STOCKHOLM SCHOOL OF ECONOMICS
Department of Economics
5350 Master's thesis in economics
Academic year 2014–2015

Complementarity between ICT and Intangible Capital

Emanuel Welander (22057)

Abstract: Major technological innovations, including ICT, often affect productivity with a long lag. One suggested explanation for this is that such technological innovations require intangible co-investments in for example business processes and human capital before being fully productive. Using industry level intangible capital data for 9 European countries for the years 1995-2007, I test this explanation for the case of ICT by examining whether ICT is more productive when it is complemented by intangible capital. Estimating a production function, I find that the output elasticity of ICT in an industry is positively related to the use of intangible capital in that industry. Decomposing intangible capital, I find that this complementarity is primarily driven by intangible assets related to organizational capital, workforce training and marketing. The results thus support the idea that ICT requires intangible co-investments in organizational capital and related intangibles to be fully productive.

Keywords: Intangible capital, ICT, productivity growth, economic growth

JEL: O47, E22, E23

Supervisors: Kelly Ragan & Harald Edquist
Date submitted: May 14, 2015
Date examined: May 25, 2015
Discussant: Lukas Kvissberg
Examiner: Johanna Wallenius

Acknowledgement

I would like to thank my supervisor at the Stockholm School of Economics, Kelly Ragan, for insightful comments on the thesis. Moreover, I would like to thank Ericsson and my supervisor there, Harald Edquist, for allowing me to write this thesis at Ericsson and for giving me support throughout the process of writing it.

1. Introduction

Economic growth depends on technological innovations.[1] But there is more than one channel through which technological innovations contribute to economic growth. In particular, many innovations allow, or require, changes in how business and production is organized. Electricity made possible better factory layouts than steam power (Devine 1983, David & Wright 2003). The telegraph made possible geographically dispersed enterprises (Milgrom & Roberts 1992). Seen in another way, technological innovation may require co-investments in human or organizational capital to fully contribute to growth. A technological innovation is simply not as productive without these co-investments. In this thesis, I will study this aspect for another important technological innovation: information and communication technology (ICT).

The idea that new technologies require co-investments is also related to the empirical phenomenon that there tends to be a long lag between a major technological breakthrough and the observation of any substantial increase in the growth of productivity (Edquist & Henrekson 2006). The first widely used steam engine was invented in 1712, followed by the famous Watt engine in 1765. But aggregate productivity growth in the frontier economy at the time, the UK, did not accelerate until after 1850. Similarly, the inventions allowing for commercial applications of electricity generation occurred during 1856 to 1880. However, US productivity growth decelerated during 1901-1919, only accelerating again in the period thereafter. With ICT, this phenomenon of large investment in new technology without any visible macroeconomic effects was dubbed the "Solow Paradox." The transistor was invented as early as 1947. But despite heavy investments in ICT during the 1970s and 1980s, productivity growth slowed, only accelerating again during the second half of the 1990's.

These productivity lags could potentially be explained by the need to make intangible co-investments. If firms do not make these intangible investments, they see no productivity growth from the new technology. If they do make the investments, they will have to divert resources for that purpose. This would lower their conventional output, with the result that their productivity drops. With regards to ICT, this could help explain the Solow Paradox. In addition, if the US had made these intangible co-investments earlier than Europe, by for example already having management better suited to ICT, complementarity between ICT and intangible capital would predict higher total factor productivity (TFP) growth in ICT-intensive industries in the US than in Europe, just as the evidence indicates (Jorgenson et al. 2008).

Implicit in all these arguments is that the new technology, here ICT, is more productive when combined with intangible capital. This is also my hypothesis, that ICT and intangibles are complements, in the sense that they are more productive when used together. Previous micro level research supports this idea.[2] I go beyond this research by considering if the same relation holds when measured at the industry level. My approach in doing this is based on recognizing that expenditures on intangibles can be considered investments and that intangible capital can be

[1] See for example Mokyr (1990).
[2] See for example Caroli and van Reenen (2001), Bresnahan et al. (2002), Brynjolfsson et al. (2002), Crespi et al. (2007) and Bloom et al. (2012).

considered a factor of production. In this way I follow the literature on intangible capital. My first research question is thus: are ICT capital and intangible capital more productive together when measured at the industry level?

Previous industry level research indicates that the accumulation of intangible capital contributes more to labor productivity growth in ICT-intensive industries.[3] I consider instead how the productivity of ICT varies with the level of intangible capital. I do this by estimating a transcendental logarithmic (translog) production function, thus imposing no prior restrictions on possible complementary relations between any inputs. Beyond using the estimated parameters to test for ICT-intangible complementarity, I use them to try to quantify the importance of any ICT-intangible complementarity to recent productivity growth. In contrast to previous research, I also derive capital service measures in levels using the superlative index numbers approach of Caves et al. (1982). Moreover, intangible capital consists of different types of assets, only some of which are related to the organizational or human capital of the firm. Previous industry level research has not thoroughly determined to what extent there are differences among different intangible assets with regards to ICT-intangible complementarity. I hypothesize that it is intangible assets related to human and organizational capital that make ICT more productive. This leads me to my second research question: are there any differences among subsets of intangible assets with regards to any potential ICT-intangible complementarity?

Using industry level data instead of firm level data provides both advantages and disadvantages. For example, an obvious disadvantage is that I lose within industry variation. However, it should be noted that industries are something different than firms. It is possible that firms with both more ICT and intangible capital are more productive than firms with only ICT capital, without this implying that there are any differences across industries. Lessons for policy differ depending on if any complementarity is solely the result of the use of intangible and ICT capital varying within industries, rather than across industries. However, the main advantage of using aggregate industry level data is that it is possible to quantify the importance of any complementarity to aggregate growth in labor productivity. Moreover, it should be noted that the use of industry data allows for better measures of real variables due to the possibility of using industry-specific price deflators. In contrast, firm-specific price deflators generally do not exist, and researchers usually have to assume that industry-specific deflators are appropriate.

To summarize, I use industry level data to first look at whether ICT is more productive when complemented by intangible capital. I then look at whether any potential complementarity is common to all types of intangible assets, or if there are differences among the assets. Using the results from this, I can quantify the importance of any ICT-intangible complementarity to aggregate productivity growth.

The thesis is organized as follows. The next section provides background, wherein I review the literature on ICT and intangible capital and discuss why we should expect them to be complements.

[3] See Chen et al. (2014) and Corrado et al. (2014).

Section 3 presents the theoretical framework and my empirical approach in testing the hypothesis. Section 4 presents the data and the evolution of the relevant variables. I present the results in section 5. In section 6 I discuss the results and their implications, while section 7 concludes.

2. Background

I start this section by providing definitions of ICT and intangibles. Following that, I review the literature on the productivity contributions from ICT and intangible capital, concluding that both have been important drivers of growth and labor productivity. I will then review the relevant literature connecting ICT and intangibles and discuss why we should expect them to be complements. I also review what empirical evidence already exists of this.

2.1 Defining ICT and intangibles

The OECD's Working Party on Indicators for the Information Society (WPIIS) provides a definition of ICT products and the ICT-producing sector. OECD (2009a, p. 18) defines ICT products by the restriction that they "[…] must primarily be intended to fulfil or enable the function of information processing and communication by electronic means, including transmission and display." OECD (2009a, p. 32) similarly defines an industry to be in the ICT producing sector if its production is primarily "[…] intended to fulfil or enable the function of information processing and communication by electronic means including transmission and display." These are the definitions generally used, and which I also use, when referring to ICT and the ICT-producing sector.

No similar definition exists for intangible capital. However, Corrado et al. (2005) provide definitions for three subsets of intangible spending. These definitions have then been used by those authors when constructing their intangible investment data. They have also been used by other authors when deriving measures of intangible investments based on the framework by Corrado et al. (2005). Corrado et al. (2005, p. 23) define intangible spending as consisting of three broad groups: computerized information, innovative property and economic competencies. Computerized information is defined as "knowledge embedded in computer programs and computerized databases." Innovative property is defined as "knowledge acquired through scientific R&D and nonscientific inventive and create activities."[4] In practice, innovative property is made up of conventional R&D and non-scientific R&D (Corrado et al. 2009). Non-scientific R&D refers to architectural and engineering designs and new product development in the financial sector. Corrado et al. (2005, p. 23) define the third group of intangible spending, economic competencies, as "knowledge embedded in firm-specific human and structural resources, including brand names." The individual intangible assets that make up economic competencies are firm-specific human capital, organizational structures and brand equity (Corrado et al. 2005, p. 24). The definitions for computerized information, innovative property and economic competencies make up the definition for intangible spending. The share of this spending that has a long-lasting effect can then be thought of as intangible investments. However, I am mainly concerned with the intangible assets defined by economic competencies and innovative property. Even though it is intangible, I group computerized information with other ICT-related capital.

[4] R&D refers to research and development.

2.2 Contribution from ICT

The start of the ICT revolution can be argued to have been with the invention of the transistor in the 1940s (Edquist & Henrekson 2006). Subsequent developments have over time then produced wide commercial applications of ICT, followed by substantial ICT capital investments.[5] However, as of the early 1990s, this could not be shown to have yielded any substantial growth in productivity. Indeed, the US and many Western European countries had experienced a slowdown in economic growth since the early 1970s (Nordhaus 2004). The situation, dubbed the "Solow Paradox," was famously summed up in a quote by Solow (1987, p. 36): "You can see the computer age everywhere but in the productivity statistics."

Oliner and Sichel (1994) and Jorgenson and Stiroh (1995) were among the first to quantify the impact of ICT using growth accounting. Their results showed only modest contributions from ICT capital up to the mid 1990's. The authors argued that investments in ICT had been relatively small. As such, ICT capital deepening should not have shown any large contributions. Using firm level data, Brynjolfsson and Hitt (1996) confirmed that ICT contributed to growth. However, these authors found a greater impact of ICT, with for example returns and marginal products of ICT capital and staff greater than non-ICT capital and staff.

US productivity growth began to accelerate after 1995. At the same time, business investment in ICT grew substantially, increasing more than fourfold between 1995 and 1999 (Oliner & Sichel 2000). By 2000, a third of nonresidential fixed investment was in ICT. Subsequent research has established a link between the productivity growth and the investments in ICT (see for example Jorgenson et al. 2008).

It is useful to distinguish between various channels by which ICT can contribute to economic growth. First of all, ICT may increase labor productivity through capital deepening in those sectors using ICT. Second, productivity in the ICT-producing sector may increase as the technology improves. This would show up as TFP growth in that sector. These are the only possible channels under the standard neoclassical assumptions used in growth accounting. But it is also possible that the use of ICT may affect productivity beyond its effect through capital deepening. In other words, the use of ICT may be related to TFP growth outside the ICT producing sector. Jorgenson et al. (2008) argue that the first two channels were the main sources of US productivity growth between 1995 and 2000, after which the third channel has been the dominant source.

The ICT-producing sector saw rapid technological development as, among other developments, computer chip density doubled every 18-24 months in accordance with Moore's Law.[6] The resulting gains in efficiency showed up as increasing TFP in those industries producing ICT. The rapid technological development led to an equally rapid decrease in prices for ICT, with the result that firms substituted ICT capital for other inputs. Using growth accounting, Jorgenson et al. (2008)

[5] The first commercial computer (the UNIVAC) was introduced in the 1950's (Jorgenson et al. 2008).

[6] See Moore (1965) for the original pronouncement about computer chip density.

show that ICT accounted for almost 60 percent of labor productivity growth in the US between 1995 and 2000.

For the years 2000 to 2006, ICT accounted for 38 percent of labor productivity growth, down from almost 60 (Jorgenson et al. 2008). This reflected a decrease in ICT capital deepening and slower TFP growth in the ICT-producing sector. Nonetheless, TFP growth in industries not producing ICT increased. Jorgenson et al. (2007) showed that this TFP growth to a large extent occurred in those industries that were the most intensive users of ICT. In addition, Stiroh (2002) has shown the post-1995 productivity acceleration is related to ICT use, with ICT-intensive industries experiencing greater productivity growth then less ICT-intensive industries. However, Oliner et al. (2007) argue that the post-2000 productivity acceleration is not related to ICT use. Instead, they present evidence that links the productivity acceleration to increased competitive pressure and restructuring among firms. So while there is agreement that ICT has been important, different authors disagree on the exact channel by which ICT increases labor productivity and for which time period ICT has been important.

So far, I have only presented research for the US. Europe did not have a similar productivity acceleration in the 1990's. Indeed, European labor productivity growth actually slowed for the period 1995-2004 compared to 1980-1995 (van Ark et al. 2008). But while aggregate productivity growth was slower, growth accounting shows that ICT capital deepening contributed to a third of labor productivity growth in the EU.[7] The contribution from TFP in the ICT-producing sector has also accelerated, albeit less than in the US. The *level* of productivity in this sector is however only 77 percent of US level (O'Mahony & Timmer 2009).[8] What mainly accounts for the difference in productivity growth and levels is that the US has higher growth and levels of TFP. As noted above, this growth in TFP was concentrated in those industries using ICT intensively and in the ICT-producing sector.

While Europe as a whole had slower productivity growth than the US for the years 1995-2004, the experience of individual European countries show some differences (O'Mahony & Timmer 2009). The countries of Belgium, Denmark and the Czech Republic all had equal or higher contributions to labor productivity from ICT capital deepening compared to the US. ICT capital deepening in the US contributed 1.0 percent to labor productivity growth during 1995 to 2004, while ICT contribution in these other three countries were at between 1.0 to 1.1 percent. Sweden, the UK, Ireland and the Netherlands were also nearly at this level, with ICT contributions in the range 0.8 to 0.9 percent. These European countries also all had productivity growth rates higher than the EU aggregate growth rate. Additionally, Sweden and Ireland even had higher productivity growth than the US.

