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Do R&D and ICT Affect Total Factor Productivity Growth Differently?

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Abstract

We analyze the effect of ICT and R&D on total factor productivity (TFP) growth across different industries in Sweden. R&D alone is significantly associated with contemporaneous TFP growth, thus exhibiting indirect effects. Although there is no significant short-run association between ICT and TFP, we find a positive association with a lag of seven to eight years. Thus, R&D affect TFP much faster than ICT-investments. We also divide ICT capital into hardware and software capital. To our knowledge, this distinction has not been made in any previous study analyzing TFP at the industry level. The results show that lagged hardware capital services growth is significantly associated with TFP growth. Hence, investments complementary to hardware are needed to reap the long-run TFP effects from reorganizing production.

Keywords: ICT; R&D; Hardware; Software; Total factor productivity; Panel data analysis.

JEL *Codes*: L16, O33, O47.

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1. Introduction

We are currently experiencing a technological breakthrough in ICT affecting virtually all aspects of our lives including what is produced, how and where it is produced, how production is organized, what skills are required, the enabling infrastructure and the regulations required to sustain or even allow the ongoing transformation (Miller and Atkinson 2014). Over the last decades, the ICT revolution has brought innovations such as personal computers, mobile phones and the Internet. These innovations have resulted in large productivity gains in many countries. Many observers believe that ICT will continue to drive productivity growth as new innovations such as the "Internet of things" (IoT) start evolving.[1] However, it is likely that large investments in ICT and R&D are required in order to realize the productivity potential of new innovations (OECD 2003). It is therefore crucial to understand how investments in ICT and R&D affect productivity growth.

Investments in ICT and R&D have arguably been important engines of growth throughout the world. Economists have used models derived from production theory to estimate the impact of ICT and R&D. For example, Jorgenson et al. (2008) used growth accounting to capture the direct effects from the accumulation of ICT capital. They found that ICT capital investments accounted for 37 percent of labor productivity growth in the U.S. in 1995–2000.[2] R&D has also been identified as an important contributor to growth (Griliches 1991). In general, the output elasticities vary between 0.10 and 0.20 in econometric estimates of cross-sectional data (McMorrow and Röger 2009).

In addition to the direct effects there may also be indirect effects. These effects are the impact on value added and productivity growth in excess of the direct effects via capital accumulation. This would be an indication that ICT and R&D are also affecting productivity through more efficient organization of production and increased product quality. In this view, ICT has computerized businesses and the economy as a whole leading to increased productivity in ICT-using and -producing sectors (Cardona et al. 2013). Thus, the returns on ICT and R&D investments cannot be fully internalized by the investors (van Ark 2014). One way of investigating if there exist indirect effects would be by testing whether investments in ICT and R&D are correlated with total factor productivity (TFP). Thus, an industry investing

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[1] The "Internet of things" (IoT) can be defined as: "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" (ITU 2012, p. 1).

[2] Jorgenson et al. (2008) also found that ICT-producing industries contributed 58 percent of TFP growth.

more in ICT would also have higher TFP growth, which would indicate more efficient organization of production.

The purpose of this study is to investigate the indirect effects of ICT and R&D capital on TFP based on Swedish industry data. Sweden is one of the countries investing the most in ICT and R&D (OECD 2015). In a previous study we found large direct effects of ICT and R&D on value added in the Swedish business sector (Edquist and Henrekson 2015). Given the high rates of aggregate ICT and R&D investment in Sweden it is of particular interest to explore whether such investments also are associated with high indirect effects. Draca et al. (2007) argue that indirect effects might apply to specific forms of ICT rather than ICT in general. We therefore make a distinction between indirect effects from hardware and software. To our knowledge, this has not been done in any previous study, primarily due to data limitations.[3] The following three questions will be addressed:

- Is there any evidence of indirect effects from ICT and R&D based on Swedish industry-level data?
- Are there any differences in how ICT and R&D affect TFP growth at the industry level?
- Do investments in hardware and software affect TFP growth differently?

We find that only R&D is positively associated with contemporaneous TFP growth, thus industries investing in R&D exhibit effects on productivity through more efficient organization of production and higher product quality in the short run. This suggests that at the industry level only investments in R&D results in additional productivity gains beyond capital accumulation.

When we use longer time periods, as suggested by Brynjolfsson and Hitt (2003), we still do not find any positive association between ICT and TFP. However, when we divide our sample into two periods and regress lagged growth in ICT capital services on current TFP growth we find a significant association. Average ICT capital growth in 1993–2003 is positively associated with average TFP growth in 2004–2013. The lagged ICT coefficient is positive and significant at the ten percent level, whereas the lagged R&D coefficient is insignificant.

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[3] Statistics Sweden began to publish hardware and software investment separately for specific industries in 2014.

Based on panel data with smoothed five-year moving averages we find that the ICT coefficient becomes increasingly positive and significant after seven years. A further disaggregation shows that the lagged positive effect on TFP emanates from hardware rather than software investments. This suggests that hardware investments require complementary investments to reap the full productivity effects from a reorganization of production. Thus, the productivity effects from new innovations such as IoT will by no means be instantaneous and require complementary investments. These findings also suggest that even if firms replace or update their current hardware with newer and more powerful versions, this cannot substitute for the need to continuously reorganize production around the new technology.

The paper is organized as follows. In section 2 we review the existing research on productivity effects from R&D and ICT. In Section 3 we present the methodological framework and in section 4 we describe the data. In section 5 we present our results and their robustness are discussed in section 6. Section 7 concludes.

2. Related literature

2.1 Understanding the differences between R&D and ICT

OECD (2009a, p. 90) defines ICT as products “intended to fulfil or enable the function of information processing and communications by electronic means, including transmission and display”. According to the Frascati Manual (OECD 2002, p. 30), R&D is defined as “creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications.”

ICT primarily consists of combinations of hardware and software, while R&D is made up of time spent by employees in order to increase the stock of knowledge available to the firm. Arrow (1962) argues that R&D is distinct from the traditional factors of production, labor and physical capital, in that the value of R&D spending is more uncertain. Moreover, knowledge generated from R&D are non-excludable unless the new knowledge can be totally protected by patents (Eberhardt at al. 2013), and the knowledge is neither rivalrous nor exhaustible.

ICT is considered a general purpose technology (GPT), characterized by pervasiveness, inherent potential for technical improvements and innovational complementarities (Bresnahan and Trajtenberg 1995). Moreover, the effects from GPTs on productivity are often delayed since many GPTs require organizational restructuring to reach their full potential (David 1990; Helpman 1998). R&D is a means by which new technologies are developed. Although R&D is not a GPT, many of the results from R&D are characterized by general purposeness. There is also a link between R&D and ICT; R&D is necessary to develop new ICT products. For example, the ICT-producing industry in Swedish manufacturing invested the most in R&D in 2013. R&D can thus be linked to ICT, but investments in R&D can also be made independently of ICT.

2.2 Measuring the economic impact of ICT and R&D

ICT and R&D can have both a direct and an indirect effect on value added and productivity growth. The direct effect is linked to capital accumulation and thus driven by investments in ICT and R&D, leading to changes in capital services. The indirect effect is the impact on value added and productivity growth in excess of the direct effect via capital accumulation. We define indirect effects as the contribution from ICT and R&D to TFP at the industry level in each specific industry.

