital services in total capital services, *ICT/(ICT+K)*						Average annualized growth	
	2002	2003	2004	2005	2006	Mean	*ICT*	*K*
All industries (full sample)	10.4	12.2	12.9	15.5	16.9	14.4	18.9	3.0
Manufacturing (15-37)	4.9	5.0	5.7	6.1	6.8	5.7	11.4	2.3
Retail trade (50, 52)	14.2	15.7	16.7	19.3	21.2	17.4	15.9	2.5
Wholesale trade (51)	20.3	24.3	26.2	30.7	32.4	26.8	18.2	0.4
Restaurants and hotels (55)	5.0	5.8	5.5	9.1	10.6	7.2	30.3	1.8
Transport and post (60-63,64.1)	4.0	8.4	7.9	11.0	10.7	8.4	45.9	4.5
Business–related services(70-74,64.2)	25.3	26.6	27.8	32.1	35.2	29.4	17.9	5.0

[a] Calculated on the basis of totals

The observed shares of aggregate ICT capital services in total aggregate capital services are higher than, for example, those calculated by Hempell (2005) for service industries in Germany in 1994–2000 (about 5%) and by Eurostat (2008) for different industries in Netherland and UK in 2002–2005 (vary between 4% and 11% for Netherlands and between 1% and 5.5% for UK). Both studies mention the measurement errors and in the case of UK the underreporting as a possible explanation for large variations in the shares of ICT capital in total capital. In the empirical application, controlling for measurement errors will therefore be an important issue.

Figure 3.1 shows the level of labour productivity in 2002–2006 for different groups of firms, where the firms are sorted by ICT capital intensity (ICT capital services per man hour) from the lowest to the highest and by share of high educated employees. We can see that the level of labour productivity is increasing over time in each group of firms. Besides, the labour productivity is higher for the firms with larger share of high educated employees and with higher intensity of ICT capital.

Figure 3.1. Labour productivity[a] in 2002–2006 by ICT capital intensity (quartiles) and share of employees with high education (%)



[a] Value added per man hour in 2001 prices

4. Empirical results

Table 4.1 presents the results from estimation of the reference model (2) for the three samples, i.e., full sample, sample of firms in Manufacturing and sample of firms in Services. First, this model is estimated by a simple pooled OLS regression (see column (1) in Table 4.1 for the corresponding sample), and then in order to take into account random unobserved firm characteristics, by GLS (see column (2) in Table 4.1 for the corresponding sample). The table focuses on the most important explanatory variables. It does not report results for control variables such as firm age, location and industry. However, most estimates associated with these variables are significant.[19]

Columns (1) of Table 4.1 show results from estimation of eq. (2) by OLS for the three defined samples. The estimates of both types of capital services, *k* and *ict*, and labour inputs, *l*, are positive and highly significant. Given the average shares of ICT and non–ICT capital services in value added of 1.6 % and 12.0 %, respectively, the results for the full sample imply a gross rate of return to ICT investment of nearly 146 % and to non–ICT investment of nearly 51 %.[20] The estimates of both types of capital for Services are significantly higher than those for Manufacturing. The estimated coefficients of time dummies pick up the general growth in the firms' productivity in 2002–2006 with a small break in 2003. The estimated return to scale is very close to 1. However, the hypothesis of constant return to scale is rejected with level of significance lower than 1 % for all three samples.