In summary, ICT has contributed to productivity growth in both the US and Europe. However, several questions remain. For one, why did the US experience a greater contribution from ICT than Europe, in particular in the ICT-using industries? Second, why did the productivity gains from ICT

---

[7] Van Ark et al. (2008) use data for ten EU countries to calculate this: Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Spain, and the United Kingdom.

[8] Only Sweden and Finland have greater levels of productivity in the ICT-producing sector than the US.

only start to appear in the mid 1990's when both the technology and commercial applications of it had existed for decades? One potential explanation for both questions is that successful implementation of new technologies requires investments in complementary assets such as educating the workforce and reorganizing business processes. This would imply that investments in intangible capital and ICT are complements, which I will get back to below.

2.3 Contribution from intangible capital

Investments in intangible capital are now understood to be of great importance for growth in productivity and output. In some cases, capital deepening including intangible capital takes over from TFP as the dominant source of growth (Corrado et al. 2013). Understanding this productive impact of intangibles had long been hampered by a lack of data. Most intangibles are treated as expenditures in the national accounts and not measured explicitly.[9] Researchers have thus had to find other ways to measure intangibles. An early approach was to use the value of securities compared to some measure of companies' tangible assets to infer the value of their intangible assets.[10] Others, like MacGratten and Prescott (2000), derive measures of intangible capital by trying to value the implicit income streams from intangible capital. While these approaches obviously have their uses, neither approach produces the kind of comprehensive measures required for national accounting or sources-of-growth analysis.

The need for comprehensive measures has successively led to the development of the approach currently standard in the sources-of-growth literature. The approach implies that investments in intangible capital are estimated based on their cost in production. It thus mirrors the cost-based accounting approach already taken for tangible assets. The approach was first taken by the OECD (1998), followed by Nakamura (1999, 2001, 2003). These attempts were followed by Corrado et al. (2005), which standardized the approach and on which most subsequent intangible measurements are based. All these attempts found sizable values of intangible investments for the US (approximately 10 percent of GDP), comparable in size to investments in tangible capital. Indeed, Nakamura (2010) later found that intangible investments reached the size of tangible investments in the US by the year 2000.

Building on the work by Corrado et al. (2005), numerous researchers have created estimates of intangible investments for other countries. Intangible investment as a share of GDP is generally lower in Europe than in the US, with most countries in a range of 6-9 percent (Jalava et al 2007, Van Rooijen-Horsten et al. 2008, Hao et al. 2009, van Ark et al. 2009). The exceptions are Sweden and the UK, with 13 and 10 percent respectively (Marrano et al. 2009, Edquist 2011a).

Using growth accounting, the contribution from intangible capital to labor productivity growth can then be calculated. A few countries have seen intangibles accounting for close to, or more than, half

[9] The exceptions are software and databases, mineral exploration, and entertainment, artistic and literary originals (OECD 2009b). These have been capitalized since the adoption of the 1993 SNA. With the introduction of the 2008 System of National Accounts, R&D is now also capitalized.
[10] See for example Hall 2000, 2001a, 2001b.

of labor productivity growth. Between 1995 and 2000, intangibles accounted for 41 percent of the labor productivity growth in Sweden (Edquist 2011a). Moreover, it contributed 59 percent in Italy and 64 percent in Spain between 1995 and 2003 (Hao et al. 2009). However, the contribution in Italy decreases to 41 percent and in Spain to 26 percent when measured over the longer period 1995 to 2006 (Van Ark et al. 2009).

The contribution from intangibles is more modest in other European countries, albeit still at a sizable level. Germany, France, Austria and the Czech Republic all had contributions in the range of 15 to 26 percent over the period 1995 to 2006 (Van Ark et al. 2009). Similar levels are found in Finland and Japan when calculated over the period 1995 to 2005, and the US and UK when calculated for 1995 to 2003 (Jalava et al. 2007, Corrado et al. 2009, Fukao et al. 2009, Marrano et al. 2009).

Measures of intangible capital for individual countries have then been harmonized and made comparable by The Conference Board and through research projects such as COINVEST and INNODRIVE. Recently, the national level measures have been disaggregated to the industry level for European countries (O'Mahony et al. 2012, Corrado et al. 2014). Comparable measures for a large number of countries have allowed the econometric estimation of intangible capital output elasticity. These estimates, particularly those using country level data, tend to be higher than the factor share of intangible capital. Roth and Thum (2013) estimate an output elasticity of intangible capital between 25 and 29 percent. Together with tangible capital, this makes capital deepening more important than TFP for labor productivity growth. Corrado et al. (2014) estimate an even greater output elasticity of almost 48 percent.

Niebel et al. (2013), using industry level instead of country level data, similarly estimate output elasticites for intangible capital that exceed their factor share. However, their elasticities are far lower, at only 10 to 20 percent. In some of their specifications, they even find no significant difference between the output elasticity and the factor share. Using industry level data thus seems to produce lower measure of output elasticity for intangible capital than estimates based on country level data.

Growth accounting using industry level intangibles has also shed light on the industry heterogeneity with regards to intangibles. Niebel et al. (2013) for Europe, Chun et al. (2012) for Japan and Edquist (2011b) for Sweden show that the contribution of intangible capital to labor productivity is higher in manufacturing than in services.

2.4 ICT-intangible complementarity

The hypothesis of ICT-intangible complementarity is mainly based on two ideas. The first builds on the fact that ICT is about information processing generally, and not simply "crunching numbers." The second builds on ICT as a general-purpose technology (GPT).

Based on case studies, the management literature was early in proposing that ICT investments may require co-investments in the organization and in business processes to increase performance

(Drucker 1988, Davenport & Short 1990, Hammer 1990). An implied lack of change in business processes at most firms investing in ICT would then be able to explain the early lack of macro level productivity growth. As Hammer (1990, p. 104) notes:

> "[…] heavy investments in information technology have delivered disappointing results – largely because companies tend to use technology to mechanize old ways of doing business. They leave the existing processes intact and use computers simply to speed them up."

This idea was further built upon by, among others, Brynjolfsson and Hitt (2000). These authors note that organizations and markets can be seen as information processors.[11] But most of our economic institutions emerged when communications costs were high and computational ability limited. Companies were thus organized to function in an environment with limited and costly information processing. This organization would not be optimal for taking advantage of the increasingly cheaper and more powerful ICT which has emerged. Organizational changes would thus be required before being able to use ICT to its fullest potential. In a sense, productivity growth depends not just on technological innovations, but also on the organizational changes enabled by them.

ICT may additionally be seen as a GPT. GPTs are technologies that are usable in a wide range of sectors and are characterized by a technological dynamism (Bresnahan & Trajtenberg 1995). Moreover, they act as "enabling technologies," in that they open up new possibilities rather than simply offering complete solutions. These new possibilities could be further technological innovation as well as organizational innovations. Since ICT fits the characteristics of a GPT, on the basis of the theory, we would expect that ICT would open up possibilities for new innovations. Intangible investments represents some of these innovations, in particular the organizational ones. Firms or industries with both intangible and ICT capital could then be expected to be more productive than firms or industries with only ICT, since those without intangible capital would not have implemented the organizational innovations enabled by ICT. In other words, ICT and intangible capital would be complements.

It is also possible to draw parallels to previous technologies, which have also contributed to productivity and growth not only through being technological innovations, but also by the organizational changes enabled by them. As an example, the telegraph allowed the creation of geographically dispersed enterprises (Milgrom & Roberts 1992). But other GPTs have also, similar to ICT, shown very long periods between invention and a visible contribution to productivity (Edquist & Henreksson 2006).

A comparison can in particular be made with electricity, another GPT. Electricity did not at first improve labor productivity or TFP in factories (Devine 1983, David & Wright 2003). The only thing that changed was the power source of the machines as steam power was phased out. As such, production was still organized around the specific restrictions given by steam powered machines. But in contrast to steam powered machines, the electric motor enabled far more flexibility in the

[11] See also Hayek (1945), Simon (1976), Galbraith (1977) and Hornstein et al. (2005).

organization of production. Labor productivity and TFP only started to grow once the electrical motor was used more efficiently by also taking advantage of the flexibility it provided in organizing production.

Empirical research on ICT-intangible complementarity has mainly focused on the micro level, and evidence there generally supports the theory. Measures of organizational change or decentralization tend to be connected to ICT, and they are together correlated with measures of productivity. One example is that more decentralized firms with above average ICT investments are more productive than firms not decentralized with above average ICT investments (Bresnahan et al. 2002). Similar results hold when considering market value instead of productivity (Brynjolfsson et al. 2002).

Another example is that Caroli and van Reenen (2001) find complementarity, albeit not robust, between organizational and technical change. Similarly, Bloom et al. (2012) note that US multinationals operating in Europe achieves higher IT productivity than non-US multinationals or domestic firms. This includes establishments taken over by US multinationals, which subsequently also achieve higher IT productivity. This productivity difference between American and European firms can be explained with US multinationals having tougher "people management" practices. Crespi et al. (2007) also find that US-owned firms operating in the UK are more likely to introduce organizational change than domestic firms. More importantly, the authors find that organizational change and IT interact in their effect on productivity growth. Returns from IT are thus greater when combined with organizational change.

Brynjolfsson and Hitt (2003) do not try to measure intangibles or organizational changes directly. Instead, they propose that complementary investments should take time. A testable implication is then that the long-run benefits of ICT should exceed the short-run. This is exactly what the authors find: normal returns roughly equal to cost on a one year basis and up to five times as high returns on a five to seven years basis.

Intangible assets have been put forward as one explanation for Solow Paradox noted above and the related US productivity miracle starting in the 90s (Caroli & van Reenen 2001). Indeed, Black and Lynch (2004) find that the variation in multifactor productivity in the US between 1993 and 1996 can be explained by new workplace practices related to ICT. Given the lower rate of intangible investments in Europe than in the US, intangibles have also been proposed as the explanation for why Europe has not experienced a similar productivity acceleration outside the ICT-producing industries. Supporting this is the fact that US multinationals operating in Europe experienced productivity growth similar to firms operating the US (Caroli & van Reenen 2001). As I noted above, it was possible to explain the firm level productivity differences with different management practices in the US multinationals.

Recently, a few papers have been investigating this proposed complementarity at a macro level instead of at the firm level. Evidence here is however more scarce, in all certainty due to the above mentioned previous lack of data for intangibles. O'Mahony & Peng (2011) were among the first to examine the intangible-ICT complementarity at the industry level. The authors capitalize workforce training and examine its effect on labor productivity at the industry level in EU countries. They then regress an interaction of this training capital with ICT capital on labor productivity. This interaction term is found to be positive and significant, implying complementarity between ICT and workforce training. Since workforce training is likely to be endogenous, the authors also implement an instrumental variable approach. The results from this still show positive and significant complementarity, although smaller in magnitude.

To my knowledge, only two papers so far attempt to measure any macro level complementarity between ICT and intangibles using a comprehensive set of intangible capital measurements. Both attempt to measure complementarity by looking at whether intangible capital is more productive in ICT-intensive industries. The first of the papers, Corrado et al. (2014), show that intangible investment at the national level is related to industry level labor productivity growth, with the growth effect being higher the more intensely an industry used ICT capital. The main problem here is that their intangible capital data is at the national level. As such, while national level intangible capital is related to higher productivity growth in more ICT-intensive industries, it is impossible to say how this capital is distributed between industries.

However, one advantage of their results is that, using country level intangibles capital, they are able to use an instrumental variable (IV) approach to mitigate the potential endogeneity of intangible capital. Their idea is that there might be unobservable technological opportunities raising both the growth of intangible capital and the growth in output. The authors argue that, on the assumption that the US is the technological frontier country, growth in US intangible capital can be used to instrument growth in European intangible capital. Interestingly, in their IV results, the interaction between country level intangible capital growth and industry level ICT-intensity is higher than in their ordinary least squares (OLS) results. In contrast to O'Mahony and Peng (2011), they thus find a negative bias.

In the second paper, Chen et al. (2014) use the same method but with industry level intangible investment data from INDICSER for ten European countries. The authors estimate a Cobb-Douglas production function with interaction terms for ICT-intensity and capital growth. The interaction between ICT-intensity and growth in intangibles is positive and significant, implying that intangible capital has higher output elasticity in ICT-intensive industries. Using industry level intangible data, these authors were not able to use the same instrumental variable approach as Corrado et al. (2014).

In summary, we have theoretical reasons for expecting complementarity between ICT and intangible capital and substantial micro level evidence for it. At the macro level we have some evidence that intangible capital is more productive in ICT-intensive industries. However, intangible capital consists of different types of assets, only some of which are related to the organizational aspects studied at the micro level. Questions thus remain, for example about what type of intangible assets may be driving any potential macro- or industry level complementarity.

