**Deliverable 2.3**

# Academic article on digitalization in the production process:

## Key concepts and measurement

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## Summary

This deliverable studies the contribution of information and communication technology (ICT) to productivity both directly, and indirectly via externalities that originate in other sectors or countries. The recent literature on the role of ICT as a driver of output growth points out that it has become a general purpose technology (GPT), as the digitalization of the production process and the introduction of new products and services spur further innovation in all industries. Specifically, ICT creates important externalities and complements tangibles or other intangibles, such as R&D and organizational capital.

This study examines the contribution of ICT to productivity in all industries based on an integrated dataset at industry/ country level, covering 15 European countries for the period 2000–2014. We build upon the theoretical model proposed by Basu et al. (2003), which focuses on two important aspects of ICT: complementarity with other intangibles and externalities among different sectors. We account for the first using data on intangible investments from the INTAN-Invest database, while bilateral trade data taken from the World Input-Output Database (WIOD) is used to examine links between sectors in different countries and develop a proxy for the intensity of potential externalities. Moreover, we distinguish between “inward” and “outward” externalities, namely externalities that originate in different sectors or countries and externalities that originate in the same sector and produce a second round effect on the same industry.

The results show evidence of various types of positive ICT spillovers: some originate in similar sectors abroad; some originate internally and spillover abroad; and some originate in the same country but in different sectors. Significant effects are found for both inward and outward spillovers. Moreover, other intangibles are found to have an important complementary role, notably organizational capital, which is observed to be an important source of improved productivity.

# THE CONTRIBUTION OF ICT TO PRODUCTIVITY FOCUSING ON INWARD/OUTWARD ICT EXTERNALITIES

## 1 INTRODUCTION

The role of information and communication technology (ICT) as an important driver of growth has been pointed out by many scholars in recent times (S. Basu & Fernald, 2007; Cardona, Kretschmer & Strobel, 2013; Jorgenson, Ho, Samuels & Stiroh, 2007; Jorgenson & Timmer, 2011; Strohmaier & Rainer, 2016). This is because it is widely-accepted as an example of a general purpose technology (GPT)—namely a technology that can produce or invent, has wide applicability across industries, and can have a protracted, aggregate impact (Jovanovic & Rousseau, 2005).[1] ICT has both economic and social effects through the introduction of new products, technologies and services (Lipsey, Carlaw & Bekar, 2006) that can spur further innovation in every industry.

When seen as a GPT, ICT makes two contributions to productivity (Cardona et al., 2013). Firstly, ICT investment creates innovation and decreases the price of products in relevant sectors (Jorgenson, Ho & Stiroh, 2005). Second, it is an 'enabling technology', as it provides new opportunities, rather than offering complete, final solutions (Bresnahan & Trajtenberg, 1995). For instance, while ICT investment contributes to the digitalization of the workplace and the production process, it also contributes to the creation of new businesses and technologies such as digital marketplaces and platforms, which connect demand and supply. Clearly, the discussion of the contribution of ICT to productivity should account for this second aspect.

Basu et al. (2003) proposed a model (hereafter, the BFOS model) to capture the above-mentioned characteristics. The model incorporates two, main features of ICT that are rarely modelled in productivity functions and are complementary to other forms of intangible capital and externality. The first concerns cross-sector co-invention and co-investment, which is essential in understanding the contribution of ICT to productivity. Complementary organizational investments in areas such as processes and working practices reduce costs and improve productivity and quality (Brynjolfsson & Hitt, 2000). Similarly, Milgrom and Roberts (1990) state that adopting computer technology and making complementary investments allows firms to implement high productivity strategies. For instance, a firm that decides to adopt more technology is likely to invest in digital devices (e.g. R&D) and other requirements (e.g. software and databases) and reorganize their working processes (e.g. organizational capital, training) to be able to use them. In other words, complementary capital (i.e. capital related to ICT) should also be considered to capture all of its benefits.[2]

The second feature pointed out by Basu et al. (2003) are externalities created by ICT. ICT is diffused across industries following an S-shaped curve, where new technologies adopted by the pioneer or leading firms

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[1] Other examples of GPT (Basu & Fernald, 2007) include electricity (Bresnahan & Trajtenberg, 1995), artificial intelligence (Brynjolfsson, Erik; Rock, Daniel; Syverson, 2018) and many others.

[2] Acharya (2016) points out that omitting complementary intangibles in the model would result in mistakenly attributing the impact of intangibles to ICT externalities.

spread out to other firms. As more firms use them, prices fall and the market grows (Pilat & Criscuolo, 2018). Examples include business information systems and business models such as the sharing economy services, e-commerce, video streaming services, cloud funding, etc. The potential of such services is evidenced by the case of Uber, as many firms worldwide have followed their example and now provide similar services. In this case, ICT technologies were key requirements for both supply and demand side, and the market share of digital platform-based mobility services is continuously growing. As organizations and firms can learn from the success and mistakes made by others simply by watching and following, without making an actual investment, ICT externalities should not be ignored (Acharya, 2016).

In this deliverable, we propose an extension to the BFOS model. The latter is based on the model developed by Acharya (2016), which empirically tests the two aspects mentioned above (externality and complementarity). We reconsider their model, revisiting the concept and measures of ICT externality, and propose new ways to analyze the contribution of ICT to productivity. In fact, Acharya (2016) considered only "inward" externalities, that is externalities caused by ICT imported from abroad and other sectors. We argue that also "outward" externalities are important. When an industries exports ICT to other countries or other sectors, it receives a second round beneficial effect. This arises because of the network characteristics of ICT (Moshiri, 2016). For example, when a company implements a new ICT technology and exports it outside, when this takes off in the whole network, it improves efficiency and productivity in the whole system. Besides, in order to account for complementarities, we correct for a wider list of intangibles, rather than considering R&D only, as previously done in other studies.