Table 4.1. Results for the ICT-augmented production function

	Full sample		Manufacturing		Services	
Variable	(1) OLS	(2) GLS	(1) OLS	(2) GLS	(1) OLS	(2) GLS
Log(non–ICT), *k*	0.061	0.039	0.054	0.031	0.068	0.042
	[87.85]**	[44.96]**	[20.80]**	[9.32]**	[80.75]**	[40.99]**
Log(ICT), *ict*	0.024	0.033	0.016	0.018	0.023	0.034
	[64.38]**	[58.91]**	[11.96]**	[9.30]**	[52.39]**	[51.65]**
Log(labour), *l*	0.916	0.852	0.954	0.950	0.905	0.833
	[774.95]**	[502.92]**	[208.67]**	[150.21]**	[649.16]**	[418.77]**
2003	-0.019	-0.026	-0.007	-0.009	-0.021	-0.030
	[5.78]**	[12.83]**	[0.71]	[1.45]	[5.28]**	[12.51]**
2004	0.059	0.045	0.078	0.071	0.057	0.038
	[18.03]**	[21.58]**	[7.75]**	[11.50]**	[14.48]**	[15.45]**
2005	0.088	0.067	0.130	0.116	0.084	0.058
	[26.90]**	[30.62]**	[13.07]**	[18.38]**	[21.52]**	[22.41]**
2006	0.155	0.125	0.180	0.171	0.152	0.115
	[46.95]**	[54.86]**	[17.86]**	[25.96]**	[38.49]**	[42.71]**
Constant	5.290	6.021	4.742	5.084	5.017	5.890
	[490.17]**	[362.66]**	[127.37]**	[84.21]**	[377.93]**	[290.48]**
RS, $\alpha_1+\alpha_2+\alpha_3$	1.001	0.924	1.024	0.999	0.996	0.909
H_0: CRS	no	no	no	yes	no	no
No. of obs.	210736	210736	14038	14038	160512	160512
No. of firms	65559	65559	3727	3727	51816	51816
R-squared	0.88	0.88	0.92	0.93	0.85	0.85

Absolute value of t-statistics in brackets. * significant at 5%, ** significant at 1%. Firm age, location and industry dummies are included in the analyses but results for these variables are not reported here.

[19] The full set of results is available upon request.

[20] The marginal returns to the given type of capital (*MPI*) are just the product of the output elasticity of this type of capital and the inverse ratio of this type of capital in output. For example for ICT capital: $MPI_{it} = \partial Y_{it} / \partial ICT_{it} = \alpha_2 \cdot Y_{it} / ICT_{it}$.

The columns (2) of Table 4.1 show results from estimation of eq. (2) by GLS, which takes into account the unobserved firm characteristics by including random firm-specific effects.[21] The figures indicate that once unobserved firm characteristics are controlled for, the output contribution of labour inputs and non–ICT capital services become lower with contribution of ICT capital services becoming higher. However, for all defined samples the relative effect of ICT capital for labour productivity is still lower than that one of non–ICT capital.[22] The results for the full sample now imply a gross rate of return to ICT investment of nearly 201 % and to non–ICT investment of nearly 33 %. Such large excess returns to ICT can be explained by higher user and adjustments costs of ICT capital, which may be "hidden" behind ICT investments. The signs and levels of significance of coefficients for the main variables are unchanged. However, the constant return to scale hypothesis cannot in this case be rejected for Manufacturing.

The columns (1) of Table 4.2 report the results from estimation of model (2a), which takes into account both the unobserved firm-specific effects and the serial correlation in the genuine error term. Compared to the results from columns (2) of Table 4.1, the estimated coefficients of labour inputs and non–ICT capital services are somewhat higher and those of ICT capital services are slightly lower. The serial correlation in the residuals is not very strong with ρ being roughly 0.18 in the full sample, 0.23 in the Manufacturing and 0.19 in the Services.

A further issue in estimating the effect of ICT on productivity is the potential bias owing to omitted variables that may be complementary to the firm's use of ICT, e.g. the differences in the skills of the workforce. Ignoring such differences might lead to overstating the true impacts of ICT on production. Columns (2) in Table 4.2 show the estimates of model (2b), which takes into account both the unobserved firm-specific effects and the heterogeneity of workforce. In addition, as in the model (2a) I allow for first order serial correlation in the genuine error terms. The estimates of the share of high-skilled workers are, as expected, positive and highly significant, indicating that high-skilled workers are more productive. The results also indicate that differences in skills of workforce do influence the effect of ICT capital services. The coefficients for *ict* are now slightly lower than in the model without heterogeneity in workforce (see results in columns (1) in Table 4.2).