The direct contribution from ICT and R&D can be measured through growth accounting, which assesses the contribution of the various inputs to value added. Assuming competitive markets and constant returns to scale the output elasticities of each input is equal to each factor's income share. Alternatively, the output elasticity of each input can be estimated econometrically (Donghyun et al. 2014). These elasticity estimates can then be used to calculate each input's contribution to growth, rather than from income statistics, which is the case when growth accounting is used.[4]

Neoclassical theory predicts that rapidly falling ICT prices have direct effects on investment, input substitution and capital deepening (Stiroh 2002a). This implies a direct effect on value added and labor productivity, but not on TFP growth. TFP gains should only appear in the production of ICT, where true technological progress allows the production of improved capital goods at lower prices (Stiroh 2002b). In this view, ICT is not a special type of capital, but rather a normal piece of equipment. However, there might also be network effects; ICT may be more effective when many firms in an industry use high levels of ICT (Van Reenen et al. 2010). This implies that industries investing more in ICT would have higher growth rates of TFP because of, among other things, improved information management, facilitated data

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[4] According to Donghyun et al. (2014) the mean rate of TFP growth was almost the same based on both estimation methods in Korean manufacturing 1987–2007.

exchange and more rapid diffusion of best practices (Rincon et al. 2013). In contrast to ICT, neoclassical production theory readily accommodates indirect effects from R&D. The results from R&D can be conceptualized as non-rival knowledge “borrowed” across research teams (Griliches 1991).

It is possible to use data at the aggregate, industry as well as the firm level to estimate indirect effects. Here we use industry-level data, investigating whether changes in capital services of ICT and R&D are associated with TFP growth. Thus, we would expect faster TFP growth in industries where the ICT and R&D capital stocks grow more rapidly as firms in these industries are able to use these inputs to reorganize production more efficiently.

It is important to keep in mind that industry-level data consist of the average for the firms in the respective industries. Hence, we measure whether firms that invest more in ICT and R&D, on average, also experience a higher average TFP growth. We are not able to test whether firms investing in R&D and ICT on average have higher TFP growth with industry-level data (Van Reenen et al. 2010). Consequently, we cannot identify whether the industry average is typical for most firms or disproportionately determined by a few firms.

2.3 Empirical findings on indirect effects from ICT and R&D

There is an extensive literature investigating indirect effects from ICT and R&D. Most studies have been focused on measuring the effects from either ICT or R&D, primarily due to the fact that R&D until recently was not capitalized in the National Accounts in many countries. Micro studies have often identified indirect effects of ICT on TFP, while it has been more difficult to identify such effects on the industry or macro level (O’Mahony and Vecchi 2005; Rincon et al. 2013). When it comes to R&D, Hall et al. (2009) asserts that the empirical evidence suggests substantial indirect effects at all levels.

Venturini (2015) found evidence of positive indirect effects from ICT based on aggregate data for 15 OECD countries. Moreover, a more intensive use of ICT leads to an improvement in TFP in EU manufacturing industries (Gehringer et al. 2015). Acharaya (2015) used data for 16 OECD countries, 24 industries and 32 years, but found no evidence of indirect effects from ICT. Stiroh (2002a) investigated whether TFP growth was linked to ICT use in U.S. manufacturing. He found that if one allows for productivity differences across industries, TFP is uncorrelated with capital inputs, including ICT. Haskel and Wallis (2010) found no indirect effects from investment in software and other intangible capital in the UK business sector.

O'Mahony and Vecchi (2005) used industry-level data for the U.S. and the UK and found similar results based on pooled regressions controlling for industry and time-specific effects. However, by using a different econometric methodology that accounted for industry heterogeneity and for the time-series nature of the data, they found a positive association between ICT and TFP. Finally, Basu and Fernald (2007) find that with long lags, ICT capital growth in the US is positively associated with the industry TFP acceleration, but contemporaneous ICT capital growth is negatively associated with TFP acceleration.

At the firm level, van Leeuwen and van der Wiel (2003) found evidence of indirect effects from ICT in Dutch firms. Brynjolfsson and Hitt (2003) found that computer capital was correlated with TFP for U.S. firms when the average growth rates over longer time periods were used. The results were not robust to first-differencing, but the estimated coefficients increased in size when the length of the growth period increased. Rincon et al. (2013) obtained similar results based on U.S. firm-level data. These findings have been linked to the GPT literature, suggesting that there is a delayed productivity effect from technology investment (David 1990; Edquist and Henrekson 2006). One reason could be that complementary investments such as organizational capital are necessary to reap the productivity effects from investments in new technology (Brynjolfsson and Hitt 2003; Chen et al. 2016).

In addition to the empirical literature exploring the effects of ICT, there is also a large literature investigating indirect effects from R&D. Griliches (1991) concluded that studies investigating indirect effects from R&D showed that they were both prevalent and important. Griliches (1994) found strong evidence of indirect effects from R&D based on U.S. industry data. However, the estimate of the indirect effects decreased considerably once the computer industry was excluded. Moreover, Griffith et al. (2004) found that R&D had been important for the convergence of TFP levels within industries across twelve OECD-countries and Badinger and Egger (2016) found sizeable R&D effects on productivity primarily within or among similar industries based on data for 12 OECD countries and 15 manufacturing industries in 1995–2005.

There are also a number of studies including both R&D and ICT in the analysis. Corrado et al. (2014) used cross-country data to analyze indirect effects from ICT and intangibles. They found indirect effects from intangibles both including and excluding R&D. However, ICT was not found to be significantly associated with TFP. Van Reenen et al. (2010) obtained similar results based on firm-level data; they found little evidence of indirect effects from ICT, while R&D was found to be strongly associated with TFP.

3. Methodology

3.1 Estimating total factor productivity

The method used to measure indirect effects from ICT and R&D is based on the neoclassical production function model (Griliches 1979; Stiroh 2002a; 2005). The production function framework relates output to labor, capital, intermediate inputs and TFP. In this paper we measure output as value added.[5] There are both advantages and disadvantages in using value added instead of gross output (Stiroh 2005). One advantage of using value added is that nominal value added sums to GDP, which is the reason why we favor this measure. A disadvantage would be that value added requires stricter assumptions of perfect competition (Basu and Fernald 1995).[6]

Assuming an augmented Cobb-Douglas production function, we have the following equation:

$$V_{i,t} = TFP_{i,t} K_{ICT,i,t}^{\beta_{ICT}} K_{O,i,t}^{\beta_N} R_{i,t}^{\beta_R} L_{i,t}^{\beta_L} \tag{1}$$

where $V_{i,t}$ is real value added, K_{ICT} is ICT capital and K_O is capital other than ICT and R&D, R is R&D capital, L is labor input and TFP is Hicks-neutral total factor productivity, all for industry i at time t. According to Jorgenson and Griliches (1967) the theoretically correct way to measure capital in a production function is by measuring capital services. The methodology used to estimate capital services is described in Appendix A.

By taking natural logarithms of equation (2):

$$\ln V_{i,t} = \beta_{ICT} \ln K_{ICT,i,t} + \beta_N \ln K_{O,i,t} + \beta_R \ln R_{i,t} + \beta_L \ln L_{i,t} + \ln TFP_{i,t} \tag{2}$$

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[5] R&D is included as gross fixed capital formation in value added and not as intermediate inputs.

[6] Value added is defined as gross output minus intermediate inputs. This implies that one must know the marginal products of these intermediate inputs. Real value added is constructed assuming that these marginal products are observable from factor payments to intermediate goods. Unless there is perfect competition the marginal product exceeds the factor payments. Thus, if competition is imperfect using value added as the output measure can lead to spurious findings. On the other hand, contestable competition may suffice; the risk of entry may be enough to deter incumbents from exploiting their market power and maintain dynamic efficiency (Audretsch et al. 2001).

where β represents the output elasticity of each input. Value added is defined as gross output minus intermediate inputs, where gross output is defined as sales plus other operating income. One way of measuring the indirect effects from ICT and R&D is to test whether there are any indirect effects by regressing ICT and R&D capital services on TFP. We base our TFP estimates on the growth accounting methodology (Oliner and Sichel 2000; Jorgenson and Stiroh 2000; Brynjolfsson and Hitt 2003).