With respect to externality, a few points should be noted. To the best of our knowledge, none of the empirical studies that used the BFOS model included ICT spillovers (with the exception of Acharya, 2016). However, most industries receive and deliver resources from and to others; therefore, it is important to control for externalities either created by or received from other industries. Furthermore, earlier work focused on ICT externalities at firm level and only considered single industries—consequently, interactions between firms belonging to different industries were ignored. One of the key advantages of the BFOS model is that these spillovers can be fully taken into account. However, in our work, we redefine the measurement of such externalities (compared to Acharya, 2016). This paper assumes that market transaction such as trade may also create flow of knowledge spillovers through more wide use of ICT and other intangibles.

The analysis is conducted on an unbalanced panel of country/ industry-level data in 15 countries, covering the period 2000–2014. The panel is constructed using growth accounting data from EU KLEMS, worldwide transaction data from the WIOD, and intangible data from INTAN-Invest. The remainder of this deliverable is structured as follows. The literature review examines the BFOS model and its key concepts. The following sections present the data and methodology. The last section describes the overall results and sets out some conclusions.

# 2 STATE OF THE ART

With the exception of Basu et al. (2003), early studies made little attempt to investigate the contribution of ICT to productivity growth, while more interest to the topic has been raised recently (Acharya, 2016; Corrado, Haskel & Jona-Lasinio, 2017). In this section, we first introduce the theoretical foundations of the BFOS model and then review the main pieces of work in the literature that focus on the role of ICT externalities, the way they are measured and their impact on productivity. In the final part of the section we clarify the distinction between inward and outward externalities and we compare how the problem of measuring spillovers has been tackled in the literature with the measures we propose in this study.

## 2.1 The BFOS model

The BFOS model provides a theoretical framework that encompasses unobservable, key intangibles with a focus on a cross-industry analysis (Acharya, 2016; Basu et al., 2003). In the model, gross output in country ($c$), and industry ($i$) at time ($t$) is given by:

$$Q_{cit} = Y_{cit} + V_{cit} = F(Z_t G(K_{cit}^{ICT}, U_{cit}), K_{cit}^{NICT}, L_{cit}, M_{cit}) \; (1)$$

where $Q$ is total output, $Y$ is output observable in national accounts, $L$ is labor, $K^{ICT}$ is ICT capital, $K^{NICT}$ is non-ICT capital, and $M$ is material input. $V$ is unobservable output created with intangible capital (ICT or other) and $U$ is unobservable input created with intangible capital. $F$ and $G$ are homogeneous of degree 1, and $Z$ is a technology term that is exogenous to each industry. For simplicity, imperfect competition, increasing returns, and capital adjustment costs are ignored. $U$ is regarded as complementary capital (e.g. business and organizational models, or training in the use of ICT) and $V$ is investment flow (e.g. time and resources used for training, or creating new business structures). To accumulate this complementary capital, industries forego producing market output $Y$:

$$U_{cit} = V_{cit} + (1 - \delta_U) U_{cit-1} \; (2)$$

Taking logs and differentiating Eq. (1) with respect to time:

$$\Delta q = \frac{F_{K^{ICT}} K^{ICT}}{Q} \Delta k^{ICT} + \frac{F_U U}{Q} \Delta u + \frac{F_{K^{NICT}} K^{NICT}}{Q} \Delta k^{NICT} + \frac{F_L L}{L} \Delta l + \frac{F_M M}{Q} \Delta m + \frac{F_Z Z}{Q} \Delta z \; (3)$$

where $\Delta x = dlnX/dt$ and $F_x$ are the partial derivative of the function $F$ with respect to variable $X$. Under constant returns to scale, and perfect competition assumptions, it can be expressed as follows:

$$\Delta y^{NT} - \frac{P_{K^{ICT}} K^{ICT}}{PY} \Delta k^{ICT} - \frac{P_{K^{NICT}} K^{NICT}}{PY} \Delta k^{NICT} - \frac{WL}{PY} \Delta l - \frac{P_M M}{PY} \Delta m = \frac{F_U U}{Y} \Delta u - \frac{V}{Y} \Delta v + s_z \Delta z$$

$$\Delta TFP = \frac{F_U U}{Y} \Delta u - \frac{V}{Y} \Delta v + s_z \Delta z \; (4)$$

where technological change is given by $s_Z = \frac{F_Z Z}{Y}$. Here, $P$, $P_{K^{ICT}}$, $P_{K^{NICT}}$, $P_M$ refer to the prices of output, ICT capital, non-ICT capital, and material inputs, respectively. As can be observed from Eq. (4), TFP (total factor productivity) growth can be biased downward due to the overestimation of unmeasurable positive effects of inputs or the underestimation of outputs. This is the case when income flows from intangibles are not taken into account, while the price of intangible input costs is overestimated. This is unlike the traditional neoclassical model where TFP growth is equal to technological change ($\Delta TFP = s_z \Delta z$) and the residual of the production function is considered as a random error.

As an observable proxy of unobservable investment and growth in complementary capital, the model uses ICT capital information. Basu and Fernald (2007) used ICT capital intensity and growth as a proxy for unmeasured intangible co-investment. Under the assumptions that ICT capital provides a reasonable proxy for unobservable complementary capital, and that the function $G$ has a CES (constant elasticity of substitution) form for its inputs $U$ and $ICT$ (Eq. (5)), TFP can be expressed as:

$$G = [\alpha K^{ICT\frac{\sigma-1}{\sigma}} + (1-\alpha)U^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \text{ (5)}$$

$$\Delta TFP_{cit} = [F_U - 1]\mu\tilde{k}^{ICT}_{cit} + \frac{(1-\delta_U)}{(1+g)}\mu\tilde{k}^{ICT}_{ci,t-1} + s_Z\Delta z_t \text{ (6)}$$

where $G$ is CES in inputs $U$ and $ICT$ capital, and $\alpha$ is ICT capital share in revenue. In Eq. (6), $\tilde{k}^{ICT}_{cit} = s_{K^{ICT}}[\Delta k^{ICT}_t + \sigma\Delta \, ln \, ln \, \left(\frac{P_{K^{ICT}}}{P_U}\right)_t]$ , and $s_{K^{ICT}} = \frac{K^{ICT}P_{K^{ICT}}}{PY}$ . At this point, Acharya (2016) decomposed technology growth ($\Delta z$) into externalities ($\Delta e$) and exogeneous technical change ($\Delta t$).