3. Method

3.1 Theoretical framework

In order to investigate whether ICT is made more productive by investments in intangible capital I use production theory. I start by assuming that the output, measured as value-added, of each industry can be written as a function of labor, capital and a factor-neutral technology parameter with the function exhibiting constant returns to scale:

$$VA_{u,c,t} = A_{u,c,t}F(\boldsymbol{K}_{u,c,t}, L_{u,c,t}).$$

$\boldsymbol{K}_{u,c,t}$ is a capital services aggregate, $L_{u,c,t}$ is a similar aggregate of labor services and $A_{u,c,t}$ is the Hicks-neutral technology parameter. All variables are indexed by industry (u), country (c) and time (t). In using value-added, I have implicitly assumed that the production function is separable in value-added from intermediate inputs. As a starting point, I assume that capital services can be divided into three separate capital inputs: ICT capital, intangible capital and non-ICT tangible capital (hereafter referred to as tangible capital). This gives me the following function:

$$VA_{u,c,t} = A_{u,c,t}F(I_{u,c,t}, N_{u,c,t}, K_{u,c,t}, L_{u,c,t}),$$

where $I_{u,c,t}$ refers to ICT capital services, $N_{u,c,t}$ to intangible capital services and $K_{u,c,t}$ to tangible capital services. I will refer to this case as the four-input model. Alternatively, I follow Corrado et al. (2005, 2009) and divide intangible capital into two types of capital: innovative property and economic competencies. This gives me a production function with five inputs:

$$VA_{u,c,t} = A_{u,c,t}F(I_{u,c,t}, E_{u,c,t}, P_{u,c,t}, K_{u,c,t}, L_{u,c,t}).$$

I denote capital services for economic competencies and innovative property by $E_{u,c,t}$ and $P_{u,c,t}$. I refer to this as the five-input model. With measures of output and all inputs, and a suitable assumed functional form for F, I can empirically test whether intangible capital and ICT are complements. However, first consider the case where we do not have information on intangible capital. The four-input model can be written as:

$$VA_t = Q_t + Z_t = A_tF(I_t, N_t, K_t, L_t),$$

where Q_t is conventional value-added not adjusted for the capitalization of intangibles.[12] Z_t is the investment in intangible capital and accounts for the difference between Q_t and VA_t. I assume that each industry hires labor and rents tangible capital in competitive markets. Following Basu et al. (2004), I assume that intangible capital in a specific industry must be accumulated through investments by firms in that industry. This is a simplification, since knowledge can obviously be sold and bought. Nonetheless, many intangible assets can be treated as specific to a firm, in particular organizational investments. While there for example exist consulting firms selling organizational

[12] I drop the indexes for country and industry to make notation easier.

services, it is not straightforward how to rent organizational capital. This holds to differing degrees for other intangible assets as well.

Differentiating the production function, dividing by output and expressing it in growth rates yields:

$$dVA_t = \frac{Q_t}{VA_t} dQ_t + \frac{Z_t}{VA_t} dZ_t = \frac{F_I I_t}{VA_t} dI_t + \frac{F_N N_t}{VA_t} dN_t + \frac{F_K K_t}{VA_t} dK_t + \frac{F_L L_t}{VA_t} dL_t + \frac{F_A A_t}{VA_t} dA_t.$$

This is the standard equation from growth accounting. TFP growth, or technological growth, can then be measured as the following residual:

$$\frac{F_A A_t}{VA_t} dA_t = dTFP_t = dVA_t - \frac{F_I I_t}{VA_t} dI_t - \frac{F_N N_t}{VA_t} dN_t - \frac{F_K K_t}{VA_t} dK_t - \frac{F_L L_t}{VA_t} dL_t.$$

However, this requires measures of intangible capital. Without this information, we would measure a potentially false TFP using the above method. The measured residual would then be:

$$dMTFP_t = dQ_t - \frac{F_I I_t}{Q_t} dI_t - \frac{F_K K_t}{Q_t} dK_t - \frac{F_L L_t}{Q_t} dL_t = \frac{F_A A_t}{Q_t} dA_t + \frac{F_N N_t}{Q_t} dN_t - \frac{Z_t}{Q_t} dZ_t.$$

Measured TFP growth, which I denote by $dMTFP_t$, would then differ from true TFP growth depending on the growth of investments in intangible capital and the growth of intangible capital inputs. Increasing intangible investments would bias measured TFP growth downwards, while increasing intangible capital inputs would bias measured TFP growth upwards. Thus, as intangible investments are growing sufficiently faster than intangible inputs, measured TFP growth would be lower than true TFP. When investment growth decreases, so that intangible inputs grow faster, measured TFP would be higher than true TFP. A limited period of high intangible investment would thus produce a pattern of low measured TPF growth followed by high measured TFP growth.

If ICT and intangible capital are complements, it would be expected that as the price of ICT declined and ICT investments rose, intangible investments would rise as well. The assumption that industries must accumulate intangible capital on their own then implies that it is in ICT-using industries that we would expect any measured decrease or increase in TFP growth. The slow productivity growth in European ICT-using industries could then be explained by those industries having made complementary intangible investments during the 90's when ICT investments were high. Similarly, in industries that have already made the necessary intangible investments, we would see high TFP growth. If thus ICT-using industries in the US had made their intangible co-investments earlier, as for example Bloom et al. (2012) propose, this could help explain the accelerating TFP growth seen in those industries.

The main assumption underlying this theory is that there exist a form of intangible co-investments, and that these intangibles and ICT are complements. By using aggregate intangible investments as a proxy for potential intangible co-investments related to ICT, I aim to test the assumption of complementarity.

3.2 Empirical approach

If I wish to empirically test whether intangibles and ICT are complements, I need to assume a functional form for the production function. I take the approach of trying to impose minimal structure on the underlying production by approximating it with a translog production function.[13] The translog production function may be viewed as a second order approximation to any unknown production function. Importantly, it allows for the output elasticities to vary with the levels of all inputs. In logarithmic form, the translog production function is given by:

$$\ln VA = \ln \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln x_i + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} \ln x_i \ln x_j,$$

where VA is the output measure value-added, x_i is input *i*, and *n* is the number of inputs. Differentiating the production function with regards to the logarithm of an input yields the function for the output elasticity of that input:

$$e_i = \frac{\partial \ln y}{\partial \ln x_i} = \alpha_i + \sum_{j=1}^{n} \beta_{ij} \ln x_j.$$

My main hypothesis is that ICT and intangible capital are complements in the sense that they are more productive when used together. The output elasticity of ICT can be seen as a measure of its productivity. The partial derivative of the ICT output elasticity with regards to intangible capital thus gives a direct measure of complementarity. For the translog production function, this derivative is given by:

$$\frac{\partial e_I}{\partial \ln N} = \beta_{I,N},$$

which is simply the coefficient for the interaction term between ICT and intangibles. Positive values for this coefficient would then imply complementarity.

As noted, I assume that the production function is homogenous of degree one, i.e. that it exhibits constant returns to scale. The main reason for this is that the data I use has been derived based on that assumption. Using the assumption, I can convert the variables into per labor terms by subtracting the log of labor services from both sides.

Adding a disturbance term to the production function then gives me an estimable function. Assuming that differences between years and country-industry pairs only result multiplicative shifts in overall output allows me to decompose the error term as:

$$\epsilon_{u,c,t} = \lambda_t + \lambda_{u,c} + \eta_{\ u,c,t}.$$

[13] See for example Christensen et al. (1973) for details about the translog production function.

λ_t denotes fixed year effects and $\lambda_{u,c}$ denotes country-industry specific fixed effects. The function I estimate is then:

$$\ln \frac{VA_{u,c,t}}{L_{u,c,t}} = \ln \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln \frac{x_{i,u,c,t}}{L_{u,c,t}} + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \ln \frac{x_{i,u,c,t}}{L_{u,c,t}} \ln \frac{x_{j,u,c,t}}{L_{u,c,t}} + \lambda_t + \lambda_{u,c} + \eta_{\,u,c,t},$$

where $\frac{VA}{L}$ refers to labor productivity. Note that I will estimate two models with two different sets of inputs. The four-input model uses the following inputs: ICT capital (I), intangible capital (N), non-ICT capital (K) and labor (L). The five-input model uses the following inputs instead: ICT capital (I), non-ICT capital (K), labor (L), economic competencies (E) and innovative property (P). Since I express the variables as input per unit of labor, the labor input will in practice not be included in either model, except for in the denominator of the other inputs.

Moreover, note that instead of estimating the production function directly, I could use the assumption of perfect competition and equate the output elasticities of the inputs to their income shares. This would give me a system of equations to estimate, from which I could derive the parameters for the translog production function (see for example Berndt and Christensen 1973). While it is likely more efficient to estimate this system of equations, I am not willing to equate a factor's output elasticity to its factor income share. The literature, with few exceptions, finds output elasticities for intangible capital greater than its factor share. I want to allow for this possibility here as well.[14]

[14] I do not consider why this is the case. There could for example be spillover effects from intangible capital, as for example Corrado et al. (2014) finds evidence of.

4. Data

4.1 Variables and data sources

I use two main data sources: the INDICSER database (O'Mahony et al. 2012) and the EU KLEMS database (ISIC rev. 3 2011 update) (O'Mahony & Timmer 2009). INDICSER provides data on intangible capital for 14 countries for the years 1995-2007. However, detailed data on tangible capital are either missing or classified for a number of these countries in EU KLEMS. This leaves me with sufficient data for 9 countries for the years 1995-2007.

Table 1: Countries included in the investigation

Country
Austria
Denmark
Finland
Germany
Italy
Netherlands
Spain
Sweden
UK

The industries I use are limited by the availability of data on intangible assets. INDICSER provides data for ten broad market industries. I use eight of these industries, dropping the mining and agricultural industries. As such, I focus on the non-farm, non-mining business sector.

Table 2: Industries included in the investigation

Industries	**NACE rev. 1.1**
Manufacturing	D
Utilities	E
Construction	F
Wholesale and Retail trade	G
Hotels and Restaurants	H
Transport, Storage, Communication	I
Financial Services	J
Other Services	K71-K74

INDICSER provides measures of intangible real fixed capital stock. Capital stocks are however not an appropriate measures of capital input, in that long-lived assets such as buildings gets too high weight compared to short-lived assets such as software. A more appropriate measure would be capital services (see for example OECD 2001a and Jorgenson and Griliches 1967). I thus construct measures of capital services, both for intangible and tangible capital (see the appendix for details on the construction of input services).

In a similar vein, hours worked is not an appropriate measure of labor input. Different types of labor have different levels of productivity. An obvious example is that people with different levels of education generally have different levels of productivity. Labor services accounts for this by assuming that hours worked by more productive workers yield more services per hour. In practice, this means giving greater weight to hours worked by groups with higher compensation. The labor services measures I use are taken from EU KLEMS.[15] These have then been adjusted to reflect cross-sectional differences (see the appendix for details).

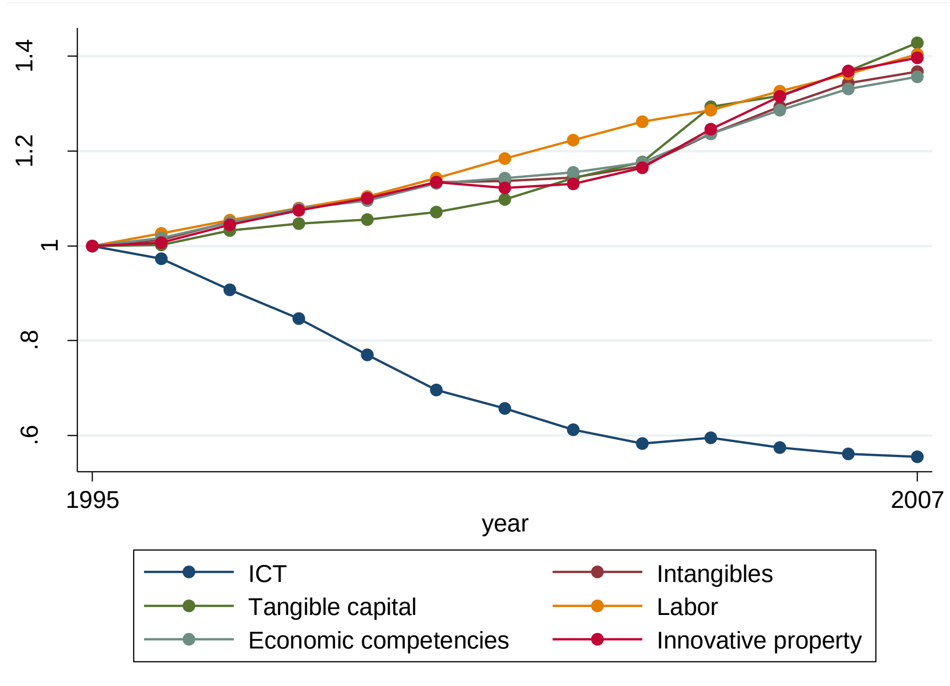
As output measure I use value-added adjusted for the capitalization of intangibles taken from INDICSER. The measure from INDICSER is in nominal terms, so I deflate it with the price index for value-added for the corresponding country and industry from EU KLEMS. This has then been purchasing power parity (PPP) adjusted using PPPs from EU KLEMS. My choice of value-added over gross output comes down to practical grounds. Both measures have their merit.[16] But using gross output requires the addition of intermediate inputs as another input variable. The translog production function already has many parameters, and I would like to avoid adding another. In addition, if I were to include intermediate inputs in the same way as other inputs, I would also have to include its interactions with the other inputs.

[15] See Timmer et al. (2007) for details about the construction of the measures of labor services.
[16] See OECD (2001b) for a discussion on output measures.

