Information Communication Technology, Broadband Infrastructure and Firm Performance

Timothy De Stefano

University of Nottingham, School of Economics

Supervisors

Professor Richard Kneller

and

Professor Sir David Greenaway

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Thesis Introduction

Given the considerable differences in the level of development around the world, much effort within the economic community has been spent trying to understand the reasons why these differences exist. The broad consensus in the literature is that disparities in total factor productivity (TFP) are key (Hsieh and Klenow 2010). Using a standard measure of economic development, output per worker, Hall and Jones (1999) report that the amount of output per US employee is 35 times larger than for a worker in Niger. The main driver of this difference is found in the Solow residual i.e. differences in productivity. These results are similar to Klenow and Rodiguez-Clare (1997) who report that almost all (90%) of the divergence in output per worker between 98 nations can be explained by differences in the growth in total factor productivity (TFP).[1]

At the same time, an increased prevalence of micro data has led to the identification of considerable differences in TFP between firms even within the same sector (Syverson 2011). For example, within the US manufacturing industry, the difference in TFP (logged average) between establishments at the 90th and 10th percentile is 0.651, suggesting that firms at the top of the productivity distribution produce double the amount of output than firms at the bottom of the distribution with the same amount of inputs (Syverson 2004).[2] Hsieh and Klenow (2009) find that differences in plant level productivity are even greater for India and China.

One of the key reasons for differences in productivity is thought to be driven by disparities in technology.[3] Arguments in support of this view have been made at the country level (Comin and Hobijin 2010; and Parente and Prescott 1994) and at the level of the firm (Parente and Prescott 2000; Schmitz 2005; Bloom and Van Reenen, 2007).[4]

1 .For a more up-to-date review of the literature see Hsieh and Klenow (2010).

2 $e^{0.651} = 1.92.$

3 Technology in the economics literature refers to a number of factors including intangible and tangible assets.

4 In terms of differences in productivity across countries, another branch of the literature suggests the importance of efficient allocation of factors of production across establishments within the economy. See a recent review of the misallocation literature in Restuccia and Rogerson (2013).

In this thesis we explore the role of one particular technology, information communication technology (ICT). These technologies have been rapidly adopted by firms since the invention of the PC in the early 1980s. They have been associated with a transformation to the way that labour is employed within the workplace, to the organisation and management of the firm, to the way that the firm communicates with its customers and suppliers and in some cases, to what the firm produces. Not surprisingly, this technology has received considerable attention in the literature since the 1980s. A large body of work finds substantial evidence of a positive relationship between ICT and productivity and has used this to suggest that ICT is a general purpose technology (Jovanovic and Rousseau 2005; Cardona et al 2013). At the aggregate level, growth accounting exercises find positive contributions of ICT to output and productivity growth (Jorgenson and Stiroh 2000). Peering below the aggregate, research also finds that much of the contribution from ICT comes from the industries producing ICT and those industries using the technology most intensively (Stiroh 2002). Through the use of more disaggregated data economists have identified positive benefits between ICT use and firm performance.[5] Some channels through which ICT appears to drive productivity are by reducing production time, enabling product and process innovation, enhancing product quality and so on (Bresnahan et al 2002; Bloom et al, 2005; Hubbard 2003; Bartel et al 2011, Brynjolfsson et al 2008 Draca et al 2006).

While there is considerable evidence of a positive correlation between ICT and productivity in general, the literature also notes heterogeneity in the gains from ICT. For example, aggregate level analysis finds considerable disparity in the effects of ICT across countries (Colecchia and Schreyer 2002). While some of the heterogeneity arises from differences in the size of the ICT producing sectors, there are also disparities in productivity gains from the use of ICT between ICT using sectors across countries (Pilat et al 2002; Van Ark, et al 2008). Not only were firms in some countries investing in more ICT, but the firms were also able to achieve greater multifactor productivity from the same technology (Van Ark, et al 2008). Clear evidence for this can be found in Bloom et al (2012), who report how US

[5] For analysis on US firms see Lichtenberg (1993), Brynjolfson and Hitt (1995, 2002, 2003), Dewan and Min (1997) Lehr & Lichtenberg (1999), Black & Lynch (2004), Hubbard (2003), Bartelsman et al. (2011) and for analysis on firms in the EU see Greenan and Mairesse (1996), Greenan et al (2001), Forth & Mason (2003), Bloom et al. (2012).

multinational enterprises (MNEs) in the UK obtain greater gains from ICT than other non-US multinationals and UK owned firms. Moreover, establishments purchased by U.S. MNEs experienced significantly higher productivity in ICT after the acquisition than UK owned firms or non-US MNEs (Bloom et al 2012). They also find evidence that this productivity advantage in using ICT is due to more effective management skills, enabling them to be more flexible to adopt and use new technologies.

Since management abilities appear to enable firms to more effectively use digital technology, an important question is the extent to which other firm attributes also enable greater gains from ICT? Building on Bloom et al (2012) and representing the first contribution of the thesis, the first chapter examines whether or not other characteristics, thought to be complementary to ICT, also result in a productivity advantage from digital technology use. In particular, chapter one examines if the gains from ICT vary across firm age, size and human capital. The literature has given some attention to these characteristics in terms of determinants for ICT adoption, however less is known regarding whether these attributes relate to the subsequent gains from digital technology.

Using the same data as Bloom et al (2012) our results find evidence of heterogeneity in productivity gains from ICT across a range of characteristics. For example, the results suggest that firms in knowledge intensive sectors obtain greater gains from ICT, however only amongst firms that tend to be older and larger. In addition, the first chapter also finds that US owned firms in knowledge intensive sectors within certain age-size cohorts obtain the greatest gains from ICT use. Furthermore, the results suggest that US firms in low-knowledge intensive sectors still obtain comparable gains in ICT to domestic firms in knowledge active industries. The results here therefore find, similar to Bloom et al (2012) that US firms possess a productivity advantage in ICT use in comparison to non-US foreign owned and domestic firms.

While extensive progress has been made regarding our understanding of the economic implications of ICT, the literature has struggled to provide convincing evidence of a causal relationship between ICT and productivity. The main source of this endogeneity bias is the likely presence of confounding factors and reverse causality (Cardona et al 2013). While ICT may make firms more productive, it may also be the case that the most productivity firms are more profitable and can therefore afford more ICT, resulting in simultaneity bias. In addition, firms do not

randomly adoption ICT. They implement the technology based on an expectation of enhanced performance (Aral et al. 2006). Moreover, the decision to invest in new technology as well as effective implementation and performance gains is found to be related to management skills and organizational change (Bresnahan et al 2002 Bartel et al., 2007; Brynjolfsson et al., 2008; Giacarno and Heaton, 2010; Bloom et al., 2012). In this case, the positive effects of ICT found in the literature may be driven by this omitted variable. The difficulty in finding an appropriate natural experiment or instrument is one of the reasons why the literature has struggled to assess the causal effects of ICT (Draca et al 2006; Cardona et al 2013).

The second chapter attempts to fill this gap by employing an instrumental variable approach to examine the potential causal links between ICT and TFP. The instruments here exploit the rollout of ADSL broadband in the UK at the turn of the 21st Century. Both the supply-side constraints as well as the size of the telecom infrastructure meant that the timing of enablement of the telephone exchanges occurred in a staggered manner. Plants that were connected to an enabled part of the ADSL infrastructure had access to a considerably more advanced form of telecommunication technology than firms connected to a non-enabled part. The instrument captures the local average treatment effect, in which access to the broadband infrastructure influences firm productivity by incentivizing ICT investment due to access to an external communication technology which delivers substantially greater connectivity. For example, firms connected to a telephone that switched from delivering narrow broadband (dial-up) to ADSL broadband, witnessed a substantial increase in the connection speed and the volume of data that can be uploaded and downloaded. This may incentivize firms to invest in new ICT, since having access to a superior telecom technology enables them to obtain higher performance out of their investment than previously possible with dial-up internet. In addition, gaining access to ADSL broadband may lead to increased usage of ICT as a result of hardware and software requirement due to greater bandwidth and data flows (BT 2015).

The first instrument we construct measures the firm's access to the ADSL infrastructure. A second instrument is constructed using our understanding of the technical functionality of ADSL broadband. ADSL is distance dependent, meaning the greater the distance between the user and the enabled telephone exchange, the

slower the connection speed becomes.[6] We therefore also use firm distance from their enabled telephone exchange as an additional instrument for firm ICT. To our knowledge this is the first time access to the broadband infrastructure and firm distance from the exchange are used as instrument variables for ICT.

We are able to show that these instruments are correlated with ICT, where access to ADSL broadband is positively related to ICT use and firm distance from the exchange negatively related. In addition, the timing of enablement is not correlated with ex-ante firm performance, such as employment and productivity providing some evidence to suggest that the instruments are valid. While the effects of these instruments are heterogeneous across various firm characteristics, overall the results suggest the presence of a causal link between ICT and TFP.

Much of the previous literature examining the effects of ICT on performance relies on a homogenous sum of ICT investment or stock. Recently, a new branch of the ICT literature has also begun to question this standard measure of ICT. Work by Garicano and Rossi-Hansberg (2006), Bloom et al (2013b) and Garicano and Heaton (2010) suggest that treating ICT as a homogenous technology may mask the possible differentiating effects from distinct types of hardware and software which possess specific technical functions. Bloom et al (2013b) provide one of the few empirical studies to assess the differentiating effects of ICTs on firms. The authors find that technology which enables more efficient internal communication results in more hierarchical firm structure whereas IT which enhances information access leads to more decentralized firm structures.

The third contribution of the thesis therefore builds off of Bloom et al (2013b) and assesses the heterogeneous effects of various types of ICT on firm productivity. Chapter three uses the same establishment level dataset used in Bloom et al (2013b), the Ci Technology Database (CiTDB). The dataset provides detailed information on specific hardware, software and ICT personnel use at the plant level. The causal relationship between these distinct technologies and productivity are assessed within an instrumental variable approach. Similarly to the previous chapter, chapter three

[6] Distance dependence of the telephone (the pre-existing network which delivers ADSL broadband) depreciates at much longer distances than ADSL, at around 15 and 2 kilometres, respectively.

relies on access to the ADSL infrastructure and firm distance to the exchange as instruments for various types of hardware, software and IT personnel.