$$\Delta TFP_{cit} = [F_U - 1]\mu\tilde{k}^{ICT}_{cit} + \frac{(1-\delta_U)}{(1+g)}\mu\tilde{k}^{ICT}_{ci,t-1} + s_Z\Delta e_{cit} + s_Z\Delta t_{cit} \text{ (7)}$$

From this equation, the coefficient $\tilde{k}^{ICT}$ indicates the effect of the product of ICT revenue share and growth in ICT capital on the industry's TFP growth. This can be interpreted as encompassing both firm investment in ICT in the industry, and as an intra-industry spillover (Acharya, 2016). Here, *spillover* refers to ICT investment made by firms in an industry that affects other firms in the same industry, which do not invest in ICT. In other words, this term captures the part of the ICT benefit that was not fully realized by the investing firm, and spilled over to other firms within the same industry. At the same time, when empirically estimating Eq.(7), the term also captures a third component: the outcome of unmeasured intangible capital that is complementary to ICT, but not considered in TFP. Acharya (2016) explains this component with the fact that investment in ICT is generally followed by an increase in the investment in a wide range of complementary intangible assets. In order to disentangle the impact of those intangibles from ICT, it is therefore necessary to control for them, as we will discuss more in detail later.

To address the matter of measuring spillovers, Acharya (2016) proposed the inclusion of various types of externalities (inter-ICT, foreign ICT, and R&D) to differentiate their effects. Since ICT externality is not only restricted to the same industry, the inclusion of ICT externalities from different countries and industry types can help us to distinguish their effects in the econometric analysis. Therefore, the following section discusses current concepts of ICT externalities and intangibles, and their measurement.

## 2.2 ICT externality at industry level

Evidence of the impact of ICT externalities on economic growth has been discussed in previous studies. Brynjolfsson and Hitt (2003) showed a positive and significant effect of computer capital on TFP. Bartel et al. (2007) used firm-level data, and found a positive and significant ICT spillover effect on productivity. O'Mahony and Vecchi (2009) investigated the relationship between intangible assets and productivity, and found higher productivity in R&D and skill-intensive industries, which they interpret as evidence of the presence of spillover effects. Meijers (2007) conducted a cross-country analysis of the external effects of ICT on economic growth and productivity, and found positive externalities for investments in IT software and telecommunication equipment, but not for IT hardware.

Most previous studies have used R&D spillovers to measure ICT externality at industry level. In particular, R&D spillovers for productivity growth in other industries are discussed from two conceptual points of view: rent and knowledge (Griliches, 1992). The former refers to a spillover that is due to intermediate inputs, while the latter refers to a spillover due to the nature of knowledge as a public good. In an empirical analysis, Castellacci (2008) measured rent spillovers as the transaction-based weight of R&D stock of other sectors, and knowledge spillovers as the technological distance between industries based on patents. While R&D focuses on R&D expenditure, ICT externality mainly refers to the contribution of ICT-centered capital on productivity growth in other industries. In this deliverable, ICT externality is measured as rent spillovers, as this is closer to the concept used in the BFOS model.

An important distinction can be made between externalities that involve similar sectors across different countries and externalities that involve different sectors not necessarily in different countries. For instance, the success of the iPhone not only influenced mobile telephone manufacturers in the whole world, but also application developers and other firms producing related devices.

Most of the studies reported in the literature rely on firm-level data. They focus on a restricted number of sectors (in order to control for heterogeneity) and, therefore, ignore externalities between different industries. The industry-level approach can fully account for externalities between firms in different sectors. However, in both cases, it is not straightforward to understand which firms and which industries interact with each other. In the case of interactions within the same industry, it is reasonable to assume that all firms belonging to that industry are potentially affected by the externality created in that sector. On the other hand, understanding which firms and sectors are affected by externalities originated in other sectors is less easy. This is one of the main novelties of our study: instead of considering each sector as potentially affected by any other sector externality (as done, for example, in Acharya, 2016), we use international trade data to evaluate which sectors actually interact with each other.

## 2.3 Direction of trade-related ICT externality: inward/outward

Besides the distinction between inter-industry and intra-industry spillovers, another distinction regarding the direction of the externality can be made, depending on whether the spillover originates in the same industry and spreads over the other industries, or it originates in another sector and spillovers in the sector of interest. The distinction is not trivial because, as we already mentioned earlier, the network characteristics of ICT can cause considerable second round effect even when the spillover originates in the same sector and spreads out abroad.

The importance of the direction of the trade or FDI has been emphasized in the literature not only for the case of externalities between different sectors, but also for the case of FDI within the same industry (Driffield & Love, 2007; Haskel, Pereira, & Slaughter, 2007; Keller & Yeaple, 2009; Xu & Sheng, 2012). In the FDI literature, vertical spillovers and knowledge transfers can be categorized as vertical backward or upstream (from MNE to supplier) and vertical forward or downstream (from MNE to buyer) linkages. Havranek & Irsova (2011) control in large meta-analysis for selection bias in journal articles and find robust evidence on economically meaningful small positive upstream FDI spillovers. Downstream spillovers of FDIs have been positive (Fernandes & Paunov, 2012; Jiang, Guo, Liang, Lai, & Wen, 2017; Wang, 2010) or negligible (Hale & Long, 2011; Havranek & Irsova, 2011; Marcin, 2008).

To sum up, Table 1 shows all of the possible externalities in our model. We distinguish three dimensions. The first indicates whether externalities originate within the same industry (*intra*-industry) or different industries (*inter*-industry). The second indicates whether the externality originated in the same country (*domestic*) or in a different country (*foreign*). Lastly, the direction of the externality is considered, i.e. whether the industry of interest receives the externality (*inward*) or creates the externality (*outward*).