Growth accounting assesses the contribution of inputs to value added assuming constant returns to scale and that each factor receives compensation equal to its marginal product (Jorgenson et al. 2008; Inklaar et al. 2005). The relation can then be written:

$$\Delta \ln V_{i,t} = s_{ICT} \Delta \ln K_{ICT,i,t} + s_N \Delta \ln K_{O,i,t} + s_R \Delta \ln R_{i,t} + s_L \Delta \ln L_{i,t} + \Delta \ln TFP_{i,t} \qquad (3)$$

where V is aggregate value added, K_{ICT} is ICT capital, K_O is other capital than ICT and R&D, R is R&D capital, L is labor input measured in hours, and TFP is total factor productivity measured as a residual.

Based on the assumptions of competitive markets and constant returns to scale it is possible to let the elasticities (s_{ICT} , s_N, s_R, s_L) be equal to each factor's income share. Thus, by transforming equation (3), TFP in industry i can be estimated based on four different inputs as follows:

$$\Delta \ln TFP_{i,t} = \Delta \ln V_{i,t} - s_{ICT} \Delta \ln K_{ICT,i,t} - s_N \Delta \ln K_{O,i,t} - s_R \Delta \ln R_{i,t} - s_L \Delta \ln L_{i,t} \qquad (4)$$

This gives us a TFP measure, where we control for the direct contribution from ICT and R&D based on each factor's income share with constant returns to scale $S_{ICT} + S_N + S_R + S_L = 1$.

3.2 Specification

In section 2.2, we defined indirect effects from investing in ICT and/or R&D as their respective contribution to TFP growth in each specific industry. In order to test for indirect effects from ICT as well as R&D we set up the following equation:[7]

$$\Delta \ln TFP_{i,t} = \beta_{Ict} \Delta \ln K_{ICT,i,t} + \beta_O \Delta \ln K_{O,i,t} + \beta_R \Delta \ln R_{i,t} + \beta_L \Delta \ln L_{i,t} + \delta_t + v_{i,t} \qquad (5)$$

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[7] We use STATA for all data analyses.

where $\Delta TFP_{i,t}$ is the TFP growth of industry *i*, which can be estimated based on the growth accounting methodology (see equation 4). K_{ICT} is ICT-related capital services and K_O is capital services other than ICT and R&D, *R* is R&D capital, *L* is labor input, δ_t are year dummies, which capture common economic shocks, and $v_{i,t}$ is the differenced residual. First-differencing the data and controlling for time-specific effects eliminate the correlation among cross-sectional units in the panel and thus accounts for cross sectional TFP growth (Eberhardt et al. 2013).If the estimated parameters from R&D and ICT capital are positive and significant this is evidence of indirect effects.[8] Thus, we measure the excess in ICT and R&D output elasticity above its theoretical value (Brynjolfsson and Hitt 2003).

In addition to the specification in equation (5), it is also possible to divide ICT capital into hardware and software:

$$K_{ICT,i,t} = K_{S,i,t} + K_{H,i,t} \tag{6}$$

where $K_{S,i,t}$ is software capital and $K_{H,i,t}$ is computer and communications hardware capital.

4. Data

The data used are based on the National Accounts provided by Statistics Sweden (2015b) and cover 50 industries for the period 1993–2013. The different industries are presented in *table 8* and follow the international standard for industry classification (ISIC 2008). Three industries were excluded due to missing data: Activities auxiliary to financial services and insurance (ISIC K66), Real estate activities with own or leased property (ISIC 68A), and Health activities (ISIC P86).

Output is measured as value added in SEK and labor input as quality adjusted hours worked. The variables used to estimate labor quality are average income, age, education and ethnicity.[9] Value added estimates are based on double deflation and are expressed in real terms in 1993 prices, the initial year of the period examined. R&D is included as gross fixed capital formation in value added and not as an intermediate input. Capital input data are based on estimates of capital services (see Appendix A). *Table 1* presents some descriptive statistics. It

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[8] The specification used implicitly assumes that elasticities are the same across industries. Moreover, by introducing time-specific effects we assume that all industries are affected equally by an economic shock.

[9] For a detailed description on how labor quality is estimated, see Hagén (2012).

shows that the mean of ICT and R&D capital is considerably lower compared to other capital. However, ICT capital is growing considerably faster on average compared to R&D and other capital. This is primarily due to high average growth of hardware capital.

Capital services are preferred to capital stock data, since that measure accounts for the substitution between assets with different marginal products. As a result, the weights will not be too large for long-lived assets such as industrial real estate. Statistics Sweden does not provide any official estimates of capital services for industries. Capital services were estimated based on data on investments, capital stocks and investment prices for the different industries.

Capital services were calculated for ICT, R&D and other capital.[10] Since 2014 R&D is capitalized in the National Accounts. This makes it possible to use R&D capital services when estimating production functions at the industry level.[11] Moreover, ICT capital services were divided into the components hardware and software.

5. Empirical results and discussion

5.1 Indirect effects

Based on our specification in equation 5, we investigate indirect effects from ICT and R&D. *Table 2* shows that the change in ICT capital is not significantly associated with TFP growth, while change in R&D capital is positively and significantly associated with TFP growth at the five percent level. Thus, only R&D exhibits contemporaneous indirect effects. This implies that the rate of return on R&D is 46 percent.[12] This is in line with other studies. Hall et al. (2009) conclude that the R&D rates of return may be as high as 75 percent and Goodridge et al. (2013) find even higher rates of return from R&D. Moreover, other capital is negatively related to TFP, indicating that capital is less important for productivity than suggested by the growth accounting model.

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[10] ICT was estimated by aggregating ICT hardware and software, while other capital was estimated by aggregating dwellings, other buildings, transportation equipment and other machinery and inventories.

[11] R&D expenditure is collected in a survey addressed to Swedish firms. The R&D expenditure is classified based on the industry classification of each firm. Thus, there is a risk that parts of the R&D activities funded by a specific industry are carried out in a different industry (see Statistics Sweden 2015a).

[12] The calculation of the net rate of return is based on Eberhardt et al. (2013). Thus, the net rate of return, $\rho = \beta_r(V/R) - \delta$, where β_r is the estimated coefficient in equation (5), V is value added in fixed prices and R is the capital stock of R&D in fixed prices, while δ is the depreciation rate of R&D. Assuming a depreciation rate of 16.5 percent (which is also approximately the depreciation rate used by Statistics Sweden), $\rho = 0.11*(5.64) - 0.165 = 0.46$.

When we make a distinction between software and hardware ICT, it becomes clear that software is significantly and negatively associated with TFP growth, while the coefficient of hardware is not significantly different from zero. One explanation could be that the introduction of new software requires reorganization, new skills and new production methods, which has a negative impact on productivity in the short run. Finally, we exclude ICT-producing industries in order to test whether the results are robust when only basing our sample on ICT-using industries. The R&D coefficient remains approximately the same and significant at the five percent level, and the results for other explanatory variables remain unchanged.

5.2 Lagged indirect effects

The initial analysis indicated that there are considerable indirect effects from R&D, but not from ICT. One reason could be that the effects from investing in ICT materialize with a lag. This is also what the GPT literature predicts (Helpman 1998). It took considerable time for manufacturing to adopt electricity and use it efficiently (David 1990). Reorganizing production around the new technology turned out to be time consuming. Similar results have been found for both ICT and the steam engine (Edquist and Henrekson 2006; Brynjolfsson and Hitt 2003).