4.2 Descriptive statistics

Two trends stand out during the period at hand. The price of ICT has decreased substantially during the period, in particular between 1996 and 2003. As of 2007, the average price is almost half of what it was in 1995. This is in contrast to the prices for the other inputs. For example, the average price of non-ICT capital has risen by more than 30 percent. Although, it should be noted that the EU KLEMS price deflator that I have used for ICT in all countries is based on a US hedonic price deflator.[17]

Figure 1: Average input prices in the investigated countries 1995-2007

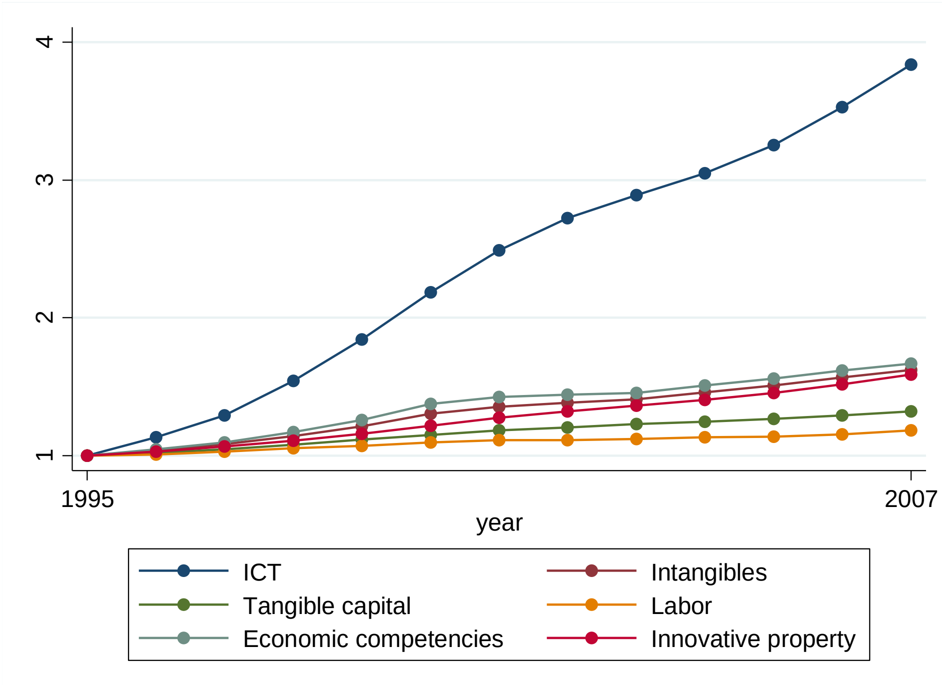


Notes: All prices have been normalized to equal 1 in year 1995.
Source: EU KLEMS, INDICSER and own calculations.

Similarly, the volume of ICT capital services has increased substantially in relation to the volume in 1995. This is not surprising given the price development. But ICT volume has continued to rise throughout the whole period. This contrasts with ICT price, which saw most of the price decrease occurring in the first half of the period. Note also the increasing volume of intangible capital services. Between 1995 and 2007, the average volume of intangible capital services has increased by almost 60 percent.

[17] For a description and discussion of the impact of hedonic price indexes see Triplett (2004).

Figure 2: Average volume of input services in the investigated countries 1995-2007



Notes: All volumes have been normalized to equal 1 in year 1995.
Source: EU KLEMS, INDICSER and own calculations.

Table 3 presents how intangible investments are allocated among different types of intangible assets. The table also contains economic competencies and innovative property, the two groups of intangible assets that I divide total intangible capital into. As can be seen, intangible investments are allocated relatively similar in most countries, with approximately 40 to 60 percent going to economic competencies and the rest to innovative property. The main exceptions are the UK and the Netherlands, where economic competencies make up 65 and 72 percent respectively of intangible investments.

Table 3: Share of different intangible assets in total intangible investments

Asset type	Austria	Denmark	Finland	Germany	Netherlands	Italy	Spain	Sweden	UK
Economic competencies	**0.56**	**0.54**	**0.48**	**0.49**	**0.65**	**0.61**	**0.59**	**0.46**	**0.72**
Firm-specific human capital	0.09	0.17	0.11	0.07	0.10	0.02	0.11	0.10	0.19
Market research and advertisement	0.16	0.16	0.14	0.17	0.20	0.28	0.27	0.11	0.14
Organizational capital	0.31	0.20	0.23	0.24	0.35	0.31	0.21	0.25	0.39
Innovative property	**0.44**	**0.46**	**0.52**	**0.51**	**0.35**	**0.39**	**0.41**	**0.54**	**0.28**
R&D	0.29	0.29	0.38	0.34	0.17	0.17	0.17	0.38	0.14
Product development in the financial sector	0.01	0.01	0.01	0.02	0.02	0.02	0.04	0.01	0.02
New Architectural and Engineering Designs	0.14	0.16	0.13	0.16	0.15	0.21	0.21	0.15	0.12

Notes: Economic competencies consist of firm-specific human capita, market research and advertisement, and organizational capital. Innovative property consists of R&D, product development in the financial sector, and new architectural and engineering designs.

Source: INDICSER and own calculations.

5. Results

5.1 Main results

As a first indication of complementarity between ICT and intangibles, their measured levels are highly correlated across both the cross-sectional and time dimensions. The Spearman rank correlation between ICT and intangibles for the full sample is 0.848 and significant at standard levels of significance. Results are similar when considering samples of industries or countries. The exception is Austria, where the correlation is only 0.658. Still, it is obvious that industries that use more ICT also use more intangible capital.

Table 4: Spearman rank correlation between ICT and intangible capital for different subsamples

Country	Spearman's ϱ	Industry	Spearman's ϱ
Austria	0.6578***	Manufacturing	0.9251***
Denmark	0.7143***	Utilities	0.9106***
Finland	0.8614***	Construction	0.8157***
Germany	0.8262***	Wholesale and Retail trade	0.8891***
Italy	0.7093***	Hotels and Restaurants	0.7778***
Netherlands	0.7807***	Transport, Storage, Communication	0.9049***
Spain	0.7712***	Financial Services	0.9078***
Sweden	0.8797***	Other Services	0.8983***
UK	0.8252***		

*** p<0.01, ** p<0.05, * p<0.1

My main regression results, using the four-input model, are presented in table 5. The first column presents the results from estimating the production function using simple OLS. Since all variables have been scaled around their mean, the coefficients for the inputs entered on their own can be interpreted as the output elasticities at the average level of the input variables. For the OLS specification, all output elasticities are positive and significant. However, except for the squared term for tangible capital, no coefficient beyond the output elasticites is significant. The interaction term between ICT and intangible capital, which measures their complementarity, is positive but not significant.

In column 2 of table 5, I add fixed country-industry effects. The output elasticity for intangible capital decreases, but otherwise the output elasticites are similar. However, once we control for fixed country-industry characteristics, the interaction term between ICT and intangible capital increases and becomes significant. Thus, having controlled for these fixed characteristics, the evidence now supports the existence of complementarity between ICT and intangible capital. Disregarding the other interaction terms, the coefficient would imply that doubling the amount of intangible capital per unit of labor in production would increase the output elasticity of ICT by 13.7 percentage points. Since the output elasticity of ICT at the average is only approximately 11 percent, this amounts to approximately doubling it. However, it should be remembered that the translog function acts as an approximation, which also grows worse as we move further away from zero, which due to the scaling of the variables is at their mean. While it is obvious from the results that intangible capital increases the output elasticity of ICT, a doubling of intangible capital might yield less than a doubling of the ICT output elasticity in reality. With that said, in the neighborhood around the mean, the magnitude of the complementarity is high. Moreover, the magnitude of the complementarity also implies that the output elasticity of ICT will not be far from to zero for industries with below average intangible capital per unit of labor. Intangible capital thus seems very important for the productivity of ICT.

Table 5: Regressions using four-input model

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) OLS	(2) FE
ICT capital per labor, $\ln(\frac{I}{L})$	0.101**	0.118*
	(0.039)	(0.063)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.272***	0.290**
	(0.041)	(0.122)
Intangible capital per labor, $\ln(\frac{N}{L})$	0.376***	0.299***
	(0.045)	(0.067)
Interaction: ICT & intangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{N}{L})$	0.099	0.137**
	(0.060)	(0.056)
Interaction: ICT & tangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{K}{L})$	-0.058	-0.000
	(0.043)	(0.039)
Interaction: intangible & tangible capital, $\ln(\frac{N}{L}) \times \ln(\frac{K}{L})$	-0.032	-0.082
	(0.062)	(0.058)
ICT capital per labor, squared, $0.5 \ln\left(\frac{I}{L}\right)^2$	0.041	-0.031
	(0.048)	(0.036)
Intangible capital per labor, squared, $0.5 \ln\left(\frac{N}{L}\right)^2$	-0.045	0.018
	(0.113)	(0.107)
Tangible capital per labor, squared, $0.5 \ln\left(\frac{K}{L}\right)^2$	0.097**	-0.043
	(0.039)	(0.079)
Constant	-0.018	0.092
	(0.045)	(0.075)
Observations	936	936

Notes: All columns include a full set of year dummies. FE includes country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean.
*** p<0.01, ** p<0.05, * p<0.1

Intangible capital consists of several different types of capital. While I have found a positive and significant relation between ICT and intangible capital, it is not clear that every type of intangible capital should be a complement with regards to ICT. Even if they were, the extent to which they make ICT more productive may differ between different assets. Still, it is not possible to test every single intangible asset type for complementarity. They are likely to be too collinear, and would in any case yield far too many parameters when using the translog production function. Instead, I follow Corrado et al. (2005, 2009) and divide intangible capital into two groups: economic competencies and innovative property. Economic competencies include intangibles related to marketing and advertising, organizational investments and firm-specific human capital. This thus represents those intangible assets which are related to how a firm is organized and the skill of its workforce. I hypothesize that it is these intangibles which are complements with regards to ICT. Innovative property is composed of R&D, architectural and engineering designs, and product development specific to the financial sector. The literature on complementarity between ICT and intangible capital emphasize investments in business processes and the organization, i.e. economic competencies, as complementary to ICT. But it is also possible to imagine ICT being made more productive by, or increasing the productivity of, R&D. As a general purpose technology, ICT should be expected to create possibilities for further technological development. It is thus possible that R&D is complementary to ICT.

Table 6 presents the results from regressions where I have decomposed intangible capital into innovative property and economic competencies. The first column shows the results of a simple OLS regression. As with the aggregate intangible OLS results, we see no significant interaction term between ICT and either subset of intangible capital. The point estimate for the output elasticity of economic competencies is also implausibly large, and significant. In column 2, I add fixed country-industry effects. The output elasticity for economic competencies is still significant, but the point estimate now decreases to a more reasonable level. The interaction terms between ICT and economic competencies also stays positive, but now becomes significant and larger. As before, no other interaction or squared term is significant. These results thus mirror those for aggregate intangible capital, with the difference that economic competencies now drives the complementarity. It thus seems that the evidence for ICT-intangible complementarity presented above is completely the result of a complementarity between ICT and economic competencies. Since economic competencies include such intangible asset types as organizational capital, this conforms to the idea that ICT requires a reorganization of business process before being fully productive.

Table 6: Regressions using five-input model

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) OLS	(2) FE
ICT capital per labor, $\ln(\frac{I}{L})$	0.058*	0.119*
	(0.034)	(0.071)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.317***	0.230**
	(0.034)	(0.108)
Econ. comp. capital per labor, $\ln(\frac{E}{L})$	0.492***	0.225*
	(0.068)	(0.126)
Innov. prop. capital per labor, $\ln(\frac{P}{L})$	-0.066	0.072
	(0.051)	(0.151)
Interaction: ICT & econ. comp., $\ln(\frac{I}{L}) \times \ln(\frac{E}{L})$	0.133	0.229***
	(0.083)	(0.079)
Interaction: ICT & innov. prop., $\ln(\frac{I}{L}) \times \ln(\frac{P}{L})$	-0.011	-0.083
	(0.072)	(0.065)
Interaction: ICT & tangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{K}{L})$	-0.060*	0.017
	(0.034)	(0.043)
Interaction: econ. comp. & tangible capital, $\ln(\frac{E}{L}) \times \ln(\frac{P}{L})$	-0.153***	-0.030
	(0.053)	(0.067)
Interaction: innov. prop. & tangible capital, $\ln(\frac{P}{L}) \times \ln(\frac{K}{L})$	0.094**	-0.048
	(0.047)	(0.089)
Interaction: econ. comp. & innov. prop., $\ln(\frac{E}{L}) \times \ln(\frac{P}{L})$	-0.000	0.003
	(0.147)	(0.148)
Econ. comp. capital per labor, squared, $0.5 \ln\left(\frac{E}{L}\right)^2$	-0.067	-0.100
	(0.201)	(0.218)
Innov. prop. capital per labor, squared, $0.5 \ln\left(\frac{P}{L}\right)^2$	0.052	0.061
	(0.123)	(0.165)
ICT capital per labor, squared, $0.5 \ln\left(\frac{I}{L}\right)^2$	0.031	-0.044
	(0.043)	(0.042)
Tangible capital per labor, squared, $0.5 \ln\left(\frac{K}{L}\right)^2$	0.073**	-0.068
	(0.035)	(0.079)
Constant	-0.027	0.108
	(0.047)	(0.081)
Observations	936	936

Notes: All columns include a full set of year dummies. FE includes country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

5.2 Economic importance

I have found positive and statistically significant relations between ICT and intangible capital and between ICT and economic competencies. However, it may not be straightforward how to interpret the economic importance of these results. In this subsection, I try to illustrate the economic importance by calculating the contribution from ICT to growth in labor productivity using growth accounting based on the estimated production function parameters instead of income shares. Of course, it might not be realistic to assume that the translog specification is able to explain all differences in output elasticities between industries and countries. With that in mind, these growth accounting results should be interpreted as an illustration of the importance of intangible capital to the contribution from ICT if the complementarity were to have the magnitude that I have estimated. As in growth accounting, I calculate the contribution from ICT in industry *u* in country *c* at time *t* as:

$$ICTcontribution_{u,c,t} = e_{I,u,c,t} \Delta \ln \frac{I_{u,c,t}}{L_{u,c,t}},$$

where $e_{I,u,c,t}$ is the output elasticity for ICT. The contribution from ICT is affected by the level of intangible capital through its effect on the ICT output elasticity. To quantify the importance of intangible capital to the contribution from ICT, I also calculate the theoretical contribution from ICT if intangible capital were to have stayed constant at 1995 levels. The difference between this counterfactual contribution and the one calculated using the observed growth in intangible capital provides a quantification of the importance of the ICT-intangible complementarity to the contribution from ICT. Moreover, I calculate analogous results based on the five-input model. I then look at the importance of the growth in economic competencies for ICT contribution. As a benchmark, I also calculate the contribution from ICT using income shares as output elasticities.