Five possible combinations of the dimensions discussed above are examined in this study. The first two are import externalities from different countries: either the same industry (inward *intra*-industry) or a different industry (inward *inter*-industry). The last three are export externalities. These can be within the same country, but a different industry (domestic outward inter-industry[3]), which is the only domestic measure we consider; from the same industry but a different country (outward intra-industry); or a different industry and different country (outward inter-industry). It should be noted that the use of industry-level data means that we cannot disentangle externalities that originate in the same industry within the same country. As discussed above, our model capture these in the term that represents ICT investment itself.

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[3] For simplicity, we remove the outward notation for domestic spillovers, as there is not ambiguity in the direction of those externalities in our model.

Table 1. ICT externalities related to trade

| ICT externality type | Definition |
|---|---|
| Inward intra-industry | ICT externality via import between the same industry in different countries |
| Inward inter-industry | ICT externality via import between different industries in different countries |
| Domestic (outward) inter-industry | ICT externality between different industries in the same country |
| Outward intra-industry | ICT externality via export between same industry in different countries |
| Outward inter-industry | ICT externality via export between different industries in different countries |

## 2.4 The role of complementary intangibles

To take full advantage of new technology, complementary investment is required. Therefore, especially for GPT, it is important to consider intangibles. Although GPT refers to current technology that can change the economic environment, its impact is not immediately observed. In order to realize its full potential, it is important to consider wider intangibles, unmeasured investment, and the (re)organization of production (Brynjolfsson, Erik; Rock, Daniel; Syverson, 2018). Based on a sample of 10 European countries, Corrado et al. (2014) showed that the marginal effect of ICT capital was higher when complemented with intangible capital. Chen et al. (2016) also analyzed 10 European countries and found that intangible capital was more productive in ICT-intensive that less intensive sectors. These findings suggest that the role of intangibles as complementary capital should be taken into consideration to estimate the effect of ICT.

One of the difficulties in analyzing intangibles, however, is that they are often unmeasurable. As Nakamura (2001) pointed out, the intangible asset is a variable that traditional measures of economic activity have failed to capture. Consequently, R&D investment has been widely used as a proxy (notably in Acharya, 2016). In reality, however, intangibles cannot be simply defined by a single variable and Corrado et al. (2009) proposed a list of items that should be considered as assets. This list consists of computerized information, innovative property, and economic competencies. *Computerized information* includes software and databases. *Innovative property* covers R&D, design, product development in financial services, mineral exploration, and spending on the production of original artists. *Economic competencies* include branding, training, and organizational capital.

This deliverable considers different types of intangible assets to control for the effects of ICT externalities. The approach contributes to our understanding of the relationship between ICT and different types of intangible assets as we can differentiate the effects of intangible types and control for ICT externality. The final selection of intangible assets is discussed later in this document.

# 3 DATA

This deliverable draws upon integrated datasets from EU KLEMS, INTAN-Invest, and the World Input-Output Database (WIOD) as shown in Table 2. Provided by the Groningen Growth and Development Centre (GGDC), EU KLEMS contains country/ industry-level datasets that include gross output, value added, capital, labor, intermediate input, etc. (Mahony & Timmer, 2009) for a total 26 of EU member states, the United States, and Japan, covered from 1995 to 2014. From EU Klems, we use gross output, ICT and non ICT capital stock, labor and intermediate inputs. In particular, in order to compute ICT and non ICT capital , following previous studies (Acharya, 2016; Spiezia, 2012), Information Technology, Communication Technology and Software are merged as ICT capital services, while the remainder are considered as non-ICT capital services (transport equipment, other machinery and equipment, total non-residential investment, residential structures, cultivated assets, research and development, and Other IPP assets). Labor is calculated as the product of compensation and total hours worked.

WIOD data tracks country/ industry-level interactions. The WIOD, developed by Timmer et al. (2015), covers a total of 43 countries including 28 EU member states and 15 major countries, from 2000 to 2014. Bilateral trade flows are based on information on demand, production and international trade data. Country/ industry-level in and outflow data is a reliable measure of the industry-level ICT externality. Specifically, WIOD data is used to calculate domestic inter-industry, foreign importing inter- and intra-industry, and foreign exporting inter- and intra-industry flows for each country and industry.

INTAN-Invest data is integrated into our sample as it provides country/ industry-level datasets. INTAN-Invest provides market sector data on intangible investments for a total of 20 countries including 19 European countries, and the United States between 1995 and 2015 (Corrado, Haskel & Jona-lasinio, 2016). The inclusion of INTAN-Invest leads to inevitable data loss because it covers a smaller sample of countries and time period compared to the other two datasets. Although using country/ industry-level R&D data from the OECD is another option, INTAN-Invest was selected as it provides details of various types of intangible investments.

The final, combined dataset was integrated by country, industry, and year. Data from 15 European countries, for the period 2000 to 2014 was included in the sample: Austria (AT), the Czech Republic (CZ), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Hungary (HU), Italy (IT), Luxembourg (LU), Netherland (NL), Sweden (SE), Slovenia (SI), Slovakia (SK), and the United Kingdom (UK). The United States (US) was excluded in order to focus on the European context. Sixteen classifications (A, B, C, D–E, F, G, H, I, J, K, L, M–N, O, P, Q, R–S) were selected, based on the Industrial Classification of All Economic Activities (ISIC Rev. 4). Industries were merged with WIOD database categories in cases where several industries were aggregated (D–E, M–N, and R–S).