Brynjolfsson and Hitt (2003) proposed to test whether the effect of ICT would change if regressions with longer time differences than one year were used. *Table 3* shows the results when regressions are run with longer differences for all variables, i.e., being smoothed with moving averages for longer periods. Brynjolfsson and Hitt found that the longer the time periods used, the larger and more significant the association between ICT and TFP growth. However, for our regressions the ICT-coefficient remains approximately unchanged and insignificant for 3- and 5-year periods. For the 10-year period, the ICT coefficient is negatively associated with TFP at the 10 percent level. For R&D, there is evidence of indirect effects based on moving averages for all periods.

Changing the length of the periods investigated may not always suffice to identify the delayed indirect effects from ICT. An additional method is to include lagged periods in the analysis. Inspired by Basu et al. (2003), we therefore divide the sample into two time periods: 1993–2003 and 2004–2013. We then run the regression based on the years 2004–2013 and include lags for ICT and R&D capital for the years 1993–2003:

$$\Delta\ln TFP_i^{2004-2013} = \beta_{ICT}\,\Delta\ln K_{ICT,i}^{2004-2013} + \beta_{ICT}\Delta\ln K_{ICT,i}^{1993-2003} + \beta_O\,\Delta\ln K_{o,t}^{2004-2013} + \beta_R\Delta\ln R_i^{2004-2013} + \beta_R\Delta\ln R_i^{1993-2003} + \beta_L\Delta\ln L_i^{2004-2013} + u_{i,t} \tag{7}$$

Table 4 presents the results based on equation (7). We first run the regression based on the period 2004–2013. As expected there is no indication of indirect effects from ICT, while R&D is again positively associated with TFP.

In the second regression in *table 4*, the average growth of ICT capital services for the period 2004–2013 are replaced by estimates for the period 1993–2003. The ICT coefficient becomes positive, but is still insignificant. However, when we include both current and lagged ICT capital the ICT coefficient becomes positively associated with TFP at the 10 percent level. The results remain robust once we include both current and lagged R&D capital services. However, the lagged R&D coefficient is not significant. Thus, there is evidence of lagged indirect effects from ICT, but no evidence of an association between lagged investments in R&D and TFP.

Table 5 presents results where ICT is divided into hardware and software. The results show that it is primarily software that is negatively associated with TFP when no lags are used. The coefficients for hardware are also negative, but not significant for most specifications. These results support the findings that there are significant negative indirect effects from software in the short run (cf. *table 2*). When we introduce lagged variables of software and hardware, the point estimates become positive for both types of ICT, but a significant result is found for hardware only. However, the result is not robust once we introduce current variables of hardware and software and lagged R&D.

The data based on two different periods showed that there exist lagged indirect effects from ICT, while indirect effects from R&D are primarily contemporaneous. In order to test the robustness of these results we set up regressions and run them based on panel data. Thus, we first smooth the variables by creating 5-year moving averages based on period t, $t + 1$, $t + 2$, t+3 and t+4. Smoothing the series removes uninformative high-frequency noise from the data (Goodridge et al. 2014). We then use the smoothed series and run the model with lags of the ICT and R&D variables, one at a time:

$$\Delta\ln TFP_{i,t}^{smoothed} = \beta_{Ict}\,\Delta\ln ICT_{ICT,i,t-k}^{smoothed} + \beta_{O}\,\Delta\ln K_{O,i,t}^{smoothed} + \beta_{R}\Delta\ln R_{i,t-k}^{smoothed} + \beta_{L}\Delta\ln L_{i,t}^{smoothed} + u_{i,t} \qquad (8)$$

where k is the year for which lags are included in the regression.

Table 6 presents results based on smoothed series with lags introduced one at a time for different years. The results support the findings based on the two-period regressions, i.e., R&D is positively associated with TFP growth in the short run, while ICT and TFP growth are positively associated when 7–8 years lags are used for ICT. When a time lag of one year is used the ICT coefficient is negative and insignificant. Gradually, the ICT coefficient becomes positive and increasingly significant, while the R&D coefficient is insignificant when longer lags are introduced. With a lag of 8 years, the ICT coefficient is 0.14 and highly significant at the 1 percent level. These findings are in accordance with findings based on firm level data (Brynjolfsson and Hitt 2003). However, based on industry data it was necessary to include lagged variables rather than increasing the length of the investigated time periods.

Table 7 shows the results when ICT is divided into hardware and software. As indicated by the regressions based on the average for two periods (see *table 4* and *5*), it is primarily hardware that is significantly associated with TFP. The hardware coefficient is not significantly different from zero when a one-year lag is used, but it gradually becomes larger and more significant over time. With a time lag of 7 years it is 0.10 and significant at the 10 percent level. It grows to 0.10 and becomes significant at the 5 percent level when the time lag is extended to 8 years.

6. Robustness

We have shown that there is a positive contemporaneous association between the change in R&D capital and TFP. According to *table 9* the results are robust for non-manufacturing industries and when we exclude the years following the global financial crisis starting in 2008. However, for manufacturing there is no significant association between the change in R&D capital and TFP, which could be due to the fact that there is only 380 observations available. In total, there is an indication of indirect effects, but there may also be other explanations to the positive association such as measurement error, omitted variables or simultaneity (Stiroh 2002a; 2005).

One possibility is that TFP growth is measured incorrectly at the industry level. This implies that value added or capital services are mismeasured, perhaps because depreciation rates are uncertain, especially for R&D (Hall et al. 2009). This would affect estimations of capital services and thus estimated TFP. Moreover, TFP is measured based on growth accounting, which imposes the assumptions of constant returns to scale and perfect competition. If these assumptions do not hold, TFP may be incorrectly measured (Stiroh 2002a).

The quality of ICT has improved enormously over time. In some countries this is accounted for by quality-adjusted hedonic price indexes. The rapid increase in computing power, as captured in the hedonic price indexes, may overstate the amount of computing power actually used (Stiroh 2002a). However, Sweden only uses hedonic indexing for imported computers and not for semiconductors and software as in the U.S. (Deremar and Kullendorff 2006; Moulton 2001). This could imply that the real growth rate of software capital services could be underestimated for Sweden. In order to test the impact on our results we have recalculated capital services for software based on U.S. deflators.[13] The results are presented in *table 8* and show that our results remain robust also when U.S. price deflators are used to calculate software capital services.

An additional problem may be that productivity is incorrectly measured in the ICT-producing industries due to hedonic prices and double deflation (Edquist 2013). We try to control for this by excluding the ICT-producing industries. In general, our results are robust to the exclusion of ICT-producing industries.

In order to allow for heterogeneous slope coefficients among industries, we introduce the mean group (MG) estimator based on Pesaran and Smith (1995). It averages separate estimates for each industry in the panel. According to Pesaran and Smith (1995), this estimator provides consistent estimates of the parameter averages. The results are presented in *table 10*.[14] In comparison to the pooled regressions (see *table 2*), labor quality adjusted hours remain positive and highly significant. The ICT component is still negative and more significant. Moreover, the contemporaneous effect from hardware is more negative and

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[13] U.S. software deflators are based on EU KLEMS (2011) and only available at the detailed industry level for the period 1993–2007.