Similar to charter two, we show these instruments are correlated with ICT, however in chapter 3, we find heterogeneity across a number of technologies. Access to the ADSL infrastructure and firm distance from the exchange is relevant for certain types of PCs and data storage devices but not for a number of software and alternative hardware devices. In addition, the timing of the effects of the instruments on ICT use varies across different types of digital technology. This chapter also carries out a number of additional instrument validity tests, such as potential anticipation and agglomeration effects suggesting that the instruments are robust. In addition to the differentiating effects found between the instruments and certain types of ICT usage, the IV results demonstrate heterogeneity in the causal links between ICT and productivity. This suggests that not only do various types of ICTs impact the organization of the firm differently as found in Bloom et al (2013b) but the effects are also heterogeneous on the performance of the firm.

The final part of the thesis will close by drawing some conclusions from the analysis.

Chapter One

Heterogeneous Effects of ICT on Firm Performance in the UK

Introduction

The effects of ICT on productivity have received considerable attention from the economic literature. Initially, empiricists found little to no evidence of a positive contribution of ICT to productivity (Kemerer and Sosa 1991; and Roach 1989) predominately due to the fact that ICT at that time represented only a small proportion of overall capital stock (Oliner and Sichel 1994). However around the mid-1990s, growth accounting methods at the macro level began documenting the contribution of ICT to aggregate TFP and labour productivity, particularly from the expansion of ICT producing sectors (Jorgenson et al 2002 & Oliner and Sichel 2000). In addition, Stiroh (2002) finds sectors which employ ICT most intensively experienced greater productivity gains than their non-IT intensive counterparts. At the same time, the effects of ICT have been found to be positive and significant for firm performance. The results here suggest that ICT leads to reduced production time, increased innovation and specialization, improved accuracy, faster replication of processes and greater productivity dispersion (Bresnahan et al 2002; Bloom et al, 2005; Hubbard 2003; Bartel et al 2007, Brynjolfsson et al 2008).

Given the likely correlation between ICT and economic performance, an important question is whether ICT benefits all firms equally or whether the effects are heterogeneous across various firms. This question gained popularity post 1995 when it became apparent that aggregate productivity growth between the US and EU was diverging. Daveri (2002) notes that despite an increase of ICT investment for some European countries, faster TFP growth was not experienced. In addition, Van Ark, et al (2008) suggest that Europe's slower growth could be attributed not only to fewer IT producing industries but also that their investment in ICT contributed less to output growth and TFP than in the US. The rationale at the time as to why the US gained more from their ICT was either the result of a geographical bias (the US had a more competitive market, more favourable product market regulations, and greater human capital) or that US firms possessed some inherent characteristics.

Addressing this question, Bloom et al (2012) find that US firms obtained a productivity advantage from their use of ICT capital due to better "people management skills" enabling them greater flexibility to technological change. Their

results suggest that an increase in firm ICT by 2 fold led to an increase in US MNE productivity of 4.9% while the productivity of non-US MNE increased by roughly 1.2%. Furthermore, firms acquired by U.S. multinationals experienced significantly higher productivity in ICT after the acquisition than incumbents or non-US multinationals. The rationale given by Bloom et al (2012) as to why US firms had better management skills and therefore utilized ICT more effectively is due to higher levels of human capital.

Since better management skills allowed US firms to more effectively adapt to technological change, an important question is whether other firm characteristics which also enable adaptability to emerging technology similarly lead to greater gains from ICT? For example, firms with a larger proportion of educated workers may be able to adjust to new technologies better than those with less. In addition, certain characteristics of the firm that influence the cost of adjustment to change such as the age and size of the firm may also impact one's ability to effectively adapt to technology shocks. It is important to note that while the effects of firm characteristics on ICT adoption have received attention within the literature, less is known as to whether these factors result in greater productivity gains from ICT use, representing a key contribution of this chapter.

In terms of human capital, the literature suggests that firms with higher skill levels are likely to adopt and use new technologies. Early on Bartel and Lichtenberg (1987) suggest that the cognitive ability of workers enables greater flexibility to the evolution of new technologies. In addition, the literature also finds a positive relationship between the education of the workforce and the amount of ICT employed. Firms which hire greater numbers of college graduates employ a greater amount of ICT than businesses with more workers educated up to the high school level (Bresnahan et al 2002). It is therefore reasonable to assume that firms with higher levels of educated workers and thus greater cognitive ability may also obtain greater gains from ICT use.

Firm size and age have also been found to influence ICT adoption, the direction of the relationship depends on whether the cost of adjustment or accumulated know-how is more important for technology use. For example, larger and older firms may find it difficult to adapt to changes in the technology environment since they are likely to

face greater adjustment costs because of a more rigid organizational structure and/or because they tend to have more accumulated stocks of vintage technology that may not be complementary with more recent technology (Utterback 1996; Baldwin and Rafiquzzaman 1998). At the same time, if accumulated know-how is more complementary to ICT adoption (of which larger and older firms are more likely to possess) then larger and older firms may more effectively invest in ICT (Gibbs and Kraemer 2004; Arvanitis and Hollenstein 2001).

Using the same data and ICT capital stock measure of Bloom et al (2012), this chapter attempts to provide additional understanding regarding the effects of ICT on the productivity of UK firms and examine the extent to which other characteristics aside from US ownership lead to heterogeneous gains from ICT. First, the chapter analyses the relationship between ICT and firm productivity assessing the strength of the relationship by including a range of control variables also thought to influence TFP. Second, the chapter examines the robustness of these results across regions, sectors and time, and with a number of ICT variables and performance measures. Third, the chapter analyses the potential heterogeneous effects of ICT by the size of the firm, their age, and human capital.

The chapter continues as follows: Section 2, provides a review of the literature on the relationship between ICT and productivity, reports evidence of heterogeneity in its effects across firms and discusses the determinants for effective ICT use. Section 3, discusses the data used, along with an explanation regarding the key variables followed by some descriptive statistics. Section 4, illustrates the empirical strategy while section 5 presents the results. Finally section 6 summarizes the key findings and provides some discussion.

Literature Review

Since the present chapter looks to assess the effects of ICT and the extent to which certain firm characteristics obtain different gains from ICT, the chapter begins by first reviewing the literature on ICT, in particular focusing on studies which find heterogeneity in gains from ICT across countries, sectors and firms. After which, the literature review assesses empirical work on the effects of firm characteristics (human capital, size and age) on ICT use. Most of these studies examine the

relationship between firm characteristics and technology adoption rather than gains to productivity, which is the area in which this chapter looks to contribute.

ICT and Economic Performance

Despite substantial evidence regarding a positive relationship between ICT and productivity, the size of the contribution and effects of ICT are found to be heterogeneous. At the macro level, empirical evidence finds substantial variation in the effects of ICT across countries. For example, Colecchia and Schreyer (2002) examine the contribution of ICT to aggregate output and find the US, Australia, Canada and Finland obtained greater gains from ICT stock than Germany, Italy, France and Japan. Similarly, Pilat et al (2002) find that the productivity gains in the ICT-using sector documented in the US and Australia were not equally experienced elsewhere. In addition, Daveri (2002) notes that although Europe increased investment in ICT during the early 2000s, an uptick of TFP growth was not experienced similar to that in the US. These differences in output and productivity obtained from ICT between Europe and the US is partly explained by the fact that the US not only invested more into ICT but their firms were able to achieve greater multifactor productivity growth potentially due to complementary organizational changes (Van Ark, et al 2008).

Blandcard (2004) suggests that differences in productivity gains across EU and the US may be explained by differences in measures of productivity across countries. However, O'Mahoney and Van Ark (2003) find that the disparities in productivity growth between the US and EU persist even when analysing the same sectors, employing the same depreciation hedonic pricing, demand conditions and capitalization of software. Others suggest that the heterogeneity across countries, industries and firms may also be due to differences in regulatory environments. Van Ark and Inklaar (2005) argue that the disparity in gains from ICT between the US and EU may be driven by European labour and product market regulations that hinder technological experimentation as well as complementary investment. In addition, recent work by Bartelsman et al (2013) suggests that employee protection regulation in Europe has adversely impacted firm adoption of ICT since it is difficult to release workers in the event of an economic slowdown, holding back productivity growth.

Bloom et al (2012) however find evidence to suggest that the reason US firms obtain greater effects of ICT is not because of a natural or geographic advantage of being located in the US but because US firms have better people management practices. In order to assess this, the authors analyse the difference in productivity linked to ICT between US owned multinational firms, non-US multinational firms and domestically owned firms in the UK. They discover that US MNEs exhibit a productivity advantage regarding their use of ICT capital. In addition, in order to ensure that US MNEs are not simply procuring the most productive firms they assess the gains from ICT before and after an establishment is acquired. Their results show that firms purchased by US multinationals experienced significantly higher productivity from ICT compared to those procured by non-US multinationals. Overall the paper suggests that the management quality of a firm may be an important omitted variable in much of the analysis on ICT and productivity.

Human capital and technology use

Early on the literature documented the differentiating effects of firm characteristics and ICT use including human capital.[7] Much of the research suggests that the adaptability of workers and their level of education are important determinants for effective ICT usage. An early case study by Brynjolfsson et al (1997) analyses a medical manufacturer as they invest in a new computer integrated manufacturing system. Initially the implementation of the new system substantially underperformed the company's prospects since the existing workers had difficulty adjusting to the new system while maintaining their "now obsolete old work practices". In order to effectively use the new integrated manufacturing system the firm ended up relocating the production facility and handpicking younger more adaptable workers which subsequently resulted in substantial increases in productivity.