*Table 2. Data sources*

| Variables | Database |
|---|---|
| Gross-output | EU-KLEMS |
| Labor | EU-KLEMS |
| ICT capital | EU-KLEMS |
| Non-ICT capital | EU-KLEMS |
| Intermediate Input | EU-KLEMS |
| Organizational Capital | INTAN-Invest |
| Training | INTAN- Invest |
| Design | INTAN- Invest |
| ICT externalities (In and out externality flows) | WIOD |

# 4 PROPOSED MODEL

As discussed above, this study builds upon the model proposed by Basu et al. (2003). The baseline version follows the growth accounting model, with gross output as the dependent variable[4]. We include labor, non-ICT capital and intermediate inputs as controls for productive factors.

For inward ICT externalities, we use import data, following the approach adopted by Helpman and Coe (1995) to model R&D externalities. Following this approach, Acharya (2016) measured ICT externality as the targeted industry's ownership of ICT capital and imports. The study measured ICT externality by the weighted sum of ICT stock from all other countries, as in the following equation:

$$Inward.ICT_{cijkt} = \sum_{c' \neq c, c' \epsilon C} K_{c'ikt}^{ICT} \frac{IN_{c'cikt}}{\sum_{c' \epsilon C, c' \neq c} IN_{c'cikt}} \quad (8)$$

Where c and i denote country and industry, j the market type of spillover (domestic or international), k the industry type of spillover (intra- or inter-industry), while IN denotes received resources.

For instance, country $c$–industry $i$'s inward ICT externality is calculated as the summation, across all the other countries j≠c, of all the foreign ICT capital in the same sector, weighted by a ratio representing how much the sector i in country c imported from each country j≠c. The same calculations are done for outward externalities, with the only difference that exports instead of imports are used, as shown in Eq.(9):

$$Outward.ICT_{cijkt} = \sum_{c \neq c', c \epsilon C} \frac{K_{cit}^{ICT}}{\sum_{c \neq c', c \epsilon C} K_{cit}} * OUT_{cc'ijkt} \quad (9)$$

Where OUT denotes delivered resources.

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[4] Value added and gross output are the most widely-used measures of productivity. The difference between them is that intermediate inputs (materials, energy, and services used in the production process) are only included in the latter. Although these differences are not significant at the aggregate (or national) level, they are greater at the industry level as intermediate usage tends to be a much higher proportion of gross output (Cobbold, 2003). Furthermore, the multi factor productivity (MFP) model, which uses gross output is more suitable for analyzing disembodied technological change (Cobbold, 2003). As the latter allows intermediate input to be used as a source of industry growth, a disembodied technological change that is not physically associated with production factors can be considered.

Inter-industry externalities share the same concept but the summation involves different sectors instead of similar sectors.

For clarification, Figure 1 shows the concept of ICT externality, including a comparison of previous and proposed definitions. In particular, the first line shows the measures proposed by Acharya (2016), while in the second we show our modifications. In this sense, two changes are proposed. The first is on the way the domestic externality is measured: while Acharya (2016) considered all the sectors within a country as linked together, i.e. he did not weighted ICT by the proportion of trade as in the summation in eq.(8). Instead, we consider sectors that are actually linked to each other by inward linkages applying the same formula in the equation but summing up over industries within the same country instead of within similar sectors in different countries. The second change is on the international spillovers. While Acharya (2016) considered only inward externalities, we consider both: inward and outward.