I first calculate the ICT contribution for each industry in each country. These are then aggregated to the country level by taking their weighted average per year, where the weights are the industries' two-year average share in country level value-added. The values I present below are the average yearly contribution at the country level over the period 1995 to 2007. This approach approximates the country level contributions, as I have for example not taken into account the effect of reallocation between industries. Nonetheless, this approximation does not seem to add much error. When I calculate industry level ICT contributions using income shares and then aggregate them, I get values very close to values calculated using growth accounting with aggregate country level data.[18]

[18] For a comparison, see for example Niebel et al. (2013) for growth accounting that includes intangible capital.

Table 7: Contribution from ICT to labor productivity growth

Country	(1) Income shares	(2) Four-input model	(3) Five-input model	(4) Share attributable to intangible capital (four-input model)	(5) Share attributable to economic competencies (five-input model)
Austria	0.45	1.56	1.08	20.70	50.08
Denmark	0.80	1.89	1.32	14.22	26.07
Finland	0.46	1.32	0.71	31.90	82.22
Germany	0.41	1.09	0.98	15.48	36.26
Italy	0.22	0.51	0.48	28.53	69.85
Netherlands	0.40	1.56	1.71	18.42	30.24
Spain	0.34	-0.03	-0.02	-	-
Sweden	0.46	1.23	0.82	13.68	40.68
UK	0.66	1.58	2.33	20.35	23.89

Notes: All values are in percentage points.

Column 1 in table 7 presents the ICT contributions for each country when calculated using income shares as output elasticities. Column 2 then presents the ICT contributions calculated using the output elasticites predicted by the estimated four-input model. As can be seen, the ICT contribution is substantially higher than the contribution based on income shares in nearly every country. This is not surprising, given that I both estimated a high output elasticity for ICT and a high ICT-intangible interaction term. In column 3, I have calculated the contribution from ICT using the output elasticities predicted by the estimated five-input model. Compared to the results from the four-input model, we now see lower ICT contribution in many countries. Still, the contribution is higher than that implied by growth accounting except in Spain. Two countries, the UK and the Netherlands, have higher ICT contribution in the five-input model than in the four-input one. This could be expected, since these two countries use more economic competencies than the other countries (see table 3 in section 4). However, the ICT contribution of 2.33 percentage points in the UK is implausibly high, and should be interpreted carefully.

Columns 4 and 5 present the share of the ICT contribution that can be attributed to growth in intangible capital or economic competencies during the period studied. The share for intangible capital is between approximately 15 and 30 percent in almost all countries, implying that the contribution from ICT to labor productivity growth would have substantially lower if industries were not to have increased their use of intangible capital. The results for economic competencies are similar, but with even greater shares attributable to the complementarity effect.

Summarizing the results in table 6, the production function parameters I have estimated imply that the contribution from ICT to labor productivity growth may have been even higher than growth accounting results imply. A substantial share of this ICT contribution is the result of the accumulation of intangible capital during the period studied. Note that I do not try to quantify the effect on ICT contributions from intangible investments prior to 1995. If I were to take these into account as well, I would likely find the complementarity effect to be even greater.

5.3 Robustness

I am interested in if the output elasticity of ICT increases when we add more intangible capital. The translog specification allows the output elasticity of an input to vary between different country-industry pairs according to input levels, thus allowing me to test this. However, the variation in output elasticities is accomplished by including squared terms of the inputs and interactions between them. This imposes a specific structure on the heterogeneity in output elasticities. In the translog function, they are only allowed to vary linearly with changes in the logarithm of input variables. Even though the translog function should be interpreted as an approximation, it might still too restrictive to impose this linear relation between the output elasticity and the logarithms of input variables. Hence, I perform a robustness test by estimating a production function where I allow the output elasticities to vary with fewer restrictions. This is done by dividing the sample by the intensity of their use of intangible capital in production, which I measure as intangible capital per labor service. I then estimate a production function for each subsample. The interaction and squared terms were included in the main regressions to allow for the output elasticities to vary between different country-industry pairs. I drop these terms here since I now allow the output elasticites to vary across different subsamples without structure and as the data dictates. The production function I estimate is thus Cobb-Douglas, which can be seen as a first-order approximation to an unknown production function.

Column 1 in table 8 presents the results from estimating a Cobb-Douglas production function for the whole sample. This is done as a benchmark. In column 2, I have estimated the same function for those country-industry pairs with intangible intensity below the 25th percentile. As might be expected, the estimate of the output elasticity for ICT drops and is now approximately zero for the sample. The third column presents the results from estimating the function for country-industry pairs with below median intangible intensity. As in the second column, the output elasticity for ICT is low and not significantly different from zero. With point estimates around zero, this supports the idea that ICT is not productive without sufficient intangible capital. In column 4, I have instead estimated the function for those country-industry pairs with above median intangible intensity. The output elasticity for ICT now increases and becomes significant. A Wald test with the null hypothesis that the output elasticity for ICT is equal for those with above median intangible intensity and those with below median intensity yields a test statistic of $\chi^2(1) = 3.77$, with a corresponding p-value of 0.0522.[19] I can thus reject the null of their equality at the conventional 10 percent significance level.

In the final column in table 8, I estimate the production function for those country-industry pairs with intangible intensity above the 75th percentile. The ICT output elasticity increases once again and

[19] Since the subsamples are related, all tests of the equality of parameters across models have been performed by first estimating the regressions jointly using seemingly unrelated estimation. The Wald tests have then taken into account the estimated cross-model covariance.

becomes even more significant. A Wald test that this output elasticity is the same as for the sample with below median intangible intensity allows us to reject the null hypothesis of equality at standard levels of significance. Finally, I perform a Wald test of the null hypothesis that the ICT output elasticity is equal for all four subsamples. This yields a test statistic of $\chi^2(3) = 9.68$ and a corresponding p-value of 0.0213. It would thus seem that the output elasticity for ICT is higher in those industries which use intangible capital more intensively.

Table 8: Comparing subsamples of differing intangible intensity (i)

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) FE All obs.	(2) FE Below 25th percentile int. cap. per labor	(3) FE Below median int. cap. per labor	(4) FE Above median int. cap. per labor	(5) FE Above 75th percentile int. cap. per labor
ICT capital per labor, $\ln(\frac{I}{L})$	0.094***	-0.005	0.027	0.157**	0.261***
	(0.035)	(0.037)	(0.025)	(0.063)	(0.082)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.156*	0.030	0.430**	0.103	0.131
	(0.091)	(0.171)	(0.189)	(0.097)	(0.084)
Intangible capital per labor, $\ln(\frac{N}{L})$	0.273***	0.199*	0.176*	0.300***	0.183**
	(0.083)	(0.112)	(0.099)	(0.088)	(0.082)
Constant	0.090***	-0.398**	-0.051	0.199***	0.255***
	(0.009)	(0.169)	(0.099)	(0.061)	(0.074)
Observations	936	234	468	468	234

Notes: All columns include a full set of year dummies and country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean. *** p<0.01, ** p<0.05, * p<0.1

Table 9 presents similar estimations as those in table 8, but where I have now split the sample according to economic competencies and innovative property per unit of labor, instead of using aggregate intangible capital per unit of labor. In column 1, I have estimated the production function for those country-industry pairs with economic competencies per unit of labor below the 25th percentile. Just as when I split the sample by intangible capital, the output elasticity for ICT is low when economic competencies capital per unit of labor is low. This is reinforced by the results in column 2, where the sample consists of country-industry pairs with below median economic competencies per unit of labor. Columns 3 and 4 present the results from regressions using those with above median and those with above the 75th percentile in economic competencies per unit of labor. As expected, the output elasticity for ICT increases and becomes significant. I can now reject at conventional levels of significance the null hypothesis that the ICT output elasticity is equal for the above median and below median samples. Similarly, I can reject the null hypothesis that the above 75th percentile sample has an equal ICT output elasticity to the below median sample. As should therefore not be a surprise, I can furthermore reject the null hypothesis that all four subsamples have equal ICT output elasticities at conventional levels of significance.

In columns 5 to 8 in table 9, I have estimated the Cobb-Douglas production function for samples of differing innovative property intensity. In order, they are: below the 25th percentile, below the median, above the median and above the 75th percentile. The estimate for the output elasticity of ICT is small and not significant when innovative property intensity is low, just as for economic competencies. Also similarly as for economic competencies, the output elasticity for ICT increases as innovative property per unit of labor rises. However, tests of the equality of the ICT output elasticity for different samples cannot reject the null that they are equal. Performing Wald tests, I cannot reject the equality of the ICT output elasticity for below median and above median innovative property intensity, nor can I reject the null hypothesis that all four subsamples yield equal ICT output elasticities.

I have thus found significant differences when dividing the sample by economic competencies per unit of labor, but not when dividing the sample by innovative property per unit of labor. This corroborates my previous results, since those suggested that ICT is made more productive by economic competencies, but not by innovative property.

Table 9: Comparing subsamples of differing intangible intensity (ii)

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) FE Below 25th percentile econ. comp. per labor	(2) FE Below median econ. comp. per labor	(3) FE Above median econ. comp. per labor	(4) FE Above 75th percentile econ. comp. per labor	(5) FE Below 25th percentile innov. prop. per labor	(6) FE Below median innov. prop. per labor	(7) FE Above median innov. prop. per labor	(8) FE Above 75th percentile innov. prop. per labor
ICT per labor, $\ln(\frac{I}{L})$	-0.015	0.017	0.210***	0.244**	0.024	0.045	0.150**	0.107*
	(0.034)	(0.024)	(0.065)	(0.087)	(0.029)	(0.032)	(0.062)	(0.058)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.159	0.313**	0.123	0.103	0.463	0.380**	0.101	0.103
	(0.148)	(0.144)	(0.094)	(0.113)	(0.298)	(0.185)	(0.089)	(0.092)
Intangible capital per labor, $\ln(\frac{N}{L})$	0.145	0.207*	0.229***	0.163**	0.340**	0.270***	0.196	0.290***
	(0.097)	(0.103)	(0.080)	(0.077)	(0.130)	(0.075)	(0.143)	(0.081)
Constant	-0.392**	-0.126	0.245***	0.406**	0.182	0.043	0.266***	0.220**
	(0.158)	(0.081)	(0.060)	(0.147)	(0.267)	(0.112)	(0.090)	(0.087)
Observations	234	468	468	234	234	468	468	234

Notes: All columns include a full set of year dummies and country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean. *** p<0.01, ** p<0.05, * p<0.1

A further issue with the translog production function is that with so many interacted and squared terms, results will most likely be uncertain due to multicollinearity. However, simply removing parameters from the model would change its interpretation and reduce its flexibility. Still, I test if the main result is robust to removing variables. These results are presented in table 10. The first column shows the results from estimating the full translog production function to serve as a benchmark. The second column removes the squared terms. As can be expected, the standard errors decrease, although only marginally. The interaction term between ICT and intangible capital is still positive and significant. Results look similar in the other columns, where I have removed the different interaction terms step by step, leaving only the interaction term between ICT and intangible capital in the final column. While still significant, the magnitude of the estimate for the interaction term decreases. Still, it is large enough for the complementarity to be economically significant.

Table 11 presents analogous results for the five-input model. The five-input results are also robust to varying the specification, with the results similar to those from the four-input model. The interaction term between economic competencies and ICT is consistently positive and significant across all specifications. Just as before, the interaction term between innovative property and ICT is negative and for most specifications not significant, thus corroborating my previous results.