A number of empirical studies also find a positive correlation between ICT and education. For example, businesses which employ more university graduates use a greater amount of IT than firms who hire more workers with a high school education (Bresnahan et al 2002). Increases in ICT also lead to an increase in human capital

[7] The following literature review only assesses characteristics and ICT use related to human capital, size and age. Additional firm characteristics and policy environments will be assessed later on in chapter three.

investment. Furthermore ICT is positively correlated with implementing human resource policies such as additional training and monitoring of workers and greater attention to employee education requirements (Bresnahan et al 2002).

ICT as a factor input also appears to be more biased towards workers with higher skill than low skilled workers (Autor et al 1998, Machin and Van Reenen 1996 Bresnahan et al 2002). For example, is reported that ICT leads to higher productivity for workers with greater education and more complementary skills than employees with less (Autor et al 2002). Given this finding, it is therefore reasonable to assume that firms with a higher proportion of skilled workers would be able to not only use more ICT but also obtain greater productivity effects from the digital technology.

The complementarity of ICT with greater skill and education does not only refer to the average employee but to the management as well. Since managers exhibit greater influence and input decisions within the organization, firms with more highly educated managers tend to use more technology. For example, it is reported that businesses which hire a greater number of professionals and managers are found to use more ICT (Bresnahan et al 2002). Gretton et al (2004) find that both intensive and early users of ICT and internet technologies were larger firms that employed higher skilled managers and employees. As mentioned earlier, Bloom et al (2012) find that the gains from ICT capital are greater for US MNEs due to superior management practices. Additional papers suggesting the importance of management skills for effective ICT use include Hubbard (2003), Crespi et al. (2007), Bartel et al., (2007), Brynjolfsson et al. (2008), Garicano and Heaton (2010) and Garicano (2010).

Additionally, recent work by Thomas (2016) finds evidence to suggest that human capital plays a role in explaining the gap in ICT use between the US and Canada. In particular, much of the gap in ICT per employee between the US and Canada can be explained by a few sectors in Business Services, Professional Scientific and Technical services and Information and Cultural industries. In 2013 for example, Information and Cultural industries in Canada spent on average $5,309 USD per employee while the US invested $20,417 USD and for Professional Scientific and Technical services, Canada spent $1,520 USD while the US used $5,272 USD. While some of the differences (particularly in the Professional Scientific and Technical services) can be explained by measurement error, for the Information and Cultural industries, managerial education and human capital are important factors.

Human capital appears to not only be important for ICT use but also for productivity.[8] Relying on merged worker-plant data, Pekka et al (2004) find a positive relationship between the education and age of the employee and productivity. Galindo-Rueda and Haskel (2005) find that firms with greater proportions of skilled workers obtain greater productivity. There is however variation across various skill levels where for example the effects from higher skilled workers is more strongly linked to productivity than more modest skill levels. Furthermore a recent paper by Bartel at al (2014) finds that the human capital of nurses (proxied by education and team specific human capital with experience) enhances patient outcomes.

Firm age and technology use

Another determinant which may also impact effective ICT usage is the age of the firm. Theoretically, firm age may either be positively or negatively related to technology use depending on whether the accumulation of knowledge or the cost of organizational change is more complementary for ICT use. For example, older firms may have greater amounts of accrued know-how, potentially allowing them to adopt and exploit advanced technology more effectively than young firms (Arvanitis and Hollenstein 2001). Alternatively, the adjustment costs incurred when implementing new forms of technology may be more substantial for older firms (Dunne 1994). Mature firms for instance are likely to have older assets which may not be compatible with newer technologies (Baldwin and Rafiquzzaman 1998).

In terms of the empirical evidence within the literature, the number of studies is minimal and the results mixed. One of the first studies to examine the effects of age on technology adoption is Dunne (1994). His results find little evidence of a statistically significant correlation between firm age and advanced technology adoption. Arvanitis and Hollenstein (2001) however find that age can be positively related to the adoption of advanced technologies when the firm is large. As a result, they conclude that the know-how effects outweigh adjustment costs effects. In contrast, Luque (2000) finds that young firms are more likely to adopt emerging technologies when they are small supporting an adjustment cost effect.

[8] For a recent review of the literature and methods see De la Fuente (2011).

As for ICT usage, Haller and Siedschlag (2011) find that young firms who are fast growers have a greater probability of owning a website. Benjamin et al (2006) suggest that the age of a firm in the real estate brokerage sector is negatively correlated with internet use. Bertschek and Fryges (2001) on the other hand examine the determinants of business to business E-commerce technology and find little evidence of a relationship between usage and age.

Firm size and technology use

Firm size has long been thought to be an important determinant of technology use in both the theoretical and empirical literature with the reasoning largely mirroring the literature on age. For example, large firms are likely to have more knowledge based capital and more accumulated technology making it easier for them to adoption emerging technologies (Gibbs and Kraemer 2004). Moreover, firm size tends to be positively correlated with new technology use because large firms have greater financial resources relative to smaller firms who may face financial constraints (Mansfield 1993 and Wang et al 2006). Furthermore, larger firms are likely to be more efficient as they tend to undertake process innovation more intensely (given their higher fixed cost of labour) than smaller firms, incentivizing technological adoption. This mechanism was earlier illustrated in David (1975) who sketches a framework on the adoption of farm technology and the size of the farm where the implementation of mechanized reapers is more likely to occur when the cost of salaries is higher than the price of the reaper, which is both related to the number of workers and the size of the farm.

At the same time, there are possible explanations as to why firm size is negatively correlated with the usage of emerging technologies. Larger firms for example, may face greater adjustment costs when implementing new technology. Businesses that are smaller may be quicker to adopt advanced capital as their organization structure is more flexible in the event of a technological shock (DePietro, Wiarda, & Fleischer, 1990; Gibbs and Kraemer 2004). Moreover large firms, given their size tend to be more protected from market forces and therefore may be less incentivized to use the most recent technology in order to reap even higher profits (Oster 1982). Therefore, similar with age, the extent to which large or small firms effectively implement ICT

depends on whether the adjustment cost effects or the know-how effects are stronger.

The empirical evidence on the effects of firm size and technology usage is again mixed. There is a long history of empirical work which finds a positive relationship between size and technology usage such as Metcalfe (1970), Levin et al (1987) and Karshenas and Stoneman (1993). However, Oster (1982) finds that firm size is negatively related to technology employment. Examining the usage of basic oxygen furnaces within the steel industry, Oster (1982) report that larger firms implemented the technology later than their smaller counterparts. In particular, the results suggest that a larger sized firms like US Steel would use basic oxygen furnaces 7 to 8 years later than say Inland or National, medium size steel producers.

Similarly the effects of firm size on ICT use vary. Swamidass and Kotha (1998) find a positive and significant relationship between firm size and advanced manufacturing technology usage. This is one of the few studies which assess the effects of firm size on the gains from ICT. The results show modest effects in which firm size influences the relationship between advanced manufacturing technology usage and performance, potentially the result of a greater accumulated know-how. Wang et al (2010) find that firm size is the key determinant impacting the implementation of radio frequency identification technology. They suggest this is due to the high costs associated with setting up and maintaining the technology which requires complementary hardware and software inputs as well as consultancy advice. Soares-Aguiar and Palma-dos-Reis (2008) use a Logit model estimation with data collected in Portugal for 2500 of the largest companies and find that firm size and IT expertise positively and significantly impact the adoption of electronic procurement systems. Moreover recent descriptive analysis from the OECD (2015) Digital Economy Outlook suggest that firms with 250 or more employees exhibit greater propensities to use advanced ICT such as Enterprise Resource Planning software and cloud computing.

In comparison, Harris and Katz (1991) examine the effect of firm size on ICT investment amongst life insurance companies and find that smaller firms spend a greater percentage of operating expenses on IT than larger firms. A cross-country study using a structural equation model with data on retail firms across 10 countries find that as firms get larger, their usage of e-business decreases, suggesting that this is due to rigid organizational structures (Zhu and Kraemer (2005). Similarly,

Hollenstien (2004) finds that for a sample of Swiss firms, large companies use the internet less intensively than medium sized firms. Love et al (2005) and Teo et al (1997) on the other hand find either no or a modest impact of firm size on adoption.

Data

This chapter relies primarily on the Annual Respondent Database (ARD). The ARD formed from the Annual Business Inquiry, is the main source for firm level data in the UK and is the same dataset used in Bloom et al (2012).[9] Constructed from a mandatory business survey, the ARD is a census of large businesses and a sample of smaller firms, which includes information on all sectors (aside from finance) from 1997.[10] This dataset contains many of the variables needed to estimate TFP such as gross output, gross value added and material inputs as well as various firm specifications such as employment, foreign ownership and sectorial indicators. Information on capital stock is taken from the Capital Stock Dataset. The capital stock variable is an estimation using Perpetual Inventory Method (PIM) with different depreciation rates for machinery and plant, vehicles and buildings (Gilhooly 2009). The ICT capital stock variable comes from the ICT Capital Stock Database and is also estimated using PIM with differentiated depreciation rates for software and hardware. Furthermore, the Business Structure Database and the National Statistics Postcode Directory datasets are used to provide additional variables such as firm age and urban/rural location indicators. The presence of a unique plant identifier across all the datasets allows us to merge the various panels.

Descriptive Statistics

The empirical analysis from this chapter uses an unbalanced panel of 44,542 observations for which there are 13,785 firms for the years 2000 to 2005.[11] The average firm size is 799 workers while the median size is 222 illustrating that our sample contains many large and medium businesses suggesting substantial heterogeneity in size. In addition the median and mean gross output is large at £16.6

[9] For a full description of the dataset see Griffith (1999).
[10] The sample of small firms is rotated on an annual base in order to prevent an over sampling of SMEs.
[11] The sample period here is restricted to these years for two reasons. First the years 1997 to 1999 are dropped from the sample since there are fewer observations during this period. Second, the ICT database only spans until 2005.

and £96.8 million, respectively. The average, firm has around £1.124 million worth of ICT capital stock with the median firm employing £67,000. Out of the different types of ICT technologies, firms on average employ more hardware than total software. Moreover, the employment of these technologies is heterogeneous with mean (median) hardware stock of £968,000 (£65,000) and £510,000 (£29,000) for software.