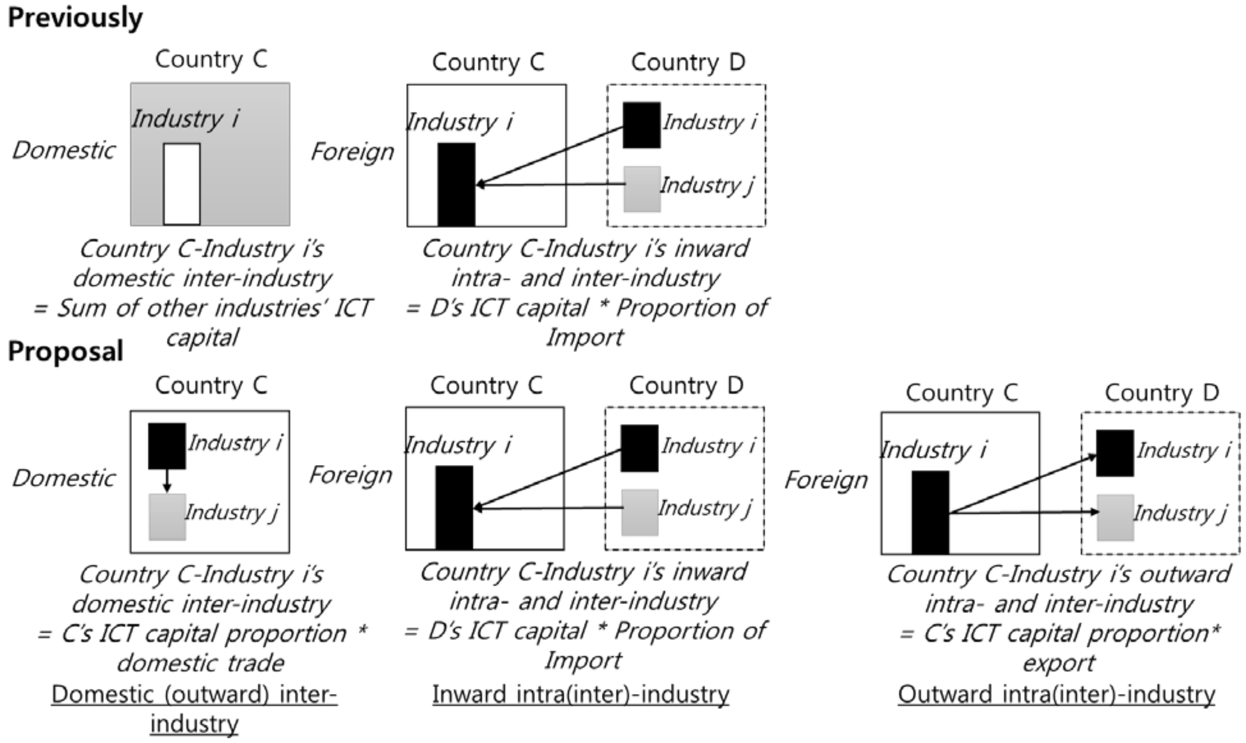

Figure 1: Concept of ICT externality

As mentioned when explaining the model, a final issue concerns controlling for complementary intangible capital, that otherwise will be confused with ICT capital in the first term on the RHS of eq. (7). A few points should be noted. The first is the potential for double-counting some items, since we are taking intangibles and ICT data from two different sources (INTAN-invest and EU Klems). INTAN-Invest classifies nine intangible assets into three categories. As some of these are already included in the calculation of ICT capital, overlaps should not be included. Secondly, although categories represent different types of intangibles, correlations between them should not be ignored. In a prior step, correlations were considered in order to avoid multicollinearity in the main analysis. As a result, organizational capital, training, and design are included in the final model. The use of these variables is supported by previous studies that emphasize the importance of considering organizational aspects in order to increase the potential benefits of ICT (Brynjolfsson & Hitt, 2003; Gargallo-Castel & Galve-Grriz, 2012; Hitt & Brynjolfsson, 2006; Soh & Markus, 1995). Based on our discussion, $s_Z \Delta e_{cit}$ (Eq. 7) is converted into a list of intangibles and ICT externalities.

$$\Delta TFP_{cit} = \beta_0 + \beta_{U1}\tilde{k}_{cit}^{ICT} + \beta_{U2}\tilde{k}_{cit-1}^{ICT} + \beta_{ITG}\Delta ITG_{cit} + \beta_{FE}^{*}\Delta k_{ci\prime t}^{ICT_*} + \beta_{FA}^{*}\Delta k_{cit}^{ICT_*} + \beta_{DE}\Delta k_{ci\prime t}^{ICT} + \beta_{FA}\Delta k_{cit}^{ICT} + \beta_{FE}\Delta k_{ci\prime t}^{ICT} + \vartheta_{it} \quad (10)$$

Here, $\beta^*$ is the coefficient of inward ICT externality, and $\beta$ refers to the coefficient of outward ICT externality. $D$, $F$, $E$, and $A$ indicate domestic, foreign, inter- and intra-industry, respectively. For instance, $\beta_{FE}^*$ is the coefficient of foreign importing inter-industry ICT externality, while $\beta_{FE}$ is the coefficient of foreign exporting inter-industry ICT externality. By replacing $\Delta TFP_{cit}$ to $\Delta y_{cit} - \beta_L \Delta l_{cit} + \beta_{ICT}\Delta k_{cit}^{ICT} + \beta_{NICT}\Delta k_{cit}^{NICT} + \beta_M \Delta m_{cit}$, the full-form estimated equation is as follows:

$$\Delta y_{cit} = \beta_0 + \beta_L \Delta l_{cit} + \beta_{ICT}\Delta k_{cit}^{ICT} + \beta_{NICT}\Delta k_{cit}^{NICT} + \beta_M \Delta m_{cit} + \beta_{U1}\tilde{k}_{cit}^{ICT} + \beta_{U2}\tilde{k}_{cit-1}^{ICT} + \beta_{ITG}\Delta ITG_{cit} + \beta_{E}^{*}\Delta k_{ci\prime t}^{ICT_*} + \beta_{A}^{*}\Delta k_{cit}^{ICT_*} + \beta_{DE}\Delta k_{ci\prime t}^{ICT} + \beta_{FA}\Delta k_{cit}^{ICT} + \beta_{FE}\Delta k_{ci\prime t}^{ICT} + \vartheta_{it} \quad (11)$$

# 5 RESULTS

## 5.1 Estimation results

Prior to the panel regression, a Hausman test was conducted to select the estimator. In all cases, a fixed effects model was selected in preference to a random effects estimation. The fixed effects model used robust and clustered (country/industry specific) standard errors in order to avoid heteroscedasticity (Hoechle, 2007; Szymczak, 2018).

*Table 3: Production function estimation using a fixed effects model*

| | Specification | | | | | | |
|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| Labor | 0.054*** | 0.055*** | 0.047*** | 0.046*** | 0.037** | 0.041** | 0.038** |
| | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) |
| ICT capital | 0.010*** | 0.001 | 0.008 | 0.008 | -0.016* | 0.005 | 0.003 |
| | (0.003) | (0.001) | (0.009) | (0.009) | (0.009) | (0.009) | (0.009) |
| non-ICT capital | 0.069*** | 0.064*** | 0.061*** | 0.058** | 0.048** | 0.059** | 0.061** |
| | (0.019) | (0.020) | (0.020) | (0.020) | (0.020) | (0.020) | (0.020) |
| Intermediate Input | 0.469*** | 0.468*** | 0.458*** | 0.453*** | 0.438*** | 0.448*** | 0.443*** |
| | (0.019) | (0.020) | (0.020) | (0.020) | (0.019) | (0.020) | (0.020) |
| ICT ratio * ICT(t) | | 0.079 | 0.194 | 0.187 | 0.295 | 0.190 | 0.274 |
| | | (0.855) | (0.856) | (0.855) | (0.832) | (0.853) | (0.851) |
| ICT ratio * ICT(t-1) | | 0.039 | 0.041 | 0.041 | 0.046 | 0.043 | 0.044 |
| | | (0.032) | (0.032) | (0.032) | (0.031) | (0.032) | (0.032) |
| Org. capital | | | 0.034*** | 0.035*** | 0.031*** | 0.035*** | 0.035*** |
| | | | (0.008) | (0.008) | (0.007) | (0.008) | (0.008) |
| Training | | | 0.001 | 0.001 | 0.003 | 0.001 | 0.001 |
| | | | (0.000) | (0.001) | (0.001) | (0.001) | (0.001) |
| Design | | | 0.003 | 0.003 | 0.001 | 0.003 | 0.001 |
| | | | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| Inward intra- ICT | | | | 0.006** | 0.007*** | 0.006*** | 0.006*** |
| | | | | (0.003) | (0.003) | (0.003) | (0.003) |
| Inward inter- ICT | | | | 0.006 | 0.005 | 0.006 | 0.006 |
| | | | | (0.006) | (0.006) | (0.006) | (0.006) |
| Domestic inter- ICT | | | | | 0.024*** | | |
| | | | | | (0.002) | | |
| Outward intra- ICT | | | | | | 0.005*** | |
| | | | | | | (0.002) | |
| Outward inter- ICT | | | | | | | 0.009*** |
| | | | | | | | (0.002) |
| Observations | 2,521 | 2,466 | 2,466 | 2,145 | 2,145 | 2,145 | 2,145 |
| R2 | 0.253 | 0.247 | 0.255 | 0.257 | 0.297 | 0.261 | 0.265 |
| Adjusted R2 | 0.191 | 0.183 | 0.190 | 0.193 | 0.235 | 0.196 | 0.260 |
| F Statistics | 196.830***<br>(df=4;2329) | 124.018***<br>(df=6;2272) | 86.154***<br>(df=9;2269) | 71.462***<br>df=11;1951) | 79.655***<br>(df=12;1950) | 66.743***<br>(df=12;1950) | 68.028***<br>(df=12;1950) |