[14] Water supply & sewerage (ISIC 36–37) and Residential care & social work (ISIC 87–88) were excluded in the regressions since their coefficient for R&D and hardware were extreme outliers.

significant compared to the pooled regression, while the opposite holds for software. Finally, other capital and R&D are not significant based on the MG estimator. An additional explanation for the association between the change in R&D capital and TFP can be omitted variables. If there are omitted inputs, TFP will be incorrectly measured. Excluded inputs could, for example, be intangibles such as design, marketing, vocational training and organizational change (Brynjolfsson and Hitt 2003; Corrado et al. 2009; Goodridge et al. 2013). According to Edquist (2011), estimated TFP decreased considerably once intangible investments were included as inputs in the Swedish business sector in 1995–2006. However, R&D accounted for a considerable share of these intangible investments in Sweden, which is something we control for.

Finally, the association between R&D and TFP could be the result of simultaneity. Input choices would then be affected by productivity shocks. This implies that firms are believed to respond to productivity shocks by increasing inputs when marginal products rise, i.e., productivity shocks could promote ICT-investments. This problem can be dealt with by instrumental variables. However, we have not been able to find valid instruments. An additional approach that is often proposed is to use lagged variables as instruments (Caselli and Paternò 2001). This method has been criticized by Reed (2015), who demonstrates that this practice does not enable one to escape simultaneity bias.

An alternative to introducing lagged variables would be to use the lagged values as instruments in 2SLS and GMM estimations. However, this is only an efficient estimation strategy if the lagged values do not themselves belong in the respective estimation equations and if they are sufficiently correlated with the simultaneously determined explanatory variables (Reed 2015). Based on the theory and empirical finding of GPTs we find it likely that lagged ICT variables belong to the estimation equation. Hence, we refrain from using this method to correct for simultaneity.

7. Conclusions

We have analyzed whether ICT and R&D-investments are associated with TFP growth based on industry-level data for the Swedish business sector. Indirect effects are defined as contributions from ICT and R&D to total factor productivity (TFP) in each specific industry. The results show that, in the short run, only growth in R&D capital is positively associated with TFP growth, thus exhibiting indirect effects. Hence, ICT capital growth is not significantly associated with TFP growth. This suggests that at the industry level R&D capital only has additional contemporaneous productivity effects beyond capital accumulation and further implies that new knowledge gained through R&D activities is rapidly translated into improvements of product quality and/or more efficient production processes.

When we use longer time periods, we still do not find any positive association between ICT capital and TFP growth. However, when we divide our sample into two time periods and introduce a lagged ICT component, we identify a significant association between lagged ICT capital and TFP growth. Specifically, the change in ICT capital services made in 1993–2003 is associated with TFP growth in the period 2004–2013, while the lagged R&D coefficient becomes insignificant.

Furthermore, we use panel data with smoothed 5-year moving averages and include lagged variables. Then the ICT coefficient becomes increasingly positive and turns significant after seven years. Likewise, the R&D coefficient grows smaller and is insignificant as we extend the lag length. Hence, the indirect effects from R&D investments materialize more rapidly compared to ICT investments, which also is consistent with the literature on General Purpose Technology

When ICT is divided into hardware and software we find that the lagged effect of hardware is significantly associated with TFP growth. Thus, the long-run productivity effects from reorganizing production are associated with hardware investments. Investments in hardware require additional and complementary investments in skills and know-how to reap the full productivity effects from reorganization. These findings also suggest that even if the hardware is replaced or updated with newer and more powerful versions, the process of reorganizing production around the new technology continues.

The delayed effects of hardware investments on TFP are consistent with the literature on general purpose technologies and experience from earlier technological breakthroughs such as electrification. Electrification required additional investments and processes of learning-by-doing to achieve the long-run benefits from reorganizing production. These findings suggest that it may take a long time before the full productivity effects from new ICT-innovations such as the “Internet of things” are realized. Hence, the long-run effects are likely to be achieved by focusing on complementary hardware investments.

TFP growth is crucial for long-term economic development. Our findings point to the importance of implementing incentives for R&D investments, but also suggest that policy should be focused on establishing institutions that encourage firms to have a long-term perspective on investments. Since there is a substantial delay before the positive productivity effects can be reaped, firms that are heavily focused on short-term performance are likely to underinvest in ICT. This is so, despite the fact that ICT investments, both in hardware and software, are likely to be of critical importance for performance for a period extending beyond the current business cycle.

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Appendix A: Capital services

There are different types of capital such as buildings, vehicles and software. Statistics Sweden publishes figures for these different types of capital in terms of capital stocks. However, using capital stocks when analyzing the impact of capital is likely to be misleading, since long-lived types of capital, such as buildings, get too high a weight compared to short-lived assets, such as software. The theoretically correct way to measure capital in a production function is by measuring capital services (Jorgenson and Griliches 1967). These services can be estimated by the rental payments that a profit-maximizing firm would pay when renting its capital.

In order to estimate capital services it is necessary to estimate the capital stock. We estimate the capital stock based on the perpetual inventory method (PIM).[15] The different types of capital included in the calculations were: dwellings, other buildings, transportation equipment, ICT hardware, other machinery and inventories, R&D, software (see *table 8*).[16]

By assuming a geometric depreciation pattern the capital stock (K), for each type of capital (s) at time (t), can be derived according to the following formula:

$$K_{s,t} = (1 - \delta_{s,t})K_{s,t-1} + I_{s,t} \qquad \text{(A.1)}$$

where $K_{s,t}$ is the capital stock, $\delta_{s,t}$ is the depreciation rate and $I_{s,t}$ is real investment.

The depreciation rates used for all types of capital except ICT hardware and R&D are based on EU KLEMS (2011; 2012). The industry structure is based on the new international ISIC rev. 4 industry classification. However, for Wood products (ISIC 16) and Rubber and plastic products (ISIC 22) depreciation rates are based on ISIC rev. 3 due to availability of depreciation rates at a more detailed industry level (see EU KLEMS 2011). *Table 8* shows the depreciation rates used for each type of capital and industry.

ICT hardware includes both communications and computer equipment. According to EU-KLEMS the depreciation rates between these differ. Statistics Sweden only publishes data for the aggregate of these two types of assets. Therefore the depreciation rates in EU KLEMS have been weighted based on the average share of each type of capital in total gross fixed

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[15] For a detailed description, see OECD (2009b).

[16] The capital stocks of (1) Cultivated biological resources and (2) Other intellectual property products were excluded. These two types of capital only accounted for 0.7 percent of total investments in 2012.

capital formation (GFCF). The data on GFCF for communications and computer equipment separately was made available by Statistics Sweden. Finally, the depreciation rate used for R&D has been set to 16.5 percent and should be close to the one used by Statistics Sweden. *Table 8* shows the depreciation rates for each type of capital and industry.

Based on the estimates of the capital stocks and investment price indexes (p^I) it is possible to calculate the internal rate of return for each industry (i):

$$irr_{i,t} = \left[p_t^K K_t + \textstyle\sum_s \left(p_{s,i,t}^I - p_{s,i,t-1}^I\right) K_{s,i,t} - \sum_s p_{s,i,t}^I \delta_{s,i,t} K_{s,i,t}\right] / \left[\textstyle\sum_s p_{s,i,t-1}^I \, K_{s,i,t}\right] \quad \text{(A.2)}$$

where the first term $p_t^K K_t$ denotes overall capital compensation in the economy. By assuming constant returns to scale it can be estimated as value added in current prices minus labor compensation. $p_{s,i,t}^I$ is the investment price of capital s in industry i at time t, $K_{s,i,t}$ is the capital stock, and $\delta_{s,i,t}$ is the depreciation rate. The internal rate of return varies across industries but not across types of capital (s), as the internal rate of return will be equalized across assets in a competitive market.