Finally, columns (3) in Table 4.2 show the results from estimation of model (2c), where I test for complementarity between use of ICT and skill composition in the firm. Again, I assume the genuine error terms to be first order serially correlated. The effects of non–ICT capital services and labour inputs are almost unchanged, while the effects of ICT capital services are now dependent on the availability of high educated workforce. We observe that, for example, the firms with no high educated employees (h=0) now have lower output elasticities with respect to ICT capital services, than what was reported in columns (2) in Table 4.2. The coefficients for the interaction term are positive and highly significant for all three samples. That means that the firms gain from increasing investments in ICT capital if they simultaneously increase the share of employees with high education. Moreover, the results indicate that this gain is higher in Manufacturing than in Services.

[21] The choice of 'random effects' (as alternative to 'fixed effects') specification assumes zero correlation between input variables and firm–specific effects. In case of non–zero correlation, this specification will lead to the biased estimates. However, I choose 'random effects' specification for two main reasons. First, this specification allows estimating the effects of 'quasi-fixed' variables, i.e., variables that vary insignificantly during quite short observation period (e.g., firm industry and location, share of high-skilled workers, etc.). Second, this specification is less sensitive to the measurement errors that are likely to be substantial in both types of capital stocks since both the depreciation and the pre–sample growth rates are assumed to be equal across firms. The sensitivity of the results for the productivity of ICT with respect to the choice of these rates is presented in Appendix B.

[22] This result is similar to one found in Hempell (2005) and Eurostat (2008), but opposite to the results on macro level, where the productivity effect of ICT capital is higher than that one of non–ICT capital. The main reason of such differences in the results could be the spill–over effects of ICT that are more difficult to account for at micro level.

Table 4.2. Results for the ICT-augmented production function with serially-correlated error terms and heterogeneous labour

Variable	Full sample			Manufacturing			Services		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Log(non–ICT), *k*	0.045	0.047	0.047	0.037	0.038	0.038	0.049	0.050	0.050
	[52.40]**	[55.15]**	[55.21]**	[11.01]**	[11.57]**	[11.56]**	[48.20]**	[49.47]**	[49.18]**
Log(ICT), *ict*	0.031	0.030	0.027	0.018	0.016	0.012	0.031	0.031	0.028
	[59.58]**	[57.40]**	[45.79]**	[9.41]**	[8.88]**	[5.40]**	[51.53]**	[50.87]**	[40.04]**
Log(labour), *l*	0.866	0.868	0.870	0.950	0.951	0.955	0.849	0.851	0.855
	[535.41]**	[540.00]**	[534.47]**	[154.26]**	[156.55]**	[155.29]**	[447.54]**	[451.53]**	[445.70]**
Share of high- skilled, *h*		0.00177	0.00170		0.00343	0.00347		0.00172	0.00164
		[31.50]**	[29.79]**		[11.00]**	[11.14]**		[27.49]**	[25.78]**
ict×*h*			0.00022			0.00057			0.00025
			[9.92]**			[4.23]**			[9.91]**
2003	-0.145	-0.025	-0.025	-0.252	-0.009	-0.009	-0.146	-0.029	-0.029
	[10.07]**	[12.46]**	[12.46]**	[4.72]**	[1.61]	[1.62]	[8.54]**	[12.12]**	[12.13]**
2004	0.063	0.047	0.047	0.077	0.07	0.07	0.059	0.041	0.04
	[34.64]**	[21.40]**	[21.29]**	[14.70]**	[10.86]**	[10.82]**	[27.52]**	[15.57]**	[15.40]**
2005	0.085	0.071	0.07	0.123	0.115	0.114	0.079	0.062	0.061
	[42.38]**	[30.42]**	[30.13]**	[21.07]**	[17.00]**	[16.91]**	[33.34]**	[22.56]**	[22.15]**
2006	0.144	0.13	0.129	0.178	0.168	0.167	0.138	0.121	0.119
	[68.10]**	[53.83]**	[53.44]**	[28.82]**	[24.08]**	[23.92]**	[54.77]**	[42.13]**	[41.59]**
Constant	5.837	5.75	5.744	5.007	4.968	4.97	5.662	5.634	5.633
	[375.88]**	[364.32]**	[363.99]**	[87.82]**	[88.40]**	[88.59]**	[298.15]**	[296.61]**	[296.78]**
No. of obs.	210736	210736	210736	14038	14038	14038	160512	160512	160512
No. of firms	65559	65559	65559	3727	3727	3727	51816	51816	51816
R-squared	0.88	0.88	0.88	0.93	0.93	0.93	0.85	0.85	0.86
AR(1) param., ρ	0.18	0.18	0.18	0.23	0.23	0.23	0.19	0.19	0.19

The applied estimation procedure is GLS. Absolute value of t-statistics in brackets. * significant at 5%, ** significant at 1%. Firm age, location and industry dummies are included in the analyses but results for these variables are not reported here. All models are based on the assumption that genuine error terms follow AR(1) process.