***Significant at the 1% level; **significant at the 5% level; *significant at the 10% level. Numbers in brackets refer to *p*-values.

Table 3 shows the regression results. Specification 1 considers the standard production function with labor, ICT capital, non-ICT capital and intermediate inputs. In the second specification, the ICT ratio as both contemporary and one-year lag is added to the standard production function. These two additional terms, the product of the share of ICT in gross output and ICT capital growth, are suggested by theory and given in the previous equations as they show either the impact of the unaccounted accumulation of ICT capital on TFP, or intra-industry ICT externalities on TFP. In the second specification shown in Table 3, the product of the ICT ratio as gross output and ICT capital growth are statistically insignificant.

In the third specification, intangibles assets are added. Here, the coefficient of organizational capital is positive and significant. This result supports the observation of Brynjolfsson and Hitt (2003) that organizational capital plays a key role in the contribution of computers to productivity growth. On the other hand, training and design coefficients are not significant. The first reason for this may be due to our analytic level. The panel regression is constructed at country/ industry level, and it may be that the selected industries do not (or rarely) invest in training. Another issue is that, in practice, investment in training and design is not always reported, and this may lead to its under-estimation.

Specifications 4–7 in Table 3 show the inclusion of ICT externalities measured by our proposed approach. The two inward ICT externalities are included together in specification 4, while the three outward ICT externalities are included separately in specifications 5–7.[5]

Inward ICT externalities are divided into inter- and intra-industry effects. For all specifications, coefficients of inward intra-industry ICT externality were statistically significant, while the inter-industry coefficient was not. To recap, *inter-industry* refers to the aggregated interaction between firms in different industries, and the *intra-industry* relationship indicates the aggregated interaction between firms in the same industry. In the case of intra-industry effects, it is more reasonable to assume that firms either compete in the same market, or have adopted a similar productivity mechanism. It may be that intra-industry ICT externality received from other countries is used to complement an industry's productivity. The impact of inter-industry ICT externality, however, is different.

The fifth specification shown in Table 3 shows the estimation including (outward) domestic inter-industry ICT externalities. This result highlights a positive and significant effect. The finding is consistent with Acharya (2016), where domestic inter-industry ICT externality is measured with firm-level data, by summing all other industries' ICT capital. As this externality is based on the interaction between industries within the same country, this result shows that an industry's ICT creates positive spillover effects for other, domestic industries. Specifications 6 and 7 (Table 3) show that coefficients of outward inter- and intra-industry ICT externality are also positive and statistically significant. Compared to the domestic externality, the effect of the foreign externality is smaller, but still significant. Moreover, unlike the inward ICT externality, the positive and significant coefficients for both outward ICT externalities highlight a spillover

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[5] This is mainly done to avoid unwanted correlations. In the case of inward ICT externalities, they are not correlated with other variables as they are based on the partner's ICT. On the other hand, outward ICT externalities are obtained by the multiplication of the firm's own ICT capital and resource transfer. Thus, it is better to separate the three of them.

effect from the focal industry's ICT, meaning that the second round effect we previously mentioned for outward externalities actually exists.

## 5.2 Sensitivity analysis

In this section, we examine the robustness of our findings, by estimating a dynamic version of the model using the generalized method of moments (GMM) estimator (Arellano & Bond, 1991). Among other advantages, the method allows us to relax the assumption of strictly exogenous regressors. In fact, our model may suffer from endogeneity due to reverse causality (Hillier, Pindado, Queiroz & Torre, 2011), and the estimated result may be biased (Wooldridge, 2010). To address this issue, Arellano and Bond (1991) proposed a dynamic panel estimator based on GMM, to overcome the limitation of conventional instrumental variables being inefficient in the presence of heteroscedasticity (Baum, Schaffer & Stillman, 2003). The results of these estimations, which include a lag for the dependent variable, are presented in Table 4. In order for a GMM analysis to yield consistent estimates, the Arellano-Bond test for autoregression (AR) and the Hansen test must be conducted. The first examines whether the error term is not serially correlated in both the difference regression and the system difference-level regression. The serial correlation is only allowed for the first-order correlation, while a second-order serial correlation violates the assumption found in the GMM procedure. The Hansen test examines the validity of instruments, and seeks to address the problem of over-identifying restrictions.

As shown in Table 4, $p$-values for AR(1) tests are below 0.01, while those for AR(2) tests are over 0.05. These results lead to a failure to reject the null hypothesis of the second-order serial correlation of error terms of the first-difference equation. $P$-values for the Hansen test are all 1, and the null hypothesis of the exogeneity of instruments cannot be rejected. In sum, the results from these two tests support the validity of the instruments, and confirm that GMM estimates are consistent. This finding provides robust evidence that organizational capital has a positive influence on output growth. Moreover, it supports the role of positive spillover in inward intra-industry, domestic inter-industry and outward inter- and intra-industry relations.