Table 1

Summary Statistics of Firms, 2000 to 2005

Variables	Mean	Median	Standard Deviation	Frequency
Gross Output	96,821	16,595	581,321	44,542
Gross Value Added	31,417	6,111	284,677	44,542
Labour	799	222	4,686	44,542
Capital Stock	92,913	8,947	663,220	44,542
Materials	63,094	8,487	392,035	44,542
Hardware Stock	968	65	10,639	29,544
Purchased Software Stock	494	29	6,464	42,058
Total Software Stock	510	29	6,612	42,129
IT Capital Stock	1,124	67	14,375	44,542

Note: All variables aside from Labour are in thousands represented in pound sterling (base year 2000). Labour represents employee headcount.

The greatest proportion of observations in our sample is located in Greater London and the South East accounting for around 31%. Next is Wales which represents around 11% while Scotland, the North West and the West Midlands, account for 10% and 9% respectively. Observations in Yorkshire and Humberside makeup 8% of the sample and East Midlands the South West each account for 7%. The regions representing the fewest observations are the North and East Anglia each containing 4% of the sample. Aside for Wales, the regional representation of the data is stable during the sample period. The regional variation in firm observations from the ARD is relatively close to the population of the UK. For example, 27.5% of Great Britain's population resides in London and the South East whereas East Midlands and York and Humberside account for 7.4% and 8.6%, respectively. Aside from Wales, whose portion of the populace actually accounts for around 5%, the sample appears to representative of the UK population (ONS 2012).

Table 2

Regional Dispersion from 2000 to 2005

Region	2000	2001	2002	2003	2004	2005	Total
Greater London & SE	31%	31%	31%	30%	30%	31%	31%
Wales	6%	11%	12%	13%	13%	12%	11%
Scotland	10%	10%	9%	9%	9%	10%	10%
North West	10%	9%	9%	9%	9%	9%	9%
West Midlands	10%	9%	9%	9%	9%	9%	9%
York & Humberside	9%	8%	7%	8%	8%	8%	8%
East Midlands	8%	7%	8%	7%	7%	7%	7%
South West	8%	8%	7%	7%	8%	8%	7%
North	4%	4%	4%	4%	4%	4%	4%
East Anglia	4%	4%	4%	4%	4%	4%	4%
Total	4,795	7,529	7,944	8,000	8,133	8,141	44,542

Decomposing the sample by industry shows that overall 58% of the observations are service firms while 42% are manufacturers. The service industry can be further broken down into the following sectors: catering, motor trade, property, retail, wholesale, construction and other services. Most of the firms in the service industry are classified as other services 34%, with the motor trade and property sectors containing the fewest observations of 2% each. When examining the sectoral dispersion across years, the production sector has experienced a continuing decline accounting for 50% in 2000 and 37% in 2005. At the same time the number of observations from the service sector increased during this time from 50% in 2000 to 63% in 2005.

Table 3

Sectoral Dispersion from 2000 to 2005

Sectors	2000	2001	2002	2003	2004	2005	Total
Production	50%	44%	42%	41%	39%	37%	42%
Other Services	30%	33%	33%	34%	36%	38%	34%
Wholesale	7%	7%	7%	8%	8%	7%	7%
Retail	4%	5%	5%	5%	5%	5%	5%
Construction	5%	5%	5%	5%	5%	5%	5%
Catering	2%	3%	3%	3%	3%	4%	3%
Motor Trade	2%	2%	3%	2%	2%	3%	2%
Property	0.4%	2%	2%	2%	2%	2%	2%
Services	50%	56%	58%	59%	61%	63%	58%
Manufacturing	50%	44%	42%	41%	39%	37%	42%
Total	4,795	7,529	7,944	8,000	8,133	8,141	44,542

Most of the firms in our sample are domestically owned. 80% are controlled by UK owners whereas 13% and 7% are respectively operated by Non-US MNE and US MNE firms. The proportion of non-US foreign and US firms is quite consistent over the sample period altering no more than a few percentage points each year. There is some increase in the proportion of foreign owned firms however this remains quite stable over the sample period.

Table 4

Domestic, non-US foreign and US owned from 2000 to 2005

Year	2000	2001	2002	2003	2004	2005	Total
Domestic	84%	81%	81%	80%	80%	79%	80%
Non-US Foreign	11%	12%	12%	13%	13%	14%	13%
US	5%	7%	7%	7%	7%	7%	7%
Total	4,795	7,529	7,944	8,000	8,133	8,141	44,542

The sample is comprised of firms with ages ranging from 0 to 30+ years old. Firms that are between the ages of 26 and 30 years old make up the majority of our sample consisting of 23% of all observations. The next largest group are firms between the ages of 11 to 15 years old attributing to 20% of the sample. Young firms ranging in ages of 0 to 5 and 6 to 10 years of age account for 10% and 16%, respectively.

Table 5

Firm Age

Age	Frequency	Percentage	Accumulation
0 to 5 years old	4,398	10%	10%
6 to 10 years old	7,061	16%	26%
11 to 15 years old	8,835	20%	46%
16 to 20 years old	5,592	13%	58%
21 to 25 years old	3,812	9%	67%
26 to 30 years old	10,316	23%	90%
30+	4,528	10%	100%
Total	44,542	100%	

In terms of firm size, (measured by employment of the establishment) most of the observations are large with 251 or more employees. This is consistent with the sampling nature of the ARD. The next greatest proportion is medium sized firms, with 51 to 250 employees representing 41% of the sample, while small firms represent the 13% of the dataset. Overtime the proportions of firms that are medium and large

have decreased slightly. At the same time however, the percentage of small firms has increased between 2000 and 2005 from 9% to 18%.

Table 6

Firm Size Observations from 2000 to 2005

Size, by Employees	2000	2001	2002	2003	2004	2005	Total
1 to 50	9%	10%	12%	13%	15%	18%	13%
51 to 250	44%	41%	41%	40%	40%	39%	41%
251 +	47%	48%	48%	47%	46%	43%	46%
Total	4,795	7,529	7,944	8,000	8,133	8,141	44,542

Table 7 illustrates the proportion of firms active in a knowledge intensive sector from 2000 to 2005. Firms are categorized as being a knowledge intensive firm by their 2 digit sector based on the Statistical Classification of Economic Activities in the European Community (Eurostat 2014). Since this chapter is interested in the gains of ICT and human capital, this analysis relies on the Knowledge Intensive Activities sectoral approach which categorizes industries by the proportion of workers with higher education for each 2 digit NACE sector from EU countries. In particular, classifications are based on industries in which 33% of total employment received tertiary education (Eurostat 2014). Out of the sample, roughly 34% of firms engage in a knowledge intensive industry where 66% of firms in low-knowledge intensive sectors. In addition, the proportion of knowledge intensive and non-intensive has been relatively stable overtime suggesting modest growth in the proportion of firms in knowledge intensive sectors.

Table 7

Firms in Knowledge Intensity Sectors from 2000 to 2005

KIS	2000	2001	2002	2003	2004	2005	Total
0	69%	67%	67%	66%	63%	63%	66%
1	31%	33%	33%	34%	37%	37%	34%
Total	4,795	7,529	7,944	8,000	8,133	8,141	44,542

Empirical Strategy

In order to examine the effects of ICT on firm performance, we estimate the equation set out in Equation 1: where tfp_{it} represents the productivity measure for firm i at

period t and ict_{it} signifies the ICT capital stock. X_{it} is a vector of control variables also thought to be related to productivity such as size, age, origin of ownership, industry, region and years. Finally μ_{it} represents the residual. All continuous variables are in natural logs.

$$tfp_{it} = \alpha_{it} + \beta_{ICT} ict_{it} + \beta_X X_{it} + \mu_{it} \quad (1)$$

The baseline TFP estimate is calculated using a standard Cobb-Douglas production function similar to that presented in (Van Beveren 2012):

$$Y_{it} = A_{it} K_{it}^{\beta_k} L_{it}^{\beta_l} M_{it}^{\beta_m} \quad (2)$$

Y_{it} refers to the gross output of firm i at time t. K_{it}, L_{it}, M_{it} are the factor inputs, capital stock, labour and intermediates and A_{it} signifies Hicksian efficiency. A linear production function can then be estimated by taking the natural logs of Equation (2) to signify Equation (3) illustrated below (where lower-case letters represent the natural logs).

$$y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \varepsilon_{it} \quad (3)$$

Hicksian neutral efficiency is represented by two components within Equation (4). First, β_0 signifies the average level of efficiency for firm i at period t. ε_{it} on the other hand is the firm and time variation from the mean which can be broken down further into both observable and unobservable elements as shown in Equation (5).

$$ln(A_{it}) = \beta_0 + \varepsilon_{it} = \beta_0 + v_{it} + u_{it}^q \quad (4)$$

Here β_0 and v_{it} indicates establishment level TFP and u_{it}^q is the unexpected variation from the mean resulting from measurement error, unanticipated interruptions and so on.

$$y_{it} = \beta_0 + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + v_{it} + u_{it}^q \quad (5)$$

Firm efficiency is thus illustrated by $\widehat{w_{it}} = \beta_0 + \upsilon_{it}$ where the baseline productivity measure is calculated by equation (6). In addition to the baseline TFP estimate in Equation 6, TFP is also calculated later on by including three-digit sector input interaction terms to control for variation of input usage across sectors.

$$tfp_{it} = \widehat{w_{it}} = y_{it} - \widehat{\beta_k} k_{it} - \widehat{\beta_l} l_{it} - \widehat{\beta_m} m_{it} \quad (6)$$

Simply relying on a standard OLS Cobb Douglas production function to estimate productivity however, may provide biased estimates (Van Beveren 2012), particularly since the explanatory variable of interest is a factor input. OLS requires that factors contained within the production function to be determined exogenously. However it was documented early on that a firm's efficiency influences their decision to invest in various inputs (Marschak and Andrews 1944). Therefore, if firms have advanced understanding of their level of efficiency when choosing factors, simultaneity bias becomes present leading to upward bias in the coefficients of labour and material inputs (Olley and Pakes, 1996).