Further, in order to investigate the heterogeneity among firms in Services, I estimated model (2c) with serially correlated genuine error terms for each service industry separately.[23] The results are presented in Table 4.3. We can first note that coefficients of the key variables (non–ICT capital services, ICT capital services, labour input and share of high-skilled workers) vary a lot among different service industries. However, they all have the right sign and most of them are statistically significant. Further, we see that ICT capital, *ict*, has the highest effect on the firm's labour productivity for the firms in Electronic processing and telecommunication, followed by Retail trade and Wholesale trade; while non–ICT capital, *k*, has the highest effect for the firms in Other business-related services and Restaurants and hotels. Furthermore, for such service industries as Electronic processing and telecommunication and Technical services the effect of non–ICT capital is very low and even not significantly different from zero, indicating that ICT capital is a more important production factor for the firms in these industries than non–ICT capital.

The returns on the use of high-skilled workers with respect to labour productivity are observed to be positive and statistically significant for all defined service industries; being highest for the firms in Transport and post and Consultancies and lowest in Retail trade. The use of high-skilled workers is also observed to be complimentary to ICT-use in most of the defined service industries, and especially in Electronic processing and telecommunication. These results confirm the assumption on that the availability of high-skilled workers is important for the effective use of ICT. However, in such industries as Restaurants and hotels, Transport and post and Technical services the interaction between human capital and ICT being positive is not statistically significant. The possible explanation for the latter observation is that in Restaurants and hotels ICT is to a large extent used in conjunction with working tasks that do not require a high level of skills. Predominance of technical education among workers in Transport and post and Technical makes the length of education not critically important for the effective use of ICT in these industries.

[23] For this analysis I divided the large group of firms in Business–related services (NACE 70-74, 64.2) into four smaller groups, i.e., Electronic processing and telecommunication (NACE 72, 64.2), Consultancies (NACE 74.1, 74.4), Technical services (NACE 73, 74.2, 74.3) and Other business-related services (NACE 70, 71, 74.5–.8).

Table 4.3. Results for the ICT-augmented production function with serially-correlate error terms and heterogeneous labour. Service industries