Table 10: Functional form robustness, four-input model

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) FE Full translog	(2) FE No squared terms	(3) FE Interaction between: I&N, I&K	(4) FE Interaction between: I&N, N&K	(5) FE Interaction between: I&N
ICT capital per labor, $\ln(\frac{I}{L})$	0.118*	0.136**	0.138**	0.128**	0.124*
	(0.063)	(0.058)	(0.058)	(0.060)	(0.064)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.290**	0.312***	0.290***	0.295***	0.213**
	(0.122)	(0.113)	(0.108)	(0.105)	(0.088)
Intangible capital per labor, $\ln(\frac{N}{L})$	0.299***	0.279***	0.277***	0.271***	0.254***
	(0.067)	(0.064)	(0.067)	(0.066)	(0.068)
Interaction: ICT & intangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{N}{L})$	0.137**	0.112***	0.108***	0.104***	0.080***
	(0.056)	(0.032)	(0.030)	(0.028)	(0.024)
Interaction: ICT & tangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{K}{L})$	-0.000	-0.024	-0.037		
	(0.039)	(0.029)	(0.030)		
Interaction: intangible & tangible capital, $\ln(\frac{N}{L}) \times \ln(\frac{K}{L})$	-0.082	-0.048		-0.078	
	(0.058)	(0.034)		(0.047)	
ICT capital per labor, squared, $0.5 \ln\left(\frac{I}{L}\right)^2$	-0.031				
	(0.036)				
Intangible capital per labor, squared, $0.5 \ln\left(\frac{N}{L}\right)^2$	0.018				
	(0.107)				
Tangible capital per labor, squared, $0.5 \ln\left(\frac{K}{L}\right)^2$	-0.043				
	(0.079)				
Constant	0.092	0.070	0.065	0.061	0.036
	(0.075)	(0.059)	(0.059)	(0.059)	(0.060)
Observations	936	936	936	936	936

Notes: All columns include a full set of year dummies and country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean. *** p<0.01, ** p<0.05, * p<0.1

Table 11: Functional form robustness, five-input model

Dependent variable: labor productivity, $\ln(\frac{VA}{L})$	(1) FE Full translog	(2) FE No squared terms	(3) FE Interaction between: I&E, I&P, I&K, E&P	(4) FE Interaction between: I&E, I&P, E&K, P&K, E&P	(5) FE Interaction between: I&E, I&P, E&P	(6) FE Interaction between: I&E, I&P
ICT capital per labor, $\ln(\frac{I}{L})$	0.119*	0.138**	0.147**	0.135**	0.137**	0.133**
	(0.071)	(0.068)	(0.064)	(0.063)	(0.067)	(0.065)
Tangible capital per labor, $\ln(\frac{K}{L})$	0.230**	0.285***	0.260**	0.284***	0.209**	0.210**
	(0.108)	(0.107)	(0.106)	(0.104)	(0.091)	(0.092)
Econ. comp. capital per labor, $\ln(\frac{E}{L})$	0.225*	0.208*	0.218**	0.205*	0.213**	0.208**
	(0.126)	(0.123)	(0.093)	(0.117)	(0.091)	(0.089)
Innov. prop. capital per labor, $\ln(\frac{P}{L})$	0.072	0.064	0.044	0.067	0.033	0.043
	(0.151)	(0.143)	(0.097)	(0.136)	(0.104)	(0.100)
Interaction: ICT & econ. comp., $\ln(\frac{I}{L}) \times \ln(\frac{E}{L})$	0.229***	0.163***	0.167***	0.161***	0.163***	0.159***
	(0.079)	(0.052)	(0.046)	(0.050)	(0.045)	(0.044)
Interaction: ICT & innov. prop., $\ln(\frac{I}{L}) \times \ln(\frac{P}{L})$	-0.083	-0.068	-0.061	-0.072	-0.079*	-0.084*
	(0.065)	(0.050)	(0.047)	(0.047)	(0.047)	(0.046)
Interaction: ICT & tangible capital, $\ln(\frac{I}{L}) \times \ln(\frac{K}{L})$	0.017	-0.007	-0.025			
	(0.043)	(0.038)	(0.028)			
Interaction: econ. comp. & tangible capital, $\ln(\frac{E}{L}) \times \ln(\frac{P}{L})$	-0.030	-0.030		-0.035		
	(0.067)	(0.064)		(0.070)		
Interaction: innov. prop. & tangible capital, $\ln(\frac{P}{L}) \times \ln(\frac{K}{L})$	-0.048	-0.031		-0.037		
	(0.089)	(0.086)		(0.074)		
Interaction: econ. comp. & innov. prop., $\ln(\frac{E}{L}) \times \ln(\frac{P}{L})$	0.003	0.010	-0.028	0.018	-0.023	
	(0.148)	(0.070)	(0.042)	(0.051)	(0.042)	
Econ. comp. per labor, squared, $0.5 \ln\left(\frac{E}{L}\right)^2$	-0.100					
	(0.218)					
Innov. prop. per labor, squared, $0.5 \ln\left(\frac{P}{L}\right)^2$	0.061					
	(0.165)					
ICT capital per labor, squared, $0.5 \ln\left(\frac{I}{L}\right)^2$	-0.044					
	(0.042)					
Tangible capital per labor, squared, $0.5 \ln\left(\frac{K}{L}\right)^2$	-0.068					
	(0.079)					
Constant	0.108	0.066	0.074	0.062	0.053	0.045
	(0.081)	(0.062)	(0.060)	(0.057)	(0.060)	(0.056)
Observations	936	936	936	936	936	936

Notes: All columns include a full set of year dummies and country-industry fixed effects. Standard errors in parenthesis under coefficients are clustered by country-industry (i.e. robust to heteroskedasticity and autocorrelation of unknown form). All variables have been scaled around their mean. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

I treat the technological progress in ICT as inducing exogenous variation in the use of ICT. That the accelerated price decline of ICT capital is the result of technological progress is supported by for example Jorgenson (2001), who linked it to a substantially shorter product cycle in the production of the key electronic components of IT equipment. If ICT and intangible capital are complements, we should also expect the exogenous increase in the use ICT to increase the use of intangible capital. So to the extent that the hypothesis of complementarity is correct, I can also treat some variation in intangible capital as exogenous. But beyond this variation, the variables are likely endogenous. As such, all the results presented in this thesis should be interpreted with caution. To the extent that the omitted variables are fixed over country, industry or time, endogeneity should be no problem. However, this might not be the case. A common issue in estimating production functions is the potential correlation between unobservable productivity shocks and input levels. Firms that experience a productivity shock may increase their inputs as a result. There would thus be a correlation between increased inputs and higher productivity, but productivity would be the cause of the input increase, not the reverse as a naïve interpretation would suggest.

However, it is not obvious in which direction any bias resulting from endogeneity would go. Corrado et al. (2014) use an instrumental variable approach to mitigate the endogeneity in country level R&D. This increases the positive relation between country level intangible capital and industry level ICT-intensity compared to their OLS results. On the other hand, O'Mahony and Peng (2011) look at the complementarity between ICT and capitalized workforce training. Their results, when using an instrumental variable approach, indicate that workforce training and ICT are complements, but that the magnitude of the complementarity is lower than the OLS results suggest. Based on these two studies, it seems that there might be an ICT-intangible complementarity, even after having accounted for the endogeneity of intangible capital. But the bias from intangible capital being endogenous may go in either direction, and even be different for different types of intangible capital.

The obvious solution to the endogeneity problem would be for me to use an instrumental variable approach as well. However, there is a lack of external instruments for intangible capital in the literature, and I have not been able to find one on my own. It is not possible to use the instrument used by Corrado et al. (2014) since it requires US intangible capital data at the industry level, when such data only exists at the country level. Another approach would be to use system- or difference-GMM, using lagged variables as instruments. However, the standard errors in the first differenced equation were serially correlated for several orders higher than one. In addition, the number of country-industry pairs is most likely too small for this to work, especially when considering that I have 13 years of data. Thirdly, structural approaches such as Olley and Pakes (1996), used by for example Bloom et al. (2012), or Levinsohn and Petrin (2003) are not readily applicable to industry level data with multiple inputs.

It should also be noted that the results presented in this thesis only hold for the specific assumption I have made. Of course, they may hold when relaxing some assumption, but we do not know beforehand. First, the results are dependent on whether the translog production function is a reasonable approximation. This is likely not the foremost problem. The translog is a flexible function, and can be seen as a second-order approximation to any underlying production function. I have additionally shown that the results hold when varying the functional form. A more problematic assumption might be that of factor-neutral technological change. While a common assumption in the ICT and intangibles literature, it may still be too restrictive. If technological change was not factor neutral, it would be correlated with the input variables, resulting in biased estimates. Finally, I have assumed that industries produce using technology with constant returns to scale. The main reason for this is that the data I have used has been derived based on this assumption. A test of the assumption is thus not possible with the data at hand, since they are only valid under the assumption of constant returns to scale.

6. Discussion

Taken together, the results presented in this thesis point toward ICT and intangible capital being complements. This complementarity seems further to be the result of a complementarity between ICT and economic competencies, which would imply that it is how firms organize and train their workforce that is important for ICT productivity.

That ICT is made more productive by intangible capital, or more specifically economic competencies, has several implications. First, it sheds light on one channel through which ICT contributes to productivity growth, and that this channel is quantitatively important when measured at the level of aggregate industries. Second, it provides a possible explanation for the Solow Paradox and, if we were to generalize the results, part of the explanation for the phenomena of productivity lags usually related to major technological innovations. Third, it provides an explanation for why recent productivity growth, and in particular the contribution from ICT to this growth, has been higher in the US than in Europe.

First, complementarity between ICT and intangible capital, in particular economic competencies, implies that organizational innovation is an important channel through which ICT contributes to productivity growth. While ICT capital is readily available for almost anyone to purchase, the same may not be true of economic competencies. Firms that have more experience in implementing ICT or transforming their organization would have an advantage in using ICT. We could then view investment in economic competencies as not only increasing the productivity of technological capital, but also increasing the ability to implement such capital in the future. Economic competencies could thus be seen to both increase productivity directly and increase the capability of the firm to absorb and use technologies. This would then mirror R&D, where evidence indicates that R&D may both increases productivity through innovation, but also indirectly through increased absorptive capacity.[20]

With regards to the Solow Paradox, complementarity between ICT and intangible capital may be part of the explanation. The idea here is that without intangible co-investments, investments in ICT would at most yield a marginal increase in productivity. Firms that made these intangible investments would have to divert resources for that purpose. If intangible capital is not taken into account, industries or firms with high intangible investments would seem to have lower productivity. Conventionally measured productivity would thus not accelerate at first, independent of whether firms made intangible co-investments or not. However, if intangible investments are made, conventionally measured TFP growth would eventually seem to accelerate. This idea of unmeasured intangible inputs and output thus provides a possible explanation for the Solow Paradox. Of course, I do not propose that this is the only explanation for the Solow Paradox. Among other things, part of it may be accounted for by increasing rates of investment in ICT during the 90's.

[20] See for example Griffith et al. (2004).

In wider sense, ICT would mirror the case of electricity if we are able to explain part of the Solow Paradox with intangible co-investments. As for example David (1990) has argued: the electrification of production only caused substantial productivity increase once production was organized to fully take advantage of it. The results in this thesis would thus also support the theory of GPTs or the related theory of macro- and microinventions put forward by Mokyr (1990). Both of these imply that major technological innovations provide the foundation for further minor innovations, and that it is through these minor innovations that the technologies contribute to productivity and growth. These innovations are not only technological. They may also be organizational, which my results suggest are important for ICT. My test of ICT-intangible complementarity thus provides industry level empirical support for these theories.

If we were to generalize the results, we could expect the productivity lags seen after major technological innovations to be related to their implementation.[21] If firms were not to invest in proper implementation, i.e. make intangible co-investments so as to reorganize the business to support the new technology, they would not experience productivity increases. Similarly as before, making these investments diverts resources from other use and lowers conventional output. If we did not measure the output that these intangible investments are, then productivity would seem to decrease while firms are investing. Once the intangible co-investments would start to slow down, we would instead see a productivity increase unless we also measured the intangible inputs. This thus provides a rationalization for productivity lags, based on failing to measure intangible inputs and output. If we were to measure all inputs and output completely, the productivity lags would according to this theory disappear. However, I would like to make clear that I have only studied ICT. While the introduction of electricity seems to fit the same story about intangible co-investments, this generalization cannot at this point be considered more than speculation.

ICT-intangible complementarity also provides a possible explanation for why Europe as a whole lagged behind the US with regards to productivity growth.[22] This divergence in productivity consists of two parts: labor productivity and TFP. With regards to TFP, if US firms were to have made their intangible co-investments earlier than Europe, measured TFP growth in the US in ICT-intensive industries would seem to accelerate. Corresponding TFP growth in Europe would then seem to decrease as European firms started making intangible co-investments. With regards to labor productivity, all else equal, more intangible capital increases the productivity of ICT and thus the incentive to use it. Generally, European countries invest less in intangible capital than the US (van Ark et al. 2009, Corrado et al. 2012). This would imply that the use of ICT in the US would grow faster, thus contributing more to labor productivity growth than in Europe, just as the evidence indicates.

My estimates of output elasticity for ICT, at approximately 11 percent, are in line with the literature, although on the high end when compared to other estimates where intangible capital is included in

[21] See Edquist and Henrekson (2006) for empirical evidence about productivity lags related to ICT, electricity and the steam engine.

[22] See van Ark et al. (2008) for a comparison of growth in the US and Europe.

the estimation. Corrado et al. (2014) and Niebel et al. (2013) estimate ICT output elasticites at below 10 percent when they include intangible capital as an input. My estimates for the output elasticity of intangible capital are positive and significant. These can also be compared to other industry level results. For example, Niebel et al. (2013), using industry level data, estimates output elasticites for intangible capital in the range 10 to 20 percent. My estimate of around 30 percent is more in line with the earlier estimates in the literature using country level data.

Finally, even if we were to disregard the econometric issues, the results presented in this thesis would still only be valid to the extent that the measures of intangible capital are valid. It should thus be remembered that the measurement of intangibles is still in its early stages and still developing. First, not all expenditures on intangibles are accurately measured. For example, own account organizational expenditures are measured using an assumption of how much time management spends on organizational development. Second, it is not always clear how much of the expenditure on intangibles should be considered investment and how much should be considered consumption. For example, the measures for investments in marketing and advertisement are based on an assumption of how long-lived the effects of such activities are. Thirdly, turning these investment streams into real capital stocks requires further assumptions about the appropriate depreciation rate and price deflator. All this implies that the measures of intangible capital I use might not be measuring what I think it does. Still, even if the measures would not accurately measure the intangibles investments, I can hope that it at least gives a reasonable proxy of it.