The internal rate of return ($irr_{i,t}$) is then used to derive the rental prices ($p_{s,i,t}^K$) of each capital type (s) in industry i. The rental price equals the price at which the investor is indifferent between buying and renting the capital good in the rental market. The rental price can be estimated as follows:

$$p_{s,i,t}^K = p_{s,i,t-1}^I irr_{i,t} + \delta_{s,i,t} p_{s.i.t}^I - \left(p_{s,i,t}^I - p_{s,i,t-1}^I\right) \quad \text{(A.3)}$$

where $irr_{i,t}$ is the internal rate of return, $\delta_{s,i,t}$ is the depreciation rate and $p_{s,i,t}^I$ is the investment price of asset s. Thus, eq. (A.3) shows that the rental price is determined by the nominal rate of return, the rate of economic depreciation and the asset-specific capital gain.

Rental prices can be used to calculate capital compensation for each type of capital and industry:

$$c_{s,i,t} = p_{s,i,t}^K K_{s,i,t} \quad \text{(A.4)}$$

Finally, the change in capital services for industry i is obtained as follows:

$$\Delta \ln K_{i,t} = \sum_s \tilde{v}_{s,i,t} \Delta \ln K_{s,i,t} \quad \text{(A.5)}$$

where the weight $\tilde{v}_{s,i,t}$ is the two-period average share of compensation by each type of capital in the total value of capital compensation for all industries:

$$\tilde{v}_{s,i,t} = \frac{1}{2}\left(v_{s,i,t} + v_{s,i,t-1}\right) \quad \text{(A.6)}$$

$$v_{s,i,t} = C_{s,i,t}/\sum_s C_{s,i,t} \quad \text{(A.7)}$$

This method is used to calculate capital services for ICT, R&D and other capital. Finally, the initial base year is 1993, where estimations of the levels of capital stocks are provided by Statistics Sweden (2015b).

Tables

Table 1 Descriptive Statistics

	Median	**Mean**	**Min.**	**Max.**	**St. Dev.**	**Obs.**
Value added	18,141	36,181	2,383	741,578	63,834	987
Quality adjusted hours worked	58	95	3	447	95	987
ICT capital	5,967	10,068	55	56,641	11,703	987
Other capital	18,297	57,208	572	1,509,355	150,467	987
R&D capital	1,087	6,098	1	140,645	17,886	987
Software capital	834	1,963	14	18,412	2,883	987
Hardware capital	5,073	9,530	7	87,549	12,909	987
Δln Value added	0.03	0.03	–1.50	0.74	0.12	940
Δln Quality adjusted hours worked	0.006	0.008	–0.27	0.28	0.03	940
Δln ICT capital	0.07	0.09	–0.12	1.04	0.10	940
Δln Other capital	0.03	0.03	–0.13	1.18	0.06	940
Δln R&D capital	0.03	0.03	–0.18	0.78	0.07	940
Δln Software capital	0.04	0.04	–0.26	2.47	0.11	940
Δln Hardware capital	0.09	0.11	–0.18	1.22	0.15	940

Note: Value added and capital stocks are in millions SEK in 1993 prices. Quality adjusted hours are also in millions.
Source: Statistics Sweden (2015b).

Table 2 Productivity regressions for the Swedish non-farm business sector

	Dependent variable: TFP (current)			
	OLS		Drop ICT-producing	
ΔQuality adjusted hours worked ($\Delta\ln L$)	0.70*** (0.205)	0.70*** (0.206)	0.76*** (0.213)	0.77*** (0.214)
ΔICT capital ($\Delta\ln K_{ICT}$)	–0.06 (0.057)		–0.06 (0.058)	
ΔSoftware capital ($\Delta\ln K_S$)		–0.08*** (0.019)		–0.08*** (0.019)
ΔHardware capital ($\Delta\ln K_H$)		–0.05 (0.036)		–0.04 (0.036)
ΔOther capital ($\Delta\ln K_O$)	–0.33*** (0.098)	–0.31*** (0.096)	–0.35*** (0.100)	–0.34*** (0.097)
ΔR&D capital ($\Delta\ln R$)	0.11*** (0.042)	0.11** (0.042)	0.11** (0.044)	0.10** (0.045)
Time dummies	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes
Adjusted R^2	0.15	0.15	0.11	0.12
Number of observations	940	940	880	880

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Hardware capital includes computer and telecommunications equipment. The following industries are defined as ICT-producing: Computer electronic and optical products (ISIC C26), telecommunications (ISIC J61) and Computer programming and related activities and information services (ISIC J62–J63).

Table 3 Productivity regressions for the Swedish non-farm business sector based on varying difference length

	Dependent variable: TFP (moving average for 3, 5 and 10 year periods)					
	3-year moving average OLS		5-year moving average OLS		10-year moving average OLS	
ΔQuality adjusted hours worked ($\Delta\ln L$)	0.49*** (0.174)	0.51*** (0.174)	0.39** (0.185)	0.41** (0.183)	0.38 (0.303)	0.42 (0.306)
ΔICT capital ($\Delta\ln K_{ICT}$)	–0.08 (0.062)		–0.05 (0.066)		–0.09* (0.047)	
ΔSoftware capital ($\Delta\ln K_S$)		–0.08* (0.042)		–0.05 (0.041)		–0.03 (0.031)
ΔHardware capital ($\Delta\ln K_H$)		–0.07* (0.038)		–0.05 (0.039)		–0.07** (0.029)
ΔOther capital ($\Delta\ln K_O$)	–0.29*** (0.084)	–0.27*** (0.082)	–0.24** (0.096)	–0.22** (0.096)	–0.03** (0.015)	–0.03** (0.015)
ΔR&D capital ($\Delta\ln R$)	0.13*** (0.049)	0.13** (0.050)	0.18*** (0.063)	0.17** (0.065)	0.25** (0.097)	0.25** (0.098)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.29	0.30	0.47	0.47	0.82	0.82
Number of observations	846	846	752	752	517	517

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Hardware capital consists of computer and telecommunications equipment.

Table 4 Productivity regressions for the Swedish non-farm business sector including lags for ICT and R&D

	Dependent variable: $TFP^{2004–2013}$					
	Base case OLS	Lag ICT (I) OLS	Lag ICT (II) OLS	Lag R&D (I) OLS	Lag R&D (II) OLS	Lag ICT and R&D OLS
ΔQuality adjusted hours worked $(\Delta\ln L)^{2004\text{-}2013}$	0.59 (0.389)	0.52* (0.310)	0.74** (0.342)	0.65 (0.388)	0.59 (0.390)	0.75** (0.348)
ΔICT capital $(\Delta\ln K_{ICT})^{2004\text{-}2013}$	−0.14 (0.139)		−0.21 (0.131)	−0.12 (0.142)	−0.14 (0.136)	−0.21 (0.130)
ΔICT capital $(\Delta\ln K_{ICT})^{1993\text{-}2003}$		0.09 (0.061)	0.13* (0.075)			0.13* (0.078)
ΔOther capital $(\Delta\ln K_O)^{2004\text{-}2013}$	−0.63** (0.265)	−0.64** (0.240)	−0.63** (0.251)	−0.58* (0.294)	−0.63** (0.268)	−0.63** (0.258)
ΔR&D capital $(\Delta\ln R)^{2004\text{-}2013}$	0.17* (0.093)	0.16* (0.093)	0.15** (0.092)		0.17 (0.159)	0.14 (0.157)
ΔR&D capital $(\Delta\ln R)^{1993\text{-}2003}$				0.11 (0.137)	−0.004 (0.202)	0.02 (0.195)
Adjusted R^2	0.19	0.20	0.22	0.15	0.17	0.20
Number of observations	47	47	47	47	47	47

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively.