One of the ways to overcome bias from input decisions found with the standard production function is to estimate TFP using the Levinsohn-Petrin (LP) estimation. The method attempts to addresses the potential endogeneity of input usage by proxing unobserved productivity shocks with intermediate inputs. Also, by relying on intermediate inputs rather than investment as in Olley and Pakes (1996) more observations can be retained since most firms' list positive use of intermediates for each year allowing a monotonicity condition to hold (Levinsohn and Petrin 2003). In addition Van Bereven (2012) also finds that the TFP estimates across these two measures are quite similar. Therefore as a robustness test, we use a TFP measure calculated *a la* Levinsohn and Petrin alongside our baseline estimate.

Empirical Results

The objective of this paper is to examine the relationship between ICT and productivity for UK firms and analyse whether specified firm characteristics result in different productivity gains from the use of ICT. This section reports OLS estimates consistent with Equation 1. The baseline model will then be examined focusing on regions, sectors, and time in order to analyse whether the results are driven by temporal, regional or industrial aspects. On the completion of this, we next examine

whether the effects of ICT are heterogeneous across firms according to their size, age and human capital. Finally, given the possibility of endogeneity between input choice and firm TFP, we use the Levinsohn-Petrin estimate to examine the consistency of our main findings.

Baseline Estimation and Robustness

When estimating Equation 1, a number of control variables are added which are perceived to influence productivity. These include firm size based on the number of plants of the firm, ownership, age, firm regional location, sector and year. For example, some evidence suggests that multi-plant firms are substantially more productive than single-plant firms (Baldwin and Gu 2006; Baldwin and Gorecki 1998). Also as documented in the literature, foreign owned firms, in particular those by US firms tend to be more productive and invest much heavier in IT than domestic firms (Javorcik and Poelhekke 2014; Bloom et al 2012 Arnold and Javorcik 2009; Guadalupe et al. 2012; and Helpman et al. 2004). As a result, foreign as well as US owned dummies are included. Another factor thought to impact firm productivity is the age illustrated by (Jensen et al 2001). Year and region dummies are also added to control for economy wide shocks and variation across geographic locations. 2 digit sector dummies are used given the documented heterogeneity in productivity found across different industries (Stiroh 2002). Finally, firm fixed effects are added to control for unobservable time invariant firm specific characteristics which may also influence productivity, such as managerial characteristics. While the use of firm fixed effects can be useful for controlling for unobservable firm heterogeneity, it is important to note that the use of these also eliminates potential gains from ICT that occur overtime (Cordona et al 2013). In addition, the use of fixed effects in the presence of measurement error may exacerbate attenuation bias. Previous studies in the literature find substantially smaller ICT coefficient estimates when including fixed effects (Brynjolfsson and Hitt 1995: Stiroh 1998; and McGuckin and Stiroh 2002).

The baseline estimates on the effect of ICT on firm TFP are reported in Table 8. The table progresses by adding new control variables which we discuss above. Consistent with the literature, we find a positive relationship between ICT and TFP throughout this table. We also note there is little variation in the coefficient size across Models 1 through Model 8 ranging from 0.030 to 0.044, suggesting that a 10% increase in ICT capital results in an increase of TFP by around 3-4%. This is of interest as it suggests

that there is no strong correlation between the controls and TFP. When adding firm fixed effects in models 9 and 10, ICT and productivity are still significantly related at the 1% level however the coefficients are substantially smaller at 0.006 and 0.005, potentially suggesting that most of the effect in regressions 1-8 is explained by between firm variations. Using within firm cross-time change we find ICT has much smaller effects on firm TFP. This downward effect from the inclusion of firm level fixed effects is consistent with the literature (Cardona et al 2013; McGuckin and Stiroh, 2002 Stiroh, 1998; and Brynjolfsson and Hitt 1995). Being an establishment connected to a multi-plant firm is negatively correlated with TFP whereas foreign ownership is positively related to productivity. In addition, we find differences in the size of the coefficients between foreign owned and USA owned firms, suggesting firms owned by US proprietors obtain greater efficiency than other foreign owned firms. Moreover, the results suggest that firm age is negatively related to TFP.

The remainder of the chapter will use Model 8 in Table 8 as the baseline model for much of the subsequent analysis. There is little difference in the estimates when using either 2-digit sector dummies or 2-digit sector year interactions between Model 8 and Model 9. In addition, while the use of fixed effects can be helpful to control for within firm time-invariant characteristics, the presence of measurement error (which can be an issue even with the best ICT estimates) can exacerbate attenuation bias (Pischke 2007 and Rossi 2013).

Table 8

Effects of ICT on TFP with Various Controls, 2000 to 2005

Dependent Variable: TFP	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11
ICT	0.033***	0.044***	0.043***	0.042***	0.044***	0.044***	0.040***	0.030***	0.030***	0.006***	0.005***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant		-0.041***	-0.041***	-0.040***	-0.038***	-0.037***	-0.040***	-0.033***	-0.033***	-0.010**	-0.009**
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Foreign			0.027***	0.034***	0.035***	0.034***	0.032***	0.033***	0.033***	0.000	0.001
			(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
USA				0.072***	0.073***	0.072***	0.069***	0.069***	0.069***	-0.003	-0.003
				(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Age					-0.030***	-0.032***	-0.028***	-0.007***	-0.007***	0.013*	0.011
					(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
Additional controls											
Year						✓	✓	✓	✓	✓	✓
Region							✓	✓	✓	✓	✓
2 digit sector								✓	✓	✓	✓
2 digit sector*year									✓		✓
Fixed effects										✓	✓
Adjusted-R^2	0.0340	0.0480	0.0490	0.0510	0.0550	0.0590	0.0780	0.3080	0.3130	0.0240	0.0410
Observations	45,549	45,549	45,549	45,549	44,543	44,543	44,542	44,542	44,542	44,542	44,542

Note: Level of significance is as follows, *** 1%, ** 5% and * 10%.

In order to investigate whether these results are consistent for the UK as a whole or whether a particular area is driving national results, we examine the effects of ICT by region using Model 8 Table 8 as a baseline. The 10 regions assessed include Greater London and South East, East Anglia, South West, West Midlands, East Midlands, York and Humberside, North West, the North, Wales and Scotland. Within Table 9 we find the existence of heterogeneity in the size of the ICT coefficient across UK regions. For all regions, ICT capital is positive and significantly related to TFP at the 1% level of significance. Therefore, it appears that increases in ICT result in greater efficiency in all areas however the magnitude of this can depend on firm location. For example, a 10% increase in ICT leads to a 4% increase in TFP in London but only a 1.4% increase in East Anglia. The effects of ICT in the North West are larger than all areas aside for London with a coefficient of 0.033. For all other regions in the UK, the ICT coefficients vary from 0.024 to 0.028. Given that firms in London on average appear to gain more from ICT it is also important to examine the extent to which this is influencing the results for the UK as a whole. When we exclude London from the sample, the ICT coefficient is 0.025, 0.005 points lower than the baseline estimate in Table 8 Model 8, suggesting that London to some extent influences the nationwide result, albeit minimal.

In all regions the multi plant variable is negative and statistically significant at the 1 and 5% levels. The effects of foreign and USA ownership across locations varies. For the regions where the foreign and USA coefficients are significant the results are positive. However in East Anglia, the East Midlands and the North, both foreign and USA are insignificant. This may be the result of a modest number of foreign firms in those regions. The age coefficient is also unexpectedly heterogeneous across regions. In the West Midlands for example the age coefficient is positive and significant at the 10% level and in other regions not significant potentially due to industrial composition.

Table 9

Effects of ICT on TFP by Region, 2000 to 2005

Dependent Variable: TFP	G London	E Anglia	South West	West Mid	East Mid	York and Humber	North West	North	Wales	Scotland	No London
ICT	0.040***	0.014**	0.024***	0.025***	0.025***	0.027***	0.033***	0.028***	0.007**	0.027***	0.025***
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.049***	-0.01	-0.025***	-0.032***	-0.020***	-0.015***	-0.024***	-0.023**	-0.017**	-0.026***	-0.022***
	(0.00)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Foreign	0.032***	0.029	0.011	0.025*	-0.020	0.057***	0.050**	0.018	0.038*	0.054***	0.027***
	(0.01)	(0.04)	(0.02)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)	(0.02)	(0.02)	(0.01)
USA	0.058***	-0.019	0.076***	0.080***	0.015	0.066***	0.039	0.057*	0.024	0.107***	0.068***
	(0.01)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.02)	(0.01)
Age	-0.009*	-0.024	-0.010	0.012*	0.002	-0.019***	-0.009	-0.014	0.000	-0.005	-0.005*
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Adjusted-R^2	0.3290	0.2510	0.3610	0.3530	0.3800	0.3870	0.2500	0.4020	0.2860	0.3600	0.2770
Observations	13,654	1,643	3,273	3,976	3,309	3,449	4,095	1,804	5,095	4,244	30,888

Note: all models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

Further examining the extent to which the regional location of firms leads to differentiated effects of ICT, we next see whether differences exist between firms located in urban and rural locations. The results suggest that the effects of ICT are larger for the sample of firms in urban locations than for rural location, the estimated coefficients are 0.031 and 0.021, respectively. This appears consistent with work which finds that rural areas in England used less ICT than urban regions during this time period (Mack-Smith 2005). For both regions, the control variables exhibit their expected signs and significances, aside from firm age in rural areas which does not appear to be related to productivity.