7. Conclusion

In this thesis, I have presented industry level evidence that point towards ICT and intangible capital being complements. Using industry level measures of intangible capital for nine European countries, I have estimated a translog production function. The parameters of the production function imply that the output elasticity of ICT increases with intangible capital. Due to the symmetric nature of the function, the output elasticity of intangible capital also increases with ICT capital. As such, the results imply that ICT and intangible capital are more productive when used together. I thus confirm previous micro level studies that have found ICT to be more productive when combined with better management or organizational change.[23] That I find evidence of ICT-intangible complementarity when comparing industries also indicate that previous micro results were not solely driven by within industry variation. Instead, industry differences in the use ICT and intangible capital seem to be economically important. Moreover, my results are in line with previous industry level research using intangible capital. In particular, Corrado et al. (2014) and Chen et al. (2014) find evidence that intangible capital is more productive in ICT-intensive industries. However, not all types of intangible assets seem to be complements to ICT. While I find evidence that economic competencies and ICT are complements, I find no evidence of a similar relation between innovative properties and ICT. The implication is that ICT is made more productive by organizational capital and workforce training, but not by R&D. Taken together with previous research, my findings imply that those investing in ICT will have to make intangible co-investments in order to reap the full potential of ICT. These intangible co-investments would then mainly consist of workforce training and a reorganization of business processes.

In relation to the literature on intangible capital, I provide further evidence for the importance of intangible capital for economic growth. I have estimated output elasticites for intangible capital greater than its factor income share, which is also what most of the literature finds. Furthermore, I provide evidence that among intangible assets, it is not only R&D that is related to growth. In particular, economic competencies emerge as important for growth, both on its own and through its complementarity with ICT. That economic competencies are important is in line with for example Roth and Thum (2014), who find sizable and significant output elasticites for economic competencies, but not for innovative property. As those authors note, this may add doubt to the focus of some policy makers (for example the EU) on R&D. Moreover, if ICT and intangible capital are complements, the increasing investments in ICT imply that the importance of intangible capital to production must have grown over time.

I have also estimated positive and significant output elasticities for ICT. While lower in magnitude than the output elasticities for intangible capital, they are nonetheless sizable at approximately 11 percent. This can be compared to the results in Corrado et al. (2014) and Niebel et al. (2013), where the authors estimate ICT output elasticites at less than 10 percent after having included intangible capital. Given that I have estimated higher output elasticities for both ICT and intangible capital, my

[23] See for example Caroli and van Reenen (2001), Bresnahan et al. (2002), Brynjolfsson et al. (2002), Crespi et al. (2007) and Bloom et al. (2012).

results point toward the knowledge economy being even more important for economic growth than previous results suggest.

As the output elasticity of ICT seems to vary with the level of intangible capital, previous estimates of it have neglected an important heterogeneity in its size. In addition, when intangible capital has been left out the production function completely, the estimates for ICT will have been biased. Industries or countries with more intangible capital would have seemed to have an even more productive ICT than in reality, since the productive effect of intangible capital would to a high degree have been attributed to ICT capital. However, this is not to say that previous research has overestimated the effect of ICT. With ICT-intangible complementarity, we could interpret intangible investments in ICT-intensive industries as a result of ICT. What I have done can thus be interpreted as a decomposition of previous estimates of ICT output elasticity into the direct output elasticity of ICT and the indirect productivity effect through intangible co-investments.

Industry level intangible data for the US was not available when this thesis was written. On average, the US has experienced greater productivity growth from ICT than Europe, and seems to have greater management and ability to benefit from ICT investments (Bloom et al. 2012). It is also in the US that ICT-intensive industries experienced an acceleration in TFP growth (Jorgenson et al. 2008). Research, including this, points towards these facts being related through complementarity between ICT and intangibles. An obvious path for future research is to look at whether this is actually the case using US data.

I started this thesis by noting that technological innovations contribute to economic growth in more ways than one. In particular, I emphasized that new technologies, especially major ones, often created opportunities for organizational change, and that this a channel through which they contribute to economic growth. While I once again emphasize that my results must be interpreted carefully, my results support that ICT is no exception to this rule, and that this effect seems to be quantitatively important at the aggregate industry or country level.

8. References

Basu, S., Fernald, J., Oulton, N. & Srinivasan, S. (2004). "The Case of the Missing Productivity growth: Or, Does Information Technology Explain Why Productivity Accelerated in the United States but not the United Kingdom?," in *NBER Macroeconomics Annual 2003,* M. Gertler & K. Rogoff (eds.), MIT Press, Cambridge.

Berndt, E. R. & Christensen, L. R. (1973). "The Translog Function and the Substitution of Equipment, Structures, and Labor in U.S. Manufacturing 1929-68," *Journal of Econometrics,* vol. 1, no. 1, pp. 81-114.

Black, S. E. & Lynch, L. M. (2004). "What's Driving the New Economy?: The Benefits of Workplace Innovation," *The Economic Journal*, vol. 114, no. 493, pp. F97-F116.

Bloom, N., Sadun, R. & Van Reenen, J. (2012). "Americans do IT better: US multinationals and the productivity miracle," *American Economic Review*, vol. 102, pp. 167-201.

Bresnahan, T. F. & Trajtenberg, M. (1995). "General Purpose Technologies: 'Engines of Growth'?," *Journal of Econometrics*, vol. 65, no. 1, pp. 83-108.

Bresnahan, T. F., Brynjolfsson, E. & Hitt, L. M. (2002). "Information Technology, Workplace Organization and the Demand for Skilled Labor: Firm-Level Evidence," *Quarterly Journal of Economics*, vol. 117, pp. 339-376.

Brynjolfsson. E. & Hitt, L. M. (1996). "Paradox Lost? Firm-Level Evidence on the Returns to Information Systems Spending," *Management Science*, vol. 42, no. 4, pp. 541-558.

Brynjolfsson. E. & Hitt, L. M. (2000). "Beyond Computation: Information Technology, Organizational Transformation and Business Performance," *Journal of Economic Perspectives*, vol. 14, no. 4, pp. 23-48.

Brynjolfsson. E. & Hitt, L. M. (2003). "Computing Productivity: Firm-Level Evidence," *Review of Economics and Statistics*, vol. 85, no. 4, pp. 793-808.

Brynjolfsson, E., Hitt, L. M. & Yang, S. (2002). "Intangible Assets: Computers and Organizational Capital," *Brookings Papers on Economic Activity*, no. 1, pp. 137-199.

Caves, D. W., Christensen, L. R. & Diewert, W. E. (1982). "Multilateral Comparisons of Output, Input and Productivity Using Superlative Index Numbers," *The Economic Journal*, vol. 92, no. 365, pp. 73-86.

Caroli, E. & van Reenen, J. (2001). "Skill-Biased Organizational Change? Evidence from a Panel of British and French Establishments," *Quarterly Journal of Economics*, vol. 116, No. 4, pp. 1449-1492.

Chen, W., Niebel, T. & Saam, M. (2014). "Are Intangibles More Productive in ICT-intensive Industries? Evidence from EU Countries," ZEW Discussion Paper No. 14-070.

Chun, H., Fukao, K., Hisa, S. & Miyagawa, T. (2012). "Measurement of Intangible Investments by Industry and Its Role in Productivity Improvement Utilizing Comparative Studies between Japan and Korea," RIETI Discussion Paper Series no. 12-E-037.

Christensen, L. R., Jorgenson, D. W. & Lau, L. J. (1973). "Transcendental Logarithmic Production Frontiers," *Review of Economics and Statistics,* vol. 55, no. 1, pp. 28-45.

Corrado, C., Haskel, J. & Jona-Lasinio, C. (2014). "Knowledge Spillovers, ICT and Productivity Growth," IZA Discussion Paper No. 8274.

Corrado, C., Haskel, J., Jona-Lasinio, C. & Iommi, M. (2012). "Intangible Capital and Growth in Advanced Economies: Measurement Methods and Comparative Results," Working paper, INTAN-Invest.

Corrado, C., Haskel, J., Jona-Lasinio, C. & Iommi, M. (2013). "Innovation and Intangible Investment in Europe, Japan, and the US," *Oxford Review of Economic Policy*, vol. 29, no. 2, pp. 281-286.

Corrado, C., Haskel, J., Jona-Lasinio, C. & Iommi, M. (2014). "Intangibles and Industry Productivity Growth: Evidence from the EU," Working paper, INTAN-Invest.

Corrado, C., Hulten, C. & Sichel, D. (2005). "Measuring Capital and Technology: An Expanded Framework," in *Measuring Capital in the New Economy*, C. Corrado, J. Haltiwanger & D. Sichel (eds.), Vol. 65, University of Chicago Press, Chicago.

Corrado, C., Hulten, C. & Sichel, D. (2009). "Intangible Capital and U.S. Economic Growth," *Review of Income and Wealth*, vol. 55, no. 3, pp. 661-685.

Crespi, G., Criscuolo, C. & Haskel, J. (2007). "Information Technology, Organisational Change and Productivity," Discussion Paper No. 6105, Centre for Economic Policy Research.

Davenport, T. H. & Short, J. E. (1990). "The New Industrial Engineering: Information Technology and Business Process Redesign", *MIT Sloan Management Review*, vol. 31, no 4, pp. 11-27.

David, P. A. (1990). "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review*, vol. 80, no. 2, pp. 355-361.

David, P. A. & Wright, G. (2003). "General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution," in *The Economic Future in Historical Perspective*, P. A. David & M. Thomas (eds.), Oxford University Press, New York & Oxford.

Devine, W. Jr. (1983). "From Shafts to Wires: Historical Perspective on Electrification," *Journal of Economic History*, vol. 43, no. 2, pp. 347-372.

Drucker, P. F. (1988). "The Coming of the New Organization," *Harvard Business Review*, January-February, pp. 45-53.

Edquist, H. (2011a). "Can Investment in Intangibles Explain the Swedish Productivity Boom in the 1990s?," *Review of Income and Wealth*, vol. 57, no. 4, pp. 658-682.

Edquist, H. (2011b). "Intangible Investment and the Swedish Manufacturing and Service Sector Paradox," IFN Working Paper no. 863.

Edquist, H. & Henrekson. M. (2006). "Technological Breakthroughs and Productivity Growth," in *Research in Economic History*, A. J. Field, G. Clark & W. A. Sundstrom (eds.), vol. 24, Emerald Group Publishing Limited, Bingley, West Yorkshire.

Fukao, K., Miyagawa, T., Mukai, K., Shinoda, Y. & Tonogi, K. (2009). "Intangible Investment in Japan: Measurement and Contribution to Economic Growth," *Review of Income and Wealth*, vol. 55, no. 3, pp. 717-736.

Galbraith, J. (1977). *Organizational Design*, Addison-Wesley, Reading.

Griffith, R., Redding, S. & Van Reenen, J. (2004). "Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries," *Review of Economics and Statistics*, vol. 86, no. 4, pp. 883-895.

Hall, R. E. (2000). "E-Capital: The Link between the Stock Market and the Labor Market in the 1990s," *Brookings Papers on Economic Activity*, no. 2, pp. 73-118.

Hall. R. E. (2001a). "The Stock Market and Capital Accumulation," *American Economic Review*, vol 91, no. 5, pp. 1185-1202.

Hall. R. E. (2001b). "Struggling to Understand the Stock Market," *American Economic Review*, vol. 91, no. 2, pp. 1-11.

Hammer, M. (1990). "Reengineering Work: Don't Automate, Obliterate," *Harvard Business Review*, July-August, pp. 104-112.

Hao, J. X., Manole, V. & van Ark, B. (2009). "Intangible Capital and Growth – An International Comparison," COINVEST Working Paper D3.6.

Hayek. F. A. (1945). "The Use of Knowledge in Society," *American Economic Review*, vol. 35, no. 4, pp. 519-530.

Hornstein, A., Krusell, P. & Violante, G. L. (2005). "The Effects of Technical Change on Labor Market Inequalities," in *Handbook of Economic Growth 1B*, P. Aghion & S. N. Durlauf (eds.), Elsevier, Amsterdam.

Jalava, J., Aulin-Ahmavaara, P. & Alanen, A. (2007). "Intangible Capital in the Finnish Business Sector, 1975-2005," ETLA Discussion Papers No. 1103, The Research Institute of the Finnish Economy, Helsinki.

Jorgenson, D. W. (2001). "Information Technology and the U.S. Economy," *American Economic Review*, vol. 91, no. 1, pp. 1-32.

Jorgenson, D. W. & Griliches, Z. (1967). "The Explanation of Productivity Change," *Review of Economic Studies*, vol. 34, no. 3, pp. 249-283.

Jorgenson, D. W., Ho, M. S., Samuels, J. & Stiroh, K. J. (2007). "Industry Origins of the U.S. Productivity Resurgence," *Economic Systems Research*, vol. 19, no. 3, pp- 229-252.

Jorgenson, D. W., Ho, M. S. & Stiroh, K. J. (2008). "A Retrospective Look at the U.S. Productivity Growth Resurgence," *Journal of Economic Perspectives*, vol. 22, no. 1, pp. 3-24.

Jorgenson, D. W. & Stiroh, K. J. (1995). "Computers and Growth," *Economics of Innovation and New Technology*, vol. 3, no. 3-4, pp. 295-316.

Levinsohn, J. & Petrin, A. (2003). "Estimating Production Functions using Inputs to Control for Unobservables," *Review of Economic Studies*, vol. 70, no. 2, pp. 317-341.