Table 5 Productivity regressions for the Swedish non-farm business sector including lags for software, hardware and R&D

	Dependent variable: $TFP^{2004–2013}$					
	Base case OLS	Lag ICT (I) OLS	Lag R&D (I) OLS	Lag ICT (II) OLS	Lag R&D (II) OLS	Lag ICT and R&D OLS
ΔQuality adjusted hours worked $(\Delta\ln L)^{2004\text{-}2013}$	0.38 (0.271)	0.51 (0.300)	0.45 (0.270)	0.49 (0.245)	0.41 (0.283)	0.51* (0.248)
ΔSoftware capital $(\Delta\ln K_S)^{2004\text{-}2013}$	−0.41* (0.230)		−0.48* (0.253)	−0.34 (0.225)	−0.44* (0.263)	−0.37 (0.255)
ΔSoftware capital $(\Delta\ln K_S)^{1993\text{-}2003}$		0.02 (0.040)		0.02 (0.045)		0.02 (0.046)
ΔHardware capital $(\Delta\ln K_H)^{2004\text{-}2013}$	−0.04 (0.063)		−0.03 (0.063)	−0.09 (0.058)	−0.03 (0.063)	−0.08 (0.058)
ΔHardware capital $(\Delta\ln K_H)^{1993\text{-}2003}$		0.07* (0.037)		0.09 (0.055)		0.09 (0.057)
ΔOther capital $(\Delta\ln K_O)^{2004\text{-}2013}$	−0.50* (0.254)	−0.63** (0.258)	−0.46 (0.295)	−0.48 (0.249)	−0.50* (0.274)	−0.48* (0.265)
ΔR&D capital $(\Delta\ln R)^{2004\text{-}2013}$	0.15 (0.097)	0.16* (0.094)		0.12 (0.089)	0.11 (0.171)	0.09 (0.159)
ΔR&D capital $(\Delta\ln R)^{1993\text{-}2003}$			0.15 (0.111)		0.08 (0.198)	0.07 (0.195)
Adjusted R^2	0.23	0.20	0.23	0.24	0.22	0.23
Number of observations	47	47	47	47	47	47

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Hardware capital consists of computer and telecommunications equipment.

Table 6 Productivity regressions for the Swedish non-farm business sector including lags for ICT and R&D

	Dependent variable: smoothed TFP								
ΔQuality adjusted hours worked ($\Delta \ln L$)	0.45* (0.245)	0.48* (0.272)	0.57* (0.299)	0.69** (0.313)	0.79** (0.319)	0.81** (0.333)	0.70** (0.346)	0.57* (0.322)	0.59* (0.302)
ΔOther capital ($\Delta \ln K_O$)	–0.18 (0.151)	–0.19 (0.193)	–0.21 (0.250)	–0.23 (0.284)	–0.17 (0.313)	–0.08 (0.336)	0.04 (0.345)	0.28 (0.447)	0.39 (0.460)
Lags included	**t – 1**	**t – 2**	**t – 3**	**t – 4**	**t – 5**	**t – 6**	**t – 7**	**t – 8**	**t – 9**
ΔICT capital ($\Delta \ln K_{ICT}$)	–0.005 (0.049)	0.01 (0.038)	0.04 (0.039)	0.06 (0.058)	0.10 (0.081)	0.12 (0.082)	0.13** (0.063)	0.14*** (0.052)	0.15** (0.077)
ΔR&D capital ($\Delta \ln R$)	0.15 (0.105)	0.11 (0.147)	0.08 (0.174)	0.09 (0.153)	0.06 (0.141)	–0.03 (0.168)	–0.15 (0.199)	–0.19 (0.239)	–0.18 (0.328)
Time dummies	No	No	No	No	No	No	No	No	No
Industry dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.40	0.38	0.37	0.39	0.41	0.43	0.44	0.44	0.42
Number of observations	705	658	611	564	517	470	423	376	329

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Data has been smoothed to a 5-year moving average.

Table 7 Productivity regressions for the Swedish non-farm business sector including lags for software, hardware and R&D

	Dependent variable: smoothed TFP								
ΔQuality adjusted hours worked ($\Delta \ln L$)	0.49* (0.243)	0.50* (0.272)	0.58* (0.305)	0.69** (0.326)	0.81** (0.341)	0.85** (0.355)	0.76* (0.386)	0.65* (0.347)	0.66** (0.310)
ΔOther capital ($\Delta \ln K_O$)	–0.16 (0.158)	–0.17 (0.197)	–0.18 (0.248)	–0.21 (0.287)	–0.15 (0.334)	–0.05 (0.382)	0.04 (0.419)	0.22 (0.532)	0.29 (0.530)
Lags included	**t – 1**	**t - 2**	**t – 3**	**t – 4**	**t – 5**	**t – 6**	**t – 7**	**t – 8**	**t – 9**
ΔSoftware capital ($\Delta \ln K_S$)	–0.01 (0.065)	0.02 (0.054)	0.05 (0.040)	0.07 (0.040)	0.10 (0.061)	0.11 (0.085)	0.06 (0.086)	–0.003 (0.085)	–0.04 (0.088)
ΔHardware capital ($\Delta \ln K_H$)	–0.02 (0.035)	–0.02 (0.029)	0.0001 (0.027)	0.02 (0.035)	0.05 (0.051)	0.08 (0.056)	0.09* (0.049)	0.10** (0.038)	0.09** (0.043)
ΔR&D capital ($\Delta \ln R$)	0.15 (0.107)	0.11 (0.148)	0.08 (0.175)	0.09 (0.152)	0.05 (0.137)	–0.03 (0.162)	–0.15 (0.194)	–0.20 (0.237)	–0.20 (0.334)
Time dummies	No	No	No	No	No	No	No	No	No
Industry dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.40	0.38	0.37	0.39	0.41	0.43	0.44	0.44	0.41
Number of observations	705	658	611	564	517	470	423	376	329

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Data has been smoothed to a 5-year moving average. Hardware capital consists of computer and telecommunications equipment.

Table 8 Depreciation rates used for each type of capital and industry

ISIC Rev.4	Industry	Dw	OtBu	TrEq	ICT–H	OtMa	R&D	ICT –S
B05–09	Mineral extraction	0.011	0.024	0.170	0.161	0.129	0.165	0.315
C10–C12	Food, beverages & tobacco	0.011	0.033	0.168	0.161	0.109	0.165	0.315
C13–C15	Textile, clothing & leather prod.	0.011	0.033	0.184	0.161	0.109	0.165	0.315
C16	Wood products	0.011	0.032	0.183	0.161	0.109	0.165	0.315
C17	Paper & paper products	0.011	0.033	0.173	0.161	0.106	0.165	0.315
C18	Printing & recorded media	0.011	0.033	0.173	0.161	0.106	0.165	0.315
C19	Coke & refined petroleum prod.	0.011	0.032	0.154	0.161	0.110	0.165	0.315
C20–C21	Chemicals& pharmaceuticals	0.011	0.033	0.181	0.161	0.104	0.165	0.315
C22	Rubber & plastic prod.	0.011	0.033	0.202	0.161	0.113	0.165	0.315
C23	Non-metallic mineral prod.	0.011	0.033	0.191	0.161	0.112	0.165	0.315
C24	Basic metals	0.011	0.033	0.169	0.161	0.106	0.165	0.315
C25	Fabricated metal products	0.011	0.033	0.169	0.161	0.106	0.165	0.315
C26	Computer, electronical and optical prod.	0.011	0.033	0.166	0.161	0.108	0.165	0.315
C27	Electrical equipment	0.011	0.033	0,166	0.161	0.108	0.165	0.315
C28	Machinery & equipment n.e.c.	0.011	0.033	0.170	0.161	0.107	0.165	0.315
C29	Motor vehicles & trailers	0.011	0.033	0.167	0.161	0.109	0.165	0.315
C30	Other transport equipment	0.011	0.033	0.167	0.161	0.109	0.165	0.315
C31–C32	Furniture & other manufacturing	0.011	0.033	0.193	0.161	0.113	0.165	0.315
C33	Repair & installation of machinery	0.011	0.033	0.193	0.161	0.113	0.165	0.315
DD35	Electricity, gas & steam	0.011	0.023	0.191	0.161	0.094	0.165	0.315
E36–E37	Water supply & sewerage	0.011	0.023	0.191	0.161	0.094	0.165	0.315
E38–E39	Waste collection &materials recovery	0.011	0.023	0.191	0.161	0.094	0.165	0.315
F41–F43	Construction	0.011	0.034	0.195	0.161	0.139	0.165	0.315