Table 10 also examines whether the effects of ICT differ between service and manufacturing firms. The results here indicate the effect is stronger for service firms. For manufactures and 10% increase in ICT stock results in an increase of TFP by around 2.7% whereas the same proportion of ICT investment would lead to a 3.1% increase in productivity for service firms. Given the substantial differences regarding the nature of operations across manufactures and services it is interesting to see that the effects of IT between the two groups are reasonably close. Multiple plants and age are both negatively correlated with TFP for manufacturers whereas foreign ownership is associated with higher TFP. For service firms, both multi plants and foreign/USA ownership have the expected signs and significance however, firm age does not seem to be significantly correlated with TFP.

Table 10

Effects of ICT on TFP, Rural/Urban Manu/Services, 2000 to 2005

Dependent Variable: TFP	Urban	Rural	Manufacturer	Service
ICT	0.031***	0.021***	0.027***	0.031***
	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.035***	-0.016***	-0.006**	-0.041***
	(0.00)	(0.00)	(0.00)	(0.00)
Foreign	0.032***	0.029**	0.022***	0.044***
	(0.01)	(0.01)	(0.01)	(0.01)
USA	0.064***	0.074***	0.066***	0.064***
	(0.01)	(0.02)	(0.01)	(0.01)
Age	-0.007***	-0.001	-0.007**	-0.005
	(0.00)	(0.01)	(0.00)	(0.00)
Adjusted-R^2	0.3230	0.2300	0.2700	0.3010
Observations	36,122	8,420	18,573	25,969

Note: all models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

Next, we decompose industries by the 8 sectoral classifications used in the ARD including, Catering, Motor Trade, Property, Retail, Other Services, Wholesale, Construction and Manufacturing. As with the previous tables, ICT is positively and significantly correlated with TFP at the 1-10% levels of significance. The differences between sectors are said to be modest, but coefficients in some sectors are more than double in comparison to other industries. The effects of ICT are the greatest in the Wholesale and Motor Trade industries with coefficients of 0.052 and 0.045, respectively. For Catering, the estimated coefficient is 0.034 and Other Services and Manufacturing as well as Property and Retail exhibit 0.027 and 0.024, respectively. Perhaps not surprisingly the ICT coefficient for the construction sector is the smallest at 0.019.

Table 11

Effects of ICT on TFP by Industry, 2000 to 2005

Dependent Variable: TFP	Catering	Motor Trade	Property	Retail	Other Services	Wholesale	Construction	Manufacturing
ICT	0.034***	0.045***	0.024*	0.024***	0.027***	0.052***	0.019***	0.027***
	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.034***	-0.070***	-0.078***	-0.019***	-0.039***	-0.079***	0.000	-0.006**
	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.01)	(0.00)
Foreign	0.070**	0.254***	-0.197	0.023	0.000	0.069***	-0.044**	0.022***
	(0.03)	(0.02)	(0.17)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)
USA	-0.002	0.180***	-0.236*	0.032	0.036*	0.120***	-0.073	0.066***
	(0.05)	(0.05)	(0.12)	(0.03)	(0.02)	(0.02)	(0.06)	(0.01)
Age	0.044***	-0.001	0.072**	-0.009	-0.012**	-0.025***	0.004	-0.007**
	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Adjusted-R^2	0.2430	0.4000	0.1640	0.1940	0.2630	0.2020	0.0640	0.2700
Observations	1,311	1,077	698	2,222	15,300	3,284	2,077	18,573

Note: all models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

Next we examine whether there is variation in the impact of ICT across each year of the sample, 2000 to 2005. For example, it may be the case that results somewhat reflect a particular surge or drop in IT investment from one year to the next such as before during and after the dot com bubble as illustrated in OECD (2015). We address this issue by regressing TFP on ICT separately for every year in the sample. The results in Table 12 imply limited variation in IT effects across the 6 years of our sample. The IT coefficients range from 0.030 in the year 2000 to 0.028 in 2005 where all coefficients are statistically significant at the 1% level. As well, these results are also consistent with our base line regression Model 8 in Table 8 where the coefficient is 0.030. Moreover these results are very stable across all sample periods.

Table 12

Effects of ICT on TFP by Year

Dependent Variable: TFP	2000	2001	2002	2003	2004	2005
ICT	0.030***	0.031***	0.030***	0.032***	0.030***	0.028***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.032***	-0.032***	-0.031***	-0.030***	-0.036***	-0.039***
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)
Foreign	0.063***	0.029**	0.037***	0.007	0.027**	0.053***
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
USA	0.046**	0.064***	0.064***	0.053***	0.082***	0.092***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Age	-0.005	-0.001	-0.015***	-0.007	-0.002	-0.009
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Adjusted-R^2	0.3040	0.3070	0.2970	0.3090	0.3090	0.2720
Observations	4,795	7,529	7,944	8,000	8,133	8,141

Note: all models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

The ICT variable used in this chapter is an estimate of ICT capital stock generated from the data sources and code provided by Bloom et al (2012). This dataset contains a number of different ICT measures. Recent work by Bloom et al (2013b) finds evidence to suggest that ICT hardware and software have different effects on firms. We consider this using information on hardware stock, total software stock, which includes purchased software stock and in-house created software stock. This

therefore enables us to assess the extent to which the effects from hardware and software impact TFP differently from ICT capital stock.

Within Table 13 we find that the effects of various types of ICT classes are heterogeneous in terms of their coefficient sizes. Despite these differences, all forms of technology are positive and significantly related to TFP at the 1% level. Hardware in particular appears to contribute the most to TFP with a coefficient of 0.031. Total software, (a combination of purchased and in-house software) exhibits a smaller effect than hardware with a coefficient of 0.026. In addition, different types of software relate to TFP differently. A 10% increase in purchased software increases TFP by 2.7% whereas increase in software created in-house by the same amount would lead to a 1.9% increase in TFP.

Table 13

Effects of Various ICT Technologies on TFP, 2000 to 2005

Dependent Variable: TFP	ICT	Hardware	Purchased Software	Own Software	Total Software
IT Technologies	0.030***	0.031***	0.027***	0.019***	0.026***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.033***	-0.033***	-0.028***	-0.024**	-0.028***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)
Foreign	0.033***	0.019***	0.042***	0.134***	0.043***
	(0.01)	(0.01)	(0.01)	(0.03)	(0.01)
USA	0.069***	0.053***	0.073***	0.129***	0.074***
	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)
Age	-0.007***	0.001	-0.004	0.024**	-0.003
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)
Adjusted-R^2	0.3050	0.3150	0.3050	0.3210	0.3050
Observations	44,542	29,544	42,102	2,184	42,129

Note: all models additionally include year, region and 2-digit sector control variables.
*** represents 1%, ** 5% and * 10% levels of significance.

Robustness test

To examine the robustness of the above results, we re-examine the relationship between productivity and ICT using alternative TFP estimates. In doing so we compare our baseline TFP estimate calculated with a standard Cobb Douglas production function with two other TFP estimates. Here TFP2 is also estimated with a Cobb Douglas production function however 3 digit sector factor input interaction terms are included to correct for potential variance in factor input usage across

sectors. In addition, the Lev Pet TFP estimate is calculated with the Levinsohn-Petrin method, where intermediates are used as a proxy to adjust for potential endogeneity between productivity and input usage (Levinsohn and Petrin 2003). In addition to the TFP estimates, we also examine whether ICT is related to labour productivity measured by output per worker and gross value added per worker.

There does not seem to be much of a difference in the effects of ICT when using either TFP1 or TFP2 suggesting that the results do not appear to be influenced by differentiation of input usage across sectors. When employing the Lev Pet TFP estimate, ICT and productivity are still positive and significantly related at the 1% level however the ICT coefficient size is considerably smaller at 0.006. While the estimates are much smaller the model appears to be well identified. Turning to our other performance measures, we find that ICT is significantly related to both types of labour productivity. Increasing ICT by 10% can lead to an increase in output per worker and gross value added per worker by 9.4 to 8.6% respectively. Multi-plant and foreign/US ownership variables exhibit consistent signs and significance to the baseline results for most models. However, surprisingly, when using the Lev Pet, the foreign ownership variable is now negatively related and the effects of US ownership are insignificant. Carrying forward, Lev Pet TFP is used along with the baseline TFP throughout the chapter to assess the robustness of some of our key regressions.

Table 14

Effects of ICT on Firm productivity with various performance measure, 2000 to 2005

Dependent Variable: TFP	TFP1	TFP2	Lev Pet	Output/Worker	GVA/Worker
ICT	0.030***	0.030***	0.006***	0.094***	0.086***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.033***	-0.028***	-0.091***	-0.094***	-0.109***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Foreign	0.033***	0.027***	-0.048***	0.412***	0.179***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
USA	0.069***	0.065***	0.017	0.357***	0.255***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Age	-0.007***	-0.003	-0.086***	0.002	0.015***
	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Adjusted-R^2	0.3050	0.1130	0.3180	0.5030	0.3530
Observations	44,542	44,542	44,542	143,703	143,703

Note: TFP1 our baseline estimate, TFP2 includes sector*factor input interaction dummies to the baseline, and Lev Pet is estimated with via the Levinsohn-Petrin algorithm using gross value added. GVA stands for Gross Value Added. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance

Heterogeneous Effects of ICT and Productivity

The objective of this section is to examine whether the effects of ICT are heterogeneous across firm age, size and human capital. This section starts by assessing differences in the ICT coefficients across samples of firm sizes and ages. After which the chapter analyses the extent to which gains from ICT are different between size-age cohorts. Next an ICT knowledge intensive indicator (ICT*KIS) will also be added to assess whether the effects of ICT are greater for firms with greater human capital. Finally, the baseline TFP measure will be replaced with the Lev Pet to assess whether the results found are influenced by potential endogeneity contained in productivity estimation.

Within Table 15 firm age is classified as follows: young firms refer to businesses between 0 to 10 years old whereas adolescent and old firms are aged between 11 to 25 and 26 years and older, respectively. Greater gains amongst older firms may suggest the importance of accumulated know-how whereas larger gains from younger cohorts may imply the advantage of a flexible adjustment structure for ICT use.