MacGratten, E. & Prescott, E. C. (2000). "Is the Stock Market Overvalued?," *Federal Reserve Bank of Minneapolis Quarterly Review*, vol. 24, no. 4, pp. 20-40.

Marrano, M. G., Haskel, J. & Wallis, G. (2009). "What Happened to the Knowledge Economy? ICT, Intangible Investment, and Britain's Productivity Record Revisited," *Review of Income and Wealth*, vol. 55, no. 3 ,pp. 686-716.

Milgrom, P. & Roberts, J. (1992). *Economics, Organization and Management*, Prentice-Hall, New York.

Mokyr, J. (1990). *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford University Press, New York & Oxford.

Moore, G. E. (1965). "Cramming More Components onto Integrated Circuits," *Electronics*, vol. 38, no. 8.

Nakamura, L. (1999). "Intangibles: What Put the New In the New Economy?," *Federal Reserve Bank of Philadelphia Business Review*, July/August, pp. 3-16.

Nakamura, L. (2001). "What is the U.S. Gross Investment in Intangibles? (At Least) One Trillion Dollars a Year!," Federal Reserve Bank of Philadelphia Working Paper no. 01-15.

Nakamura, L. (2003). "The Rise in Gross Private Investment in Intangible Assets Since 1978," Federal Reserve Bank of Philadelphia, mimeo.

Nakamura, L. (2010). "Intangible Assets and National Income Accounting," *Review of Income and Wealth*, vol. 56, no. 1 (special issue), pp. S135-S155.

Niebel, T., O'Mahony, M. & Saam, M. (2013). "The Contribution of Intangible Assets to Sectoral Productivity Growth in the EU," ZEW Discussion Paper no. 13-062.

Nordhaus, W. (2004). "Retrospective on the 1970s Productivity Slowdown," NBER Working Paper no. 10950.

OECD (1998). *Measuring Intangible Investment*, OECD, Paris.

OECD (2001a). *Measuring Capital: A Manual on the Measurement of Capital Stocks, Consumption of Fixed Capital and Capital Services*, OECD, Paris.

OECD (2001b). *OECD Productivity Manual: A Guide to the Measurement of Industry-Level and Aggregate Productivity Growth*, OECD, Paris.

OECD (2009a). *Guide to Measuring the Information Society*, OECD, Paris.

OECD (2009b). *Handbook on Deriving Capital Measures of Intellectual Property Products*, OECD, Paris.

Oliner, S. D., & Sichel, D. E. (1994). "Computers and Output Growth Revisited: How Big is the Puzzle?," *Brookings Papers on Economic Activity*, no. 2, pp. 273-317.

Oliner, S. D., & Sichel, D. E. (2000). "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?," *Journal of Economic Perspectives*, vol. 14, no. 4, pp. 3-22.

Oliner, S.D., Sichel, D. E. & Stiroh, K. J. (2007). "Explaining a Productivity Decade," *Brookings Papers on Economic Activity*, no. 1, pp. 81-137.

Olley, S. & Pakes, A. (1996). "The Dynamics of Productivity in the Telecommunications Equipment Industry," *Econometrica*, vol. 64, no. 6, pp. 1263-1297.

O'Mahony, M., Niebel, T. & Saam, M. (2012). "Estimating Intangible Capital by Industry," INDICSER Discussion Paper 33.

O'Mahony, M. & Peng, F. (2011). "Intangible Training Capital and Productivity in Europe," MPRA Paper No. 38648.

O'Mahony, M. & Timmer, M. P. (2009). "Output, Input and Productivity Measures at the Industry Level: the EU KLEMS database," *Economic Journal*, vol. 119, no. 538, pp. F374-F403.

Roth, F. & Thum, A.-E. (2013). "Intangible Capital and Labor Productivity Growth: Panel Evidence for the EU from 1998-2005," *Review of Income and Wealth*, vol. 59, no. 3, pp. 486-508.

Simon, H. A. (1976). *Administrative Behavior*, The Free Press, New York.

Solow, R. M. (1987). "We'd Better Watch Out," *New York Times Book Review*, July 12, p. 36.

Stiroh, K. J. (2002). "Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say?," *American Economic Review*, vol. 92, no. 5, pp. 1559-1576.

Timmer, M. P., van Moergastel, T., Stuivenwold, E., Ypma, G., O'Mahony, M. & Kangasniemi, M. (2007). "EU KLEMS Growth and Productivity Accounts Version 1.0. Part I methodology."

Triplett, J. E. (2004), *Handbook on Hedonic Indexes and Quality Adjustment in Price Indexes*, Directorate for Science, Technology and Industry, OECD, Paris.

van Ark, B., Hao, J. X., Corrado, C. & Hulten, C. (2009). "Measuring Intangible Capital and Its Contribution to Economic Growth in Europe," *European Investment Bank Papers*, vol. 14, no. 1, pp. 62-93.

van Ark, B., O'Mahoney, M. & Timmer, M. P. (2008). "The Productivity Gap between Europe and the United States: Trends and Causes," *Journal of Economic Perspectives*, vol. 22, no. 1, pp. 25-44.

Van Rooijen-Horsten, M., van den Bergen, D. & Tanriseven, M. (2008). "Intangible Capital in the Netherlands: A Benchmark," Discussion Paper No. 08001, Statistics Netherlands.

Appendix

Construction of input services

INDICSER provides measures of intangible real fixed capital stock. Capital stocks are however not appropriate measures of capital input, in that long-lived assets such as buildings gets too high weight compared to short-lived assets such as software. A more appropriate measure would be capital services (see for example OECD 2001a and Jorgenson and Griliches 1967). EU KLEMS already provide capital services measures for non-intangible capital. However, capitalizing intangibles will affect capital services for other asset types when the interest rate of capital is calculated with the internal rate of return method. As this is the method used in EU KLEMS, I will have to derive new measures of capital services for both intangible and tangible capital. To do this I follow the methodology from EU KLEMS (see O'Mahony & Timmer 2009 or Timmer et al. 2007).

Assuming constant returns to scale, capital compensation in industry *j* can be calculated by subtracting labor compensation from value-added (index notation for country has been dropped to make the notation simpler):

$$CAP_{j,t} = VA_{j,t} - LAB_{j,t}.$$

Capitalizing intangibles affects value-added. Purchased intangibles will increase value-added since they are no longer classified as intermediate inputs. Own-account intangibles increase gross output and thus also value-added. The INDICSER database provides nominal measures of value-added adjusted for this, which I use in calculating capital compensation. To deflate value-added I use the price index for value-added for the corresponding country and industry from EU KLEMS. An industry's nominal rate of return can then be derived as:

$$i_{j,t} = \frac{CAP_{j,t} + \sum_k \left(p^I_{k,j,t} - p^I_{k,j,t-1}\right) S_{k,j,t} - \sum_k p^I_{j,t} \delta_{k,j} S_{k,j,t}}{\sum_k p^I_{k,j,t-1} S_{k,j,t}},$$

where k denotes asset type, $p^I_{k,j,t}$ is the investment price index, $\delta_{k,j}$ the time-invariant depreciation rate, and $S_{k,j,t}$ the real stock of capital. To implement the above relation in practice, I follow EU KLEMS by calculating the rate of return as:

$$i_{j,t} = \frac{CAP_{j,t} + \sum_k \frac{1}{2}\left[\ln\left(\frac{p^I_{k,j,t}}{p^I_{k,j,t-1}}\right) + \ln\left(\frac{p^I_{k,j,t-1}}{p^I_{k,j,t-2}}\right)\right] p^I_{k,j,t-1} S_{k,j,t} - \sum_k p^I_{j,t} \delta_{k,j} S_{k,j,t}}{\sum_k p^I_{k,j,t-1} S_{k,j,t}}.$$

The price index for all intangible assets except firm-specific human capital is based on the value-added price index for the total business sector. The price index for firm-specific human capital comes instead from INDICSER and is based on an earnings deflator. Other price indexes are taken from EU KLEMS. Asset-specific depreciation rates for intangibles are taken from Corrado et al. (2012) and those for tangible assets from EU KLEMS. Using the rate of return, I then calculate the asset-specific user cost of capital. The user cost is defined according to the standard formulation by Hall and Jorgenson (1967), albeit without taxes:

$$p^K_{k,j,t} = p^I_{k,j,t-1} i_{j,t} + \delta_k p^I_{k,j,t} - \left(p^I_{k,j,t} - p^I_{k,j,t-1}\right).$$

To calculate the user cost in practice, I use the following formula:

$$p^K_{k,j,t} = i_{j,t} - \frac{1}{2}\left[\ln\left(\frac{p^I_{k,j,t}}{p^I_{k,j,t-1}}\right) + \ln\left(\frac{p^I_{k,j,t-1}}{p^I_{k,j,t-2}}\right)\right] p^I_{k,j,t-1} + \delta_k p^I_{k,j,t}.$$

In the event of a negative user cost I have set it to zero on the basis that a firm always has the option of not using an asset.

I assume that the flow of capital services from each asset is proportional to the stock of the asset. I further assume that aggregate capital services are a translog function of the services of the individual assets. This means I can derive the growth in aggregate capital services in industry *j* as:

$$\Delta \ln K_{j,t} = \ln K_{j,t} - \ln K_{j,t-1} = \sum_k \bar{v}_{k,j,t}\left(\ln S_{k,j,t} - \ln S_{k,j,t-1}\right).$$

The weights for each asset in the above equation are their two-period average share of compensation in the relevant industry's total capital compensation for the assets in the relevant group:

$$\bar{v}_{k,j,t} = \frac{1}{2}\left(v_{k,j,t} + v_{k,j,t-1}\right),$$

$$v_{k,j,t} = \frac{p^K_{k,j,T} S_{k,ji,T}}{\sum_k p^K_{k,j,T} S_{k,ji,T}}.$$

I aggregate the different capital asset types into three measures of capital services: ICT, intangible and non-ICT tangible. I also follow Corrado et al. (2005, 2009) in dividing intangible capital into two broad groups, economic competencies and innovative property, and create measures of capital services for each of these groups.

Table A1 presents the different asset types that make up the different aggregate capital measurements. Note that I include software in ICT, even though it can be seen as an intangible asset. However, I regard it as more related to ICT, and thus include it there. Additionally, the category *other assets* under non-ICT tangibles include two types of intangible assets: mineral exploration, and entertainment, artistic and literary originals. I have not been able to remove them from this category, so non-ICT tangibles will have to include them. However, I drop the mining industry from the dataset, so mineral exploration will likely not be a problem.

Table A1: Capital asset types

ICT	**Non-ICT tangible**	**Intangible**	**Economic competencies**	**Innovative property**
Computing equipment	Transport equipment	Scientific R&D	Firm-Specific Human Capital	Scientific R&D
Communications equipment	Other machinery and equipment	Firm-Specific Human Capital	Market Research	New Product Development Costs in the Financial Industry
Software	Non-residential structures and infrastructure	New Product Development Costs in the Financial Industry	Advertising Expenditure	New Architectural and Engineering Designs
	Residential structures	New Architectural and Engineering Designs	Own Account Development of Organizational Structures	
	Other assets	Market Research	Purchased Organizational Structures	
		Advertising Expenditure		
		Own Account Development of Organizational Structures		
		Purchased Organizational Structures		

Both the capital service measures from EU KLEMS and those I have calculated above are in the form of growth rates. As such, they tell us nothing about the relative levels of capital services between countries and industries. To calculate the cross-sectional differences in levels I create a multilateral Törnqvist index based on Caves et al. (1982). I start with a translog bilateral input index as in Caves et al. (1982). The bilateral index is defined as:

$$\ln \gamma_t^{AB} = \sum_k \bar{v}_k^{AB} \ln\left(\frac{S_{k,t}^A q^B}{S_{k,t}^B q^A}\right),$$

$$\bar{v}_k^{AB} = \frac{1}{2}\left(v_{k,t}^A + v_{k,t}^B\right).$$

A and B denote country-industry pairs (for example manufacturing in Denmark or financial intermediation in Spain). q^A and q^B are the PPPs for the countries corresponding to country-industry pairs A and B, which I take from EU KLEMS. $v_{k,t}^A$ is the weight used for calculating the capital services growth rate for country-industry pair A. $v_{k,t}^{B}$ is defined analogously. The multilateral input index between A and B is then defined as:

$$\tilde{\gamma}_t^{AB} = \bar{\gamma}_t^{A} - \bar{\gamma}_t^{B},$$

where $\bar{\gamma}_t^{A}$ is the geometric mean of the bilateral input index between A and each of the *N* country-industry pairs:

$$\bar{\gamma}_t^{A} = \frac{1}{N}\sum_{i=1}^{N} \ln \gamma_t^{Ai}.$$

I set capital services in the manufacturing industry in the UK in 1995 to 1. The values in other industries and countries for that year are then calculated relative to UK manufacturing by using the multilateral input index. Changes over time are calculated by using the growth rates of capital services calculated above. All capital input variables are then scaled around their mean.

Indexes for labor services are taken directly from EU KLEMS. Their cross-sectional variation is then derived in a way analogous to that for capital services, but with skill groups instead of asset types and hours worked instead of capital stocks. I only have access to data on labor compensation and working hours for groups divided by education: low, medium and high skill (see Timmer et al. 2007 for definitions of these skill groups per country). It would have been preferable to have hours and labor compensation divided into additional groups. However, the temporal variation is still based on labor services from EU KLEMS, which are derived with groups based on age and gender in addition to education. Similarly as with capital, I scale the labor variable around its mean.

Finally, the price indexes used for descriptive statistics are calculated by taking the inputs PPP-adjusted compensation divided by their quantity indices.