Variable	Retail trade (50, 52)	Wholesale trade (51)	Restaurants and hotels (55)	Transport and post (60–63, 64.1)	Electronic processing and telecommunication (72, 64.2)	Consultancies (74.1, 74.4)	Technical services (73, 74.2, 74.3)	Other business-related services (70, 71, 74.5–.8)
	Service industry (NACE digit)							
Log(non–ICT), *k*	0.046	0.026	0.067	0.049	0.002	0.029	0.004	0.093
	[27.59]**	[9.42]**	[19.11]**	[15.42]**	[0.39]	[8.25]**	[0.98]	[33.24]**
Log(ICT), *ict*	0.034	0.033	0.020	0.029	0.067	0.027	0.024	0.020
	[33.85]**	[17.19]**	[9.54]**	[13.25]**	[7.15]**	[8.51]**	[5.50]**	[10.36]**
Log(labour), *l*	0.812	0.921	0.768	0.870	0.938	0.875	0.966	0.834
	[244.36]**	[170.93]**	[124.70]**	[154.25]**	[74.67]**	[127.23]**	[120.69]**	[157.58]**
Share of high- skilled, *h*	0.00057	0.00154	0.00130	0.00227	0.00131	0.00208	0.00194	0.00199
	[4.35]**	[9.15]**	[4.08]**	[9.12]**	[2.68]**	[12.37]**	[9.06]**	[12.70]**
ict×*h*	0.00021	0.00016	0.00024	0.00018	0.00043	0.00019	0.00014	0.00029
	[3.35]**	[2.18]*	[1.74]	[1.53]	[2.42]*	[2.78]**	[1.66]	[4.42]**
2003	-0.032	-0.054	-0.033	-0.039	-0.025	0.003	-0.031	0
	[9.53]**	[8.83]**	[4.14]**	[4.99]**	[1.84]	[0.42]	[3.31]**	[0.00]
2004	0.021	0.038	-0.009	0.055	0.058	0.070	0.047	0.071
	[5.55]**	[5.65]**	[1.00]	[6.44]**	[3.82]**	[8.68]**	[4.55]**	[7.24]**
2005	0.023	0.080	0	0.083	0.072	0.096	0.107	0.085
	[5.76]**	[11.18]**	[0.03]	[9.37]**	[4.33]**	[11.10]**	[9.87]**	[8.33]**
2006	0.056	0.150	0.064	0.140	0.122	0.172	0.200	0.149
	[13.52]**	[20.07]**	[6.53]**	[15.32]**	[6.80]**	[18.93]**	[17.54]**	[14.10]**
Constant	6.099	5.495	6.178	5.661	4.929	5.689	5.351	5.529
	[198.99]**	[113.91]**	[92.33]**	[104.72]**	[53.70]**	[92.71]**	[77.58]**	[95.34]**
No. of obs.	54595	26985	12263	14488	6327	15395	10497	19962
No. of firms	16791	8507	4218	4365	2418	5344	3404	7852
R-squared	0.85	0.86	0.85	0.91	0.89	0.81	0.89	0.82
AR(1) of error, ρ	0.22	0.20	0.24	0.18	0.16	0.18	0.14	0.14

The applied estimation procedure is GLS. Absolute value of t-statistics in brackets. * significant at 5%, ** significant at 1%. Firm age, location and industry dummies are included in the analyses but results for these variables are not reported here. All models are based on the assumption that genuine error terms follow AR(1) process.

The main shortage of the provided analysis is that I can hardly claim on causality of the estimated effects. The obtained results confirm only the existence of positive correlation between ICT-use and use of high-skilled workers and firm productivity, and hence, should be interpreted with a care. Though I address several estimation problems that may bias the results (measurement errors, serial correlation in the genuine error terms and the omission of worker skills), the possible problem of endogeneity in the right-hand variables is still remains unsolved. If firms determine input and output simultaneously, exogenous shocks — like demand shifts, for example — result in an increase of both input and output for the profit–maximising firm. In this case the error term will be positively correlated with the input variables in Eq. (2) causing an upward bias in the input coefficients. However, the simultaneity bias may apply in particular to factors that can be adjusted easily in the short term that is not so much the case for capital stocks. Moreover, I use capital stocks at the beginning of the corresponding years when estimating models. Therefore, the (upwards) simultaneity bias is expected to be rather small for the two capital coefficients. However, this issue requires further investigation.

Another important issue for further discussion is the applied estimation specification where I choose firm–specific effect to be random. As I mentioned, this specification has some advantages compared to the 'fixed effects' specification, i.e., this specification allows estimating the effects of 'quasi-fixed' variables and is less sensitive to the measurement errors. The estimation of models with fixed firm–specific effects for the full sample gives illogical results for some key variables that can be caused by serious measurement errors problem.[24] Nevertheless, the 'random effect' specification may give the biased results if investment strategies of highly productive firms are systematically different from their less productive competitors. In this case input variables will be correlated with firm–specific effect, while 'random effects' specification assumes that they are uncorrelated. This issue is also keeping the room for further research.

[24] These results are not presented here, but are available upon request.

5. Conclusions

This paper presents the results from an empirical analysis of the impacts of ICT on the firm labour productivity using a rich panel data of Norwegian firms in the period 2002–2006. A measure of ICT capital is constructed and three different models are formulated, i.e., a basic model (based on the production framework with labour and two types of capital as inputs and with i.i.d. error terms), a model with serially-correlated genuine error terms and a model with heterogeneous labour force. These models are estimated for three different samples, i.e., full sample, firms in Manufacturing and firms in Services. The results show that controlling for serial correlation in the errors and for labour heterogeneity is important for more precise estimation of ICT impacts on firm productivity.