The size of the ICT coefficients across young, adolescent and old firms are heterogeneous while at the same time the results are all significant at the 1% level. Old firms appear to obtain the greatest effects from ICT with a coefficient of 0.035. The effects of ICT for adolescent firms is slightly less at 0.033, suggesting that the difference in age between adolescent and old firms results in little difference in the magnitudinal effect from ICT capital stock. For young firms, the ICT coefficient is 0.018, around half the size for that of old firms. These results provide some preliminary support that accumulated know-how effect discussed in the literature may be important for effectively utilizing ICT (Haller and Siedschlag 2001; Benjamin et al 2006).

Similar to firm age, heterogeneity exists with regards to the magnitude of the ICT coefficients across firm sizes. Here firm size is categorized as follows: small firm are those with 1-50 employees, medium firm contain between 51-250 employees, and large firm employ 251 or more employees. In a similar manner to firm age, greater ICT gains from larger firms potentially imply that knowledge accumulation matter for ICT use whereas greater effects for smaller firms point to the importance of more malleable firm structures. For all cohorts, ICT and TFP are positively correlated at the 1% level. Small firms exhibit the largest ICT coefficient of 0.046, suggesting that TFP would increase by around 4.6% with a 10% increase in ICT stock. The next highest effects are for large firms with an estimated effect of 0.038. Medium size firms receive the smallest gain amongst the cohorts with roughly a 2.7% increase in TFP if ICT stock increased by 10%. In contrast to the effects of ICT by age, the estimates conditional on firm size appear to suggest that adjustment costs matter however this is not entirely clear from these results.

Table 15

Effects of ICT on TFP, Firm Age and Size, 2000 to 2005

Dependent Variable: TFP	Young	Adolescent	Old	Small	Medium	Large
ICT	0.018***	0.033***	0.035***	0.046***	0.027***	0.038***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.038***	-0.041***	-0.026***	-0.012	-0.018***	-0.034***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Foreign	-0.013	0.042***	0.042***	0.140***	0.057***	-0.002
	(0.01)	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)
USA	0.048***	0.069***	0.072***	0.224***	0.075***	0.045***
	(0.02)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)
Age	0.019***	-0.016	-0.086	-0.003	-0.008**	0.012***
	(0.01)	(0.01)	(0.06)	(0.01)	(0.00)	(0.00)
Adjusted-R^2	0.2840	0.2980	0.3970	0.3010	0.2720	0.3810
Observations	11,459	18,239	14,844	5,767	18,064	20,711

Note: Classifications as follows: Young, 1-10 years, Adolescent, 11-25, Old 26+, Small 1-50 workers, Medium 51 to 250, Large, 251+. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

To examine this further, we next assess the effects of ICT across age-size cohorts as an additional way to examine the potential presence of an adjustment cost or knowledge-accumulation effect. For example, Arvanitis and Hollenstein (2001) and Luque (2000) find evidence of greater ICT use across age-size cohorts. The estimates reported in Table 16 illustrate large differences in the size of ICT coefficient across groups compared to other tables. Despite this however the effects of ICT are positive and significant at the 1% level for all models. Adolescent-small firms appear to gain the most from ICT followed by old-large and small-young with coefficients ranging from 0.048, 0.045 and 0.042, respectively. The results do not imply any particular pattern between firm age and size. Thus it is not conditional on size the effect gets larger or smaller as age increases. Similarly, it is not that the effect is smaller or larger as firm age increases. It is therefore unclear as to whether the effects of accumulated knowledge or adjustment cost are more relevant to ICT use.

Table 16

Effects of ICT on TFP, Firm Age by Size Cohorts, 2000 to 2005

Dependent Variable: TFP	Young-Small	Young-Med	Young-Large	Ad-Small	Ad-Med	Ad-Large	Old-Small	Old-Med	Old-Large
ICT	0.042***	0.010***	0.026***	0.048***	0.036***	0.039***	0.028***	0.031***	0.045***
	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Multi Plant	0.012	-0.028***	-0.032***	-0.047*	-0.025***	-0.037***	-0.019	-0.009*	-0.033***
	(0.03)	(0.01)	(0.01)	(0.03)	(0.01)	(0.00)	(0.02)	(0.01)	(0.00)
Foreign	0.070	0.005	-0.038*	0.152***	0.068***	0.012	0.256***	0.058***	0.000
	(0.05)	(0.02)	(0.02)	(0.05)	(0.01)	(0.01)	(0.05)	(0.01)	(0.01)
USA	0.160**	0.055**	-0.01	0.276***	0.089***	0.050***	0.115*	0.050***	0.059***
	(0.07)	(0.03)	(0.03)	(0.08)	(0.02)	(0.01)	(0.07)	(0.02)	(0.01)
Age	0.031**	0.014	0.038***	0.114*	-0.020	-0.021	-0.052	-0.311***	0.121
	(0.01)	(0.01)	(0.01)	(0.06)	(0.02)	(0.02)	(0.21)	(0.09)	(0.09)
Adjusted-R^2	0.33	0.263	0.348	0.269	0.272	0.382	0.426	0.358	0.464
Observations	2,713	4,795	3,951	1,764	7,306	9,169	1,290	5,963	7,591

Note: Age and Size follow the pattern as Young-Small, firms between the ages of 1-10 years with 1-50 employees, and so on. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

As discussed in the literature review, the existing literature finds evidence regarding the importance of complementary assets, and gains from ICT. Historically, earlier IT prototypes were implemented by firms to substitute repetitive tasks (Brynjolfsson and Hitt 2000). However ICT has evolved and requires the firm to undertake organizational restructuring and add human capital (Autor et al 2002; and Bresnahan et al 2002). Although our current data restricts us from examining the importance of specific skills and education of firm employees, we are able to examine whether firms in sectors that use workers with higher education more intensively obtain greater gains from ICT. As mentioned previously in the data section, this definition of knowledge intensive sectors is measured at the 2 digit sector level and is based on the Statistical Classification of Economic Activities in the European Community (Eurostat 2014). These are summarized as a 0/1 variable where high knowledge sectors=1.

Given the perceived importance of age and size, we retain this classification when adding the effects of knowledge intensity. Interestingly, firms in high knowledge intensive sectors do not appear to better utilize ICT consistently across all cohorts, although there are some interesting exceptions to this. This is given by the ICT*KIS interaction reported in Table 17. In particular, there is no statistical difference in the effects of ICT between KIS and low-KIS firms amongst, young-small, young-large, adolescent-small, adolescent-medium, and old-small. In addition, firms that are young-medium in KIS sectors appear to obtain lower gains from ICT than low-KIS. Indeed the effects of ICT for this group is negative (0.029-0.037=-0.008). Firms in knowledge intensive sectors that are adolescent-large, old-medium and old-large experience statistically significant larger gains from their use of ICT. This may imply that the importance of human capital for ICT improves as firms' age and grow. For adolescent-large, old-medium and old-large, the coefficient for firms in knowledge intensive sectors is 0.042, 0.040 and 0.053, respectively which is larger than the baseline estimate of 0.030.[12]

[12] To see whether results here are driven by sectoral composition across cohorts, ICT*KIS is assessed for the entire baseline sample. See table A1 in the appendix.

Table 17

Effects of Various Technologies on TFP, Firm Age-Size Cohorts and Knowledge Intensity, 2000 to 2005

Dependent Variable: TFP	Young-Small	Young-Med	Young-Large	Ad-Small	Ad-Med	Ad-Large	Old-Small	Old-Med	Old-Large
ICT	0.039***	0.029***	0.028***	0.056***	0.035***	0.036***	0.026***	0.028***	0.042***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
ICT*KIS	0.006	-0.037***	-0.004	-0.026	0.002	0.006**	0.01	0.012**	0.011***
	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.00)	(0.02)	(0.01)	(0.00)
Multi Plant	0.011	-0.027***	-0.032***	-0.045	-0.025***	-0.037***	-0.018	-0.010**	-0.034***
	(0.03)	(0.01)	(0.01)	(0.03)	(0.01)	(0.00)	(0.02)	(0.01)	(0.00)
Foreign	0.071	-0.004	-0.037*	0.152***	0.068***	0.011	0.254***	0.059***	0.002
	(0.05)	(0.02)	(0.02)	(0.05)	(0.01)	(0.01)	(0.05)	(0.01)	(0.01)
USA	0.162**	0.047*	-0.009	0.277***	0.089***	0.049***	0.118*	0.049***	0.059***
	(0.07)	(0.03)	(0.03)	(0.08)	(0.02)	(0.01)	(0.07)	(0.02)	(0.01)
Age	0.031**	0.014	0.038***	0.112*	-0.020	-0.022	-0.061	-0.310***	0.119
	(0.01)	(0.01)	(0.01)	(0.06)	(0.02)	(0.02)	(0.22)	(0.09)	(0.09)
Adjusted-R^2	0.3300	0.2680	0.3480	0.2700	0.2720	0.3830	0.4260	0.3580	0.4650
Observations	2,713	4,795	3,951	1,764	7,306	9,169	1,290	5,963	7,591

Note: ICT*KIS refer to ICT stock knowledge intensive sector interaction term. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

In order to assess whether the results found in Table 17 are somehow influenced by potential endogeneity contained within the productivity estimate, the regressions from the previous table are replicated however now with the Levinsohn-Petrin TFP estimate. Consistent to what is found in Table 17, firms in knowledge intensive sectors within cohorts adolescent-large, old-medium and old-large appear to obtain the greatest gains from ICT. In addition, the gains from ICT from KIS firms in these cohorts are substantially larger (aside for old-large) with coefficients of 0.053, 0.051 and 0.048 respectively. In fact, the gains from ICT received by firms in KIS sectors are almost double that of firms in low-KIS sectors. The results suggest human capital appears to be an important complement to ICT particularly for more mature and larger firms.