G45	Wholesale & retail trade of motor vehicles	0.011	0.031	0.229	0.161	0.121	0.165	0.315
G46	Wholesale trade, except motor vehicles	0.011	0.031	0.204	0.161	0.143	0.165	0.315
G47	Retail trade, except motor vehicles	0.011	0.027	0.215	0.161	0.137	0.165	0.315
H49	Land transport	0.011	0.028	0.092	0.161	0.118	0.165	0.315
H50	Water transport	0.011	0.028	0.092	0.161	0.118	0.165	0.315
H51	Air transport	0.011	0.028	0.092	0.161	0.118	0.165	0.315
H52–H53	Warehousing for transportation & postal activities	0.011	0.027	0.201	0.161	0.096	0.165	0.315
H55–H56	Hotels & restaurants	0.011	0.028	0.203	0.161	0.140	0.165	0.315
J58	Publishing activities	0.011	0.033	0.173	0.161	0.106	0.165	0.315
J59–J60	Motion pictures & broadcasting	0.011	0.033	0.173	0.161	0.106	0.165	0.315
J61	Telecommunications	0.011	0.027	0.201	0.161	0.096	0.165	0.315
J62–J63	Computer programming & consultancy	0.011	0.044	0.155	0.161	0.144	0.165	0.315
K64	Financial services, except insurance	0.011	0.044	0.187	0.161	0.149	0.165	0.315
K65	Insurance & pension funding	0.011	0.044	0.187	0.161	0.149	0.165	0.315
K66	Activities auxiliary to financial services & insurance	0.011	0.044	0.187	0.161	0.149	0.165	0.315
L68A	Real estate activities with own or leased property	0.011	0.027	0.227	0.161	0.147	0.165	0.315
L68B	Management of real estate	0.011	0.027	0.227	0.161	0.147	0.165	0.315
M69–M70	Legal, accounting & management consultancy activities	0.011	0.044	0.155	0.161	0.144	0.165	0.315
M71–M72	Architectural & engineering activities	0.011	0.044	0.155	0.161	0.144	0.165	0.315
M73–M75	Advertising & marketing research	0.011	0.044	0.155	0.161	0.144	0.165	0.315
N77	Rental & leasing activities	0.011	0.044	0.155	0.161	0.144	0.165	0.315
N78–N82	Administration & support activities	0.011	0.044	0.155	0.161	0.144	0.165	0.315
P85	Education	0.011	0.025	0.173	0.161	0.138	0.165	0.315
P86	Health activities	0.011	0.027	0.225	0.161	0.149	0.165	0.315
Q87–Q88	Residential care & social work	0.011	0.027	0.225	0.161	0.149	0.165	0.315
R90–R93	Art, entertainment & recreation	0.011	0.051	0.223	0.161	0.136	0.165	0.315
S94–T98	Other service activities	0.011	0.051	0.223	0.161	0.136	0.165	0.315

Note: Dw = Dwellings, OtBu = Other buildings, TrEq = Transport equipment, ICT-H = ICT Hardware, OtMa = Other Machinery, ICT–S = ICT Software.

Source: EU KLEMS (2011; 2012) and Statistics Sweden (2015b).

Table 9 Robustness regressions for the Swedish non-farm business sector

	Dependent variable: TFP (current)					
	Manufacturing		Other industries		1993–2007	
ΔQuality adjusted hours worked ($\Delta\ln L$)	1.15* (0.556)	1.13* (0.561)	0.32* (0.168)	0.33* (0.168)	0.42*** (0.115)	0.43*** (0.114)
ΔICT capital ($\Delta\ln K_{ICT}$)	–0.12 (0.144)		–0.07 (0.063)		–0.07 (0.069)	
ΔSoftware capital ($\Delta\ln K_S$)		–0.15 (0.146)		–0.06*** (0.019)		–0.06*** (0.013)
ΔHardware capital ($\Delta\ln K_H$)		–0.14 (0.107)		–0.04 (0.037)		–0.05 (0.047)
ΔOther capital ($\Delta\ln K_O$)	0.26 (0.490)	0.36 (0.491)	–0.35*** (0.068)	–0.34*** (0.065)	–0.33*** (0.048)	–0.32*** (0.049)
ΔR&D capital ($\Delta\ln R$)	0.11 (0.095)	0.10 (0.099)	0.10* (0.055)	0.09* (0.055)	0.26** (0.118)	0.26** (0.120)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.21	0.21	0.19	0.19	0.27	0.27
Number of observations	360	360	580	580	658	658

Note: The estimates are based on OLS for 47 industries in the period 1993–2013. Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Hardware capital includes computer and telecommunications equipment. Manufacturing industries are defined as ISIC 10–33 and other industries as ISIC 05–09 and ISIC 35–98.

Table 10 Robustness regressions for the Swedish non-farm business sector

	Dependent variable: TFP (current)			
	Mean group (MG) estimator		US software deflators 1993–2007	
ΔQuality adjusted hours worked (Δln$L$)	0.86*** (0.274)	0.91*** (0.275)	0.42*** (0.115)	0.43*** (0.114)
ΔICT capital (ΔlnK_{ICT})	–0.12* (0.060)		–0.07 (0.069)	
ΔSoftware capital (ΔlnK_S)		0.02 (0.076)		–0.06*** (0.013)
ΔHardware capital (ΔlnK_H)		–0.08* (0.044)		–0.06 (0.047)
ΔOther capital (ΔlnK_O)	–0.15 (0.206)	–0.22 (0.205)	–0.33*** (0.048)	–0.32*** (0.048)
ΔR&D capital (Δln$R$)	0.05 (0.139)	0.09 (0.140)	0.26** (0.119)	0.26** (0.120)
Industry trend	–0.003** (0.002)	–0.002 (0.002)		
Time dummies	-	-	Yes	Yes
Industry dummies	-	-	Yes	Yes
Adjusted R^2	-	-	0.27	0.27
Number of observations	900	900	658	658
Number of industries	45	45	47	47
Number of sign. trends	5	4	-	-
RMSE	0.080	0.078	-	-

Note: Estimates are based on the mean of each industry based on Pesaran and Smith (2005). RMSE is the root mean squared error. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Hardware capital includes computer and telecommunications equipment. Water supply & sewerage (ISIC 36–37) and Residential care & social work (ISIC 87–88) were excluded in the mean group regressions since their coefficient for R&D and hardware were extreme outliers. Data on US software price deflators are based on EU KLEMS (2011) and were only available for the period 1993–2007.