The main objective of the paper is to provide a comparative analysis of effects of ICT and human capital and their combined use on labour productivity for firms in Manufacturing and Services and for firms in more narrowly defined service industries. For all the three samples, ICT and human capital have statistically significant positive impacts on firm labour productivity. Moreover, the results from the estimation of the model that accounts for labour heterogeneity, i.e., for different skills of the workforce, show that inclusion of such heterogeneity is important for not overestimating the impact of ICT. Also for all the three samples the estimation results give evidence on complementarities between ICT and the use of high-skilled workers.

I have also found considerable differences between the firms in Manufacturing and Services. First, the importance of ICT for labour productivity is much higher in Services than in Manufacturing. For human capital the result is opposite, i.e., the availability of high-skilled workers seems to be more important in Manufacturing than in Services.

Second, for both samples the relative importance of ICT capital for labour productivity is lower compared to non–ICT capital. However, looking at more narrowly defined service industries, I find that for some industries the impact of ICT capital on labour productivity is much higher than the one of non–ICT capital, i.e., for Wholesale trade, Electronic processing and telecommunication and Technical services. For Consultancies these two effects are equal.

Third, the gain of simultaneous use of ICT and high-skilled workers is higher in Manufacturing than in Services. Even for firms in Electronic processing and telecommunication, where the highest interaction effect between ICT and share of high-skilled workers is observed among service industries, this effect is lower than for firms in Manufacturing. In industries such as Restaurants and hotels, Transport and post and Technical services the interaction between human capital and ICT being positive is not statistically significant. These findings indicate that availability of high-skilled workers is necessary for more productive use of ICT in most service industries and especially in Manufacturing.

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Appendix A

Data sources

The structural statistics: The term "structural statistics" is a general name for the different industrial activities statistics (e.g., Manufacturing statistics, Building and construction statistics, etc.), which are based on General Trading Statements, given in an appendix to the tax return. They all have the same structure and include information about production, input factors and investments at the firm level. Since 2002 this data comprise information on annual investments in hardware (purchased) and software (both purchased an own account). The structural statistics are organised according to the Standard Industrial Classification (SN2002) and are collected for the following industries:

- Mining and quarrying (NACE 10-14)
- Manufacturing (NACE 15-37)
- Building and construction (NACE 45)
- Wholesale and retail trade (NACE 50-52)
- Hotels, restaurants and catering (NACE 55)
- Transport, storage and communication (NACE 60-64)
- Other services (NACE 70-74, 92).

Accounts statistics: In the accounts statistics, a firm is defined as “the smallest legal unit comprising all economic activities engaged in by one and the same owner” and corresponds in general to the concept of a company (Statistics Norway, 2001). A firm can consist of one or more establishments which are the geographically local units conducting economic activity within an industry class. Another unit is the consolidated group, which consists of a parent company and one or more subsidiaries. Both the parent company and the subsidiaries are firms as defined here. All joint-stock companies in Norway are obliged to publish company accounts every year. The accounts statistics contain information obtained from the income statements and balance sheets of joint-stock companies, in particular, the information about operating revenues, operating costs and operating result, labour costs, and the book values of a firm's tangible fixed assets at the end of a year, their depreciation and write-downs. These data were matched with the data from the structural statistics.

The Register of Employers and Employees (REE) contains information about each individual employee’s contract start and end, wages and working hours. Containing both the firm identification number ant the personal identification number these data can easily be aggregated to the firm level.

The National Education Database (NED) includes individually based statistics on education and contains a six-digit number where the leading digit describes the educational level of the person. I use this data set to identify the length of education of employees. This information was first integrated into a common data base wit REE and then aggregated to the firm level.