*Table 4: Production function estimations using the GMM estimator (Arellano & Bond, 1991)*

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Gross output (lag 1) | -0.103** | -0.085* | -0.110* | -0.120** | -0.121** | -0.118** | -0.119** |
| | (0.047) | (0.044) | (0.044) | (0.043) | (0.036) | (0.043) | (0.042) |
| Labor | 0.103** | 0.094** | 0.086*** | 0.081*** | 0.051 | 0.056* | 0.056** |
| | (0.040) | (0.039) | (0.031) | (0.031) | (0.031) | (0.029) | (0.028) |
| ICT capital | 0.010*** | 0.013 | 0.020 | 0.019 | -0.013 | 0.009 | 0.006 |
| | (0.003) | (0.019) | (0.016) | (0.014) | (0.013) | (0.013) | (0.013) |
| non-ICT capital | 0.069 | 0.049 | 0.030 | 0.035 | 0.032 | 0.028 | 0.022 |
| | (0.052) | (0.053) | (0.054) | (0.052) | (0.053) | (0.050 | (0.050) |
| Intermediate Input | 0.538*** | 0.536*** | 0.521*** | 0.500*** | 0.478*** | 0.547*** | 0.540*** |
| | (0.137) | (0.128) | (0.117) | (0.108) | (0.100) | (0.118) | (0.119) |
| ICT ratio * ICT(t) | | 0.002 | 0.062 | 0.138 | 0.482 | 0.291 | 0.380 |
| | | (0.773) | (0.701) | (0.591) | (0.617) | (0.606) | (0.575) |
| ICT ratio * ICT(t-1) | | 0.685 | 0.795 | 0.866 | 0.921* | 1.032** | 1.194** |
| | | (0.516) | (0.515) | (0.530) | (0.617) | (0.606) | (0.575) |
| Org. capital | | | 0.022* | 0.024** | 0.023** | 0.025** | 0.025** |
| | | | (0.012) | (0.012) | (0.011) | (0.012) | (0.012) |
| Training | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| Design | | | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 |
| | | | (0.003) | (0.003) | (0.002) | (0.003) | (0.003) |
| Inward intra- ICT | | | | 0.008** | 0.009*** | 0.007** | 0.008** |
| | | | | (0.003) | (0.003) | (0.003) | (0.003) |
| Inward inter- ICT | | | | 0.005 | 0.005 | 0.004 | 0.004 |
| | | | | (0.008) | (0.007) | (0.007) | (0.007) |
| Domestic inter- ICT | | | | | 0.024*** | | |
| | | | | | (0.004) | | |
| Outward intra- ICT | | | | | | 0.006* | |
| | | | | | | 0.003) | |
| Outward inter- ICT | | | | | | | 0.012** |
| | | | | | | | (0.005) |
| Observations | 2,159 | 2,140 | 2,140 | 2,140 | 2,140 | 2,104 | 2,104 |
| AR (1) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| AR (2) | 0.306 | 0.447 | 0.263 | 0.215 | 0.183 | 0.300 | 0.221 |
| Hansen test | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

# 6 CONCLUSION

In this deliverable, we analyzed the role of ICT and ICT externality as a driver for productivity. We develop a revised, empirical version of the BFOS model that focuses on ICT externality and intangibles. ICT externalities are measured by the "link" between the industries. In other words, no consideration is given to ICT spillovers among industries that do not interact with each other. Moreover, we distinguish several dimensions of externalities: industries of the same type in different countries; different types of industry in the same country; and the direction (whether the analyzed industry creates or receives the externality). Using this classification, five types of externalities are identified (outward: domestic inter-, foreign exporting intra- and inter-industry; inward: foreign importing intra- and inter-industry). The inward externality is used to control for resources from other countries, while the outward externality is used to examine how spillover from the industry itself contributes to output growth. In addition, we include three types of intangible assets (organizational capital, training, and design) in order to control for their effects on output. The distinction between inward and outward externalities is the main novelty of our studies. We assume that spillovers that originate in a sector have a feedback effect on the exporting industry after spreading out to other industries.

The empirical analysis was conducted with an integrated, country/ industry-level dataset for 15 European countries over 15 years. Positive ICT spillover effects for different types of externalities were observed. Our findings imply that ICT contributes not only directly to output growth, but also through spillover effects to other industries, which is not observable in the productivity function. This finding provides evidence that ICT promotes productivity in both industries that produce it, and those that use it. Even industries that do not produce any ICT-related products or services can still benefit through spillover effects.

Moreover, we were able to distinguish different types of externalities. In particular, externalities that originate in the same sector were found to have a significant effect, regardless of the direction (i.e. whether they originate abroad and spillover domestically, or originate domestically and spillover in the same sector abroad). Externalities that originate abroad but operate in different sectors were also found to have a positive effect, while in the case of the same country a distinction has to be made between different sectors: when the externality originates abroad and the spillover is domestic, the effect is positive, while no evidence is found in the opposite case. To sum up, we find that not only inward externalities matter, but also outward externalities have a positive role in driving productivity, for example by enhancing the transformation of knowledge between industries, improving competition, and thus increasing innovation intensity (Aghion, Bloom, Blundell, Griffith, & Howitt, 2005).

Lastly, our findings provide empirical evidence to support the importance of specific intangibles, notably organizational capital. As discussed in the introduction, complementary investment is needed to fully benefit from ICT; therefore, the inclusion of these variables in the model is not trivial. Our findings suggest that organizational capital plays a key role in the improvement of productivity. This result is supported by other findings reported in the literature, which confirm the idea that accumulated knowledge is reflected in a firm's working practices (Brynjolfsson & Hitt, 2003), and accompanies the implementation of any new information system.

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