Appendix B

The sensitivity of the results with respect to the choice of depreciation and the pre–sample growth rates for the ICT capital stocks construction

As is obvious from Eqs. (5) and (6), both the level and the evolution of the capital stocks of the firms depends on the choice of parameters used for annual depreciation and pre–sample growth rates of investment , δ_k and g_k with $k=1,2,3$, respectively. For exploring the sensitivity of the econometric results with respect to the parameters assumed for the construction of ICT capital stocks, I subject the reference regression underlying Col. (2) of Table 3.1 for full sample to two kinds of robustness checks. In the first, I calculate alternative ICT capital stocks assuming the same depreciation rate δ for all three types of ICT ($\delta_1 = \delta_2 = \delta_3 = \delta$) and use then different values for δ while holding assumed growth rates g_k , $k=1,2,3$ fixed. In the second, I hold the assumed values for depreciation rates δ_k , $k=1,2,3$, while varying the common growth rate g ($g_1 = g_2 = g_3 = g$).

The estimates for the elasticity of ICT for these variations are reported in Table B1. We see that the qualitative result of significant productivity contributions of ICT is robust to both kinds of variations. Lowering the assumed depreciation rates for three types of ICT capital be equal to 30 % as in Hempell (2005) or to 36 % as in Eurostat (2008) changes the estimated elasticity of ICT only modestly from 0.033 to 0.034 and 0.032, respectively. The same yields when I put the growth rate equal to 40 % as in Hempell (2005), i.e., the estimated elasticity of ICT only changes modestly from 0.033 to 0.032. Further variations show that the point estimate of the elasticity decreases in both parameters with slightly higher effect from variation of δ . For the extreme case of a complete depreciation of ICT within one year ($\delta_1 = \delta_2 = \delta_3 = \delta$ =100%), the point estimate is very small. This finding shows that employing ICT investments instead of ICT capital stocks is an unreliable proxy for estimation of ICT to productivity contribution. The main message from the whole exercise is that the empirical results reported in this paper are robust to the choice of certain values for δ_k and g_k .

Table B1. Sensitivity analysis of the ICT productivity effect with respect to the choice of parameters for the ICT capital stocks construction

	Varying parameterisation of δ [b] (g_1=24.4 %, g_2=7.9 %, g_3=26.2%)							
	Reference	1 %	20 %	30 %	36 %	46 %	56 %	100 %
Est. coeff. of log(ICT)[a]	0.033	0.044	0.037	0.034	0.032	0.030	0.026	0.002
Mean *ICT*, NOK thousands	139.4	63.3	124.2	135.0	139.4	143.7	151.8	161.5
Mean *ICT/Y*, %	1.6	1.0	1.4	1.6	1.6	1.7	1.7	1.8
Mean of *ICT/(ICT+K)*, %	14.4	7.2	13.0	14.0	14.4	14.7	15.3	15.6
Mean of *ICT* growth, %	18.9	21.4	19.4	18.8	18.6	18.2	18.0	16.7
	Varying parameterisation of g [c] (δ_1=31.2 %, δ_2=55.0 %, δ_3=33.0 %)							
	Reference	1 %	10 %	20 %	40 %	60 %	80 %	100 %
Est. coeff. of log(ICT)[a]	0.033	0.034	0.033	0.033	0.032	0.032	0.031	0.030
Mean *ICT*, NOK thousands	139.4	174	155.1	135	125.4	116.2	111.1	106.7
Mean *ICT/Y*, %	1.6	2.1	1.8	1.6	1.5	1.4	1.3	1.2
Mean of *ICT/(ICT+K)*, %	14.4	16.8	15.6	14.6	13.5	12.8	12.4	12.0
Mean of *ICT* growth, %	18.9	8.4	13.5	18.5	27.0	34.4	41.1	47.3

[a] Estimated coefficients (est. coeff.) are obtained from the reference model specification, Eq. (2), estimated by GLS for full sample (see column (2) in Table 4.1 for full sample).
[b] The same depreciation rate δ for all types of ICT ($\delta_1 = \delta_2 = \delta_3 = \delta$) with reference values δ_1=31.2 % (hardware), δ_2=55.0 % (purchased software), δ_3=33.0 % (own account software).
[c] The same growth rate g for all types of ICT ($g_1 = g_2 = g_3 = g$) with reference values g_1=24.4 % (hardware), g_2=7.9 % (purchased software), g_3=26.2% (own account software).

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