Table 18

Effects of Various Technologies on Lev Pet TFP , Firm Age-Size Cohorts and Knowledge Intensity, 2000 to 2005

Dependent Variable: TFP	Young-Small	Young-Med	Young-Large	Ad-Small	Ad-Med	Ad-Large	Old-Small	Old-Med	Old-Large
ICT	0.031***	0.006	0.011	0.042***	0.029***	0.024***	0.025*	0.033***	0.023***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
ICT*KIS	0.014	-0.007	0.030**	-0.047**	0.005	0.029***	0.028	0.028**	0.023***
	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)
Multi Plant	0.008	-0.059***	-0.086***	-0.026	-0.028**	-0.093***	0.003	-0.035***	-0.092***
	(0.04)	(0.02)	(0.01)	(0.04)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)
Foreign	-0.079	-0.059*	-0.140***	-0.069	-0.027	-0.035	0.242***	-0.006	-0.028
	(0.09)	(0.04)	(0.04)	(0.07)	(0.03)	(0.02)	(0.09)	(0.03)	(0.02)
USA	0.031	-0.029	-0.064	0.115	0.108***	-0.002	0.244*	-0.011	0.070**
	(0.12)	(0.05)	(0.05)	(0.10)	(0.03)	(0.03)	(0.13)	(0.04)	(0.03)
Age	-0.004	-0.006	-0.023	-0.067	-0.107***	-0.047	-0.485	-0.365*	-0.356*
	(0.02)	(0.02)	(0.02)	(0.08)	(0.03)	(0.03)	(0.41)	(0.20)	(0.20)
Adjusted-R^2	0.3900	0.2780	0.3120	0.3800	0.2670	0.3840	0.3310	0.3050	0.4580
Observations	2,713	4,795	3,951	1,764	7,306	9169	1290	5963	7591

Note: ICT* KIS refer to ICT stock knowledge intensive sector interaction term. All models additionally include year, region and 2-digit sector control variables.
*** represents 1%, ** 5% and * 10% levels of significance.

The results in Tables 17 and 18 report that adolescent-large, old-medium and Old-large obtain the greatest gains from ICT, than other cohorts in particular for firms in KIS sectors. However this result may be driven by the presence of foreign firms within these cohorts. In order to assess this, we pool the data across these cohorts, adolescent-large, old-medium and old-large and include additional ICT interaction terms ICT*foreign and ICT*USA. These now test whether the effect of ICT is different for this group when we condition on the knowledge intensity of the sector (the ICT*KIS interaction).

Within Table 19, the interactions are added incrementally to the baseline (Model 8 in Table 8) aside for Model 5 which uses the Lev Pet productivity estimate in place to TFP 1, in order to examine whether the outcomes are substantially influenced by the productivity measure. Regardless of whether TFP 1 or Lev Pet productivity is used, the results suggest that firms owned by US proprietors in KIS sectors obtain the greatest gains from ICT amongst these cohorts with coefficients of 0.052 (0.035+0.008+0.009=0.052) and 0.043 (0.018+0.020+0.005=0.043) in Model 4 and Model 5, respectively. In addition, the productivity gains from ICT amongst US owned firms in low-KIS sectors (0.035+0.009=0.044) is still somewhat higher than domestic firms in KIS sectors (0.035+0.008=0.043) in Model 4. The results here in this pooled sample are consistent with Bloom at al (2012) suggesting that US firms obtain greater gains from ICT than non US firm, regardless of whether the firms are owned by a non-US foreign proprietors.

Interestingly, the differences in the productivity gains between foreign owned firms in KIS and domestic owned firms in KIS are reasonably small. In Model 4, foreign firms in knowledge intensive sectors have an estimate of 0.046 (0.035+0.008+0.003=0.046) while the effect for domestic firms in KIS sectors is 0.043 (0.035+0.008=0.043). When using the Lev Pet estimated productivity, domestic firms in KIS obtain greater gains than foreign firms residing in knowledge intensive sectors where the estimated parameters are 0.038 (0.018+0.02=0.038) and 0.034 (0.018+0.02-0.004=0.034), respectively.

Table 19

Effects of ICT by KIS, and ownership for Ad-Large, Old-Med and Old-Large firms, 2000 to 2005

	Model 1	Model 2	Model 3	Model 4	Model 5
Dependent Variable: TFP	TFP 1	TFP 1	TFP 1	TFP 1	Lev Pet
ICT	0.039***	0.037***	0.035***	0.035***	0.018***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
ICT*KIS		0.008***	0.008***	0.008***	0.020***
		(0.00)	(0.00)	(0.00)	(0.00)
ICT*Foreign			0.005***	0.003***	-0.004**
			(0.00)	(0.00)	(0.00)
ICT*USA				0.009***	0.005*
				(0.00)	(0.00)
Multi Plant	-0.030***	-0.031***	-0.030***	-0.030***	-0.087***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Age	-0.020***	-0.021***	-0.019***	-0.019***	-0.019
	(-0.01)	(-0.01)	(-0.01)	(-0.01)	(-0.01)
Additional Controls					
Year	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓
Sector	✓	✓	✓	✓	✓
Adjusted-R^2	0.3910	0.3910	0.3920	0.3920	0.3920
Observations	22,723	22,723	22,723	22,723	22,723

Note: ICT*KIS ICT*Foreign and ICT*USA refer to ICT stock knowledge intensive sector, and foreign/USA ownership interaction term. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.

Conclusion

While a large body of work documents positive economic outcomes from ICT, the gains from these technologies are not equally obtained across countries, sectors and firms (Daveri 2002; Pilat et al 2002; Van Ark, et al 2008). At the firm level, Bloom et al (2012) find that US firms possess a productivity advantage in their use of ICT due to better management, making them more flexible to technology change. Since better management skills allow US firms to more effectively adapt to technology shocks, an important question is whether other firm characteristics also enable adaptability to emerging technology and similarly lead to greater gains from ICT? The literature has long focused on the effects of firm characteristics on ICT adoption, however less is known regarding the extent to which these factors enable firms to obtain a productivity advantage through their use of ICT.

Using the same data as Bloom et al (2012), this chapter attempts to contribute to our understanding on whether firm characteristics such as size, age and human capital result in heterogeneous productivity gains from ICT use. Consistent with the literature, the present chapter finds evidence of a positive relationship between ICT and TFP. In terms of heterogeneity across firm characteristics, old firms appear to gain more from ICT than young firms while small firms obtain larger gains than larger firms. Additionally, when assessing the effects of ICT across age-size cohorts, there is no clear trend consistent with the theories of knowledge accumulation or adjustment cost effect and ICT use.

While firms with greater human capital appear to gain more from ICT than firms with less human capital, this is not consistent across all size-age cohorts. However the results do suggest that firms that are in KIS sectors that are both mature and large exhibit the greatest productivity advantage from their ICT stock. This result is persistent regardless of whether productivity is estimated with the baseline TFP measure or with the Levinsohn-Petrin estimate. As a result, the productivity advantage of firms in KIS sectors tends to be for larger and older firms implying both the importance of accumulated know-how and relative human capital for effective ICT usage.

Focusing within adolescent-large, old-medium and old-large cohorts, we next examine whether the gains of ICT are heterogeneous across firm ownership. We find that US firms in KIS sectors obtain greater gains from ICT than non-US foreign and domestic firms in KIS sectors. These findings are consistent with Bloom et al (2012) regarding the documented US firm productivity advantage in ICT usage. Interestingly, the results in this chapter also demonstrate that ICT gains by UK owned firms in KIS are not considerably different than non-US foreign firms in KIS sectors.

While the results find a robust correlation between ICT and productivity in addition to heterogeneity across a number of factors, additional analysis is needed in terms of whether a causal relationship exists between ICT and productivity. At the moment, few papers have been able to identify evidence of causality between ICT and TFP given the difficulty to control for endogeneity bias. Chapter two will attempt to contribute to this question by exploiting the rollout of the ADSL infrastructure in the UK as an instrument of ICT capital stock.

Chapter Two

The Impact of ICT on Firm Performance in the UK

Introduction

Researchers and policy makers have for many years grappled with the question of whether information communication technology (ICT) increases productivity. Up until the early 1990s empirical research found sparse evidence regarding a positive relationship between ICT and productivity (Thurow 1987; Kemerer and Sosa 1991; and Roach 1989). This phenomenon became known as the Solow Paradox. One of the main reasons as to why the effects of ICT were not captured in early growth accounting exercises was the fact that ICT represented only a small percentage of overall capital stock (Oliner and Sichel 1994).

By the mid-1990s however, empirical evidence began suggesting that ICT and productivity were positively correlated. In particular, the timing in the resurgence of the US economy following substantial investment in ICT provided suggestive evidence regarding a link between ICT and aggregate productivity growth. Empirical evidence regarding this relationship was eventually made by Jorgensen and Stiroh (2000) and further supported by Oliner and Sichel (2000). Much of the early gains from ICT at the sectoral level appeared to be concentrated within ICT producing sectors, raising questions as to whether growth was driven by the technologies themselves or due to the particular nature of the ICT producing industry (Gordon 2000). The use of more disaggregated data at the industry level found that the origin of growth not only came from ICT producing but also ICT intensive using sectors (Jorgenson 2001; Sichel and Oliner 2002).

In addition, a substantial number of papers find evidence of a positive relationship between ICT and productivity at the firm level (Brynjolfsson and Hitt 1995; Dewan and Min 1997; Black and Lynch 2001). The literature identifies channels through which ICT impacts aggregate growth and productivity. For example Hubbard (2003) finds ICT increases capacity utilization and efficiency while Bartel et al (2007) presents evidence that ICT increases product specialization and decreases production time. The literature also finds evidence suggesting important complements to ICT such as organizational structure, changes in employment practices, management, skills and so on (Black and Lynch 2004, Bresnahan et al 2002; Brynjolfsson et al 2002; Mairesse et al 2001 and Hempell 2005 Bloom et al 2012).

While substantial improvements have been achieved regarding our understanding of ICT and firm performance, there appears to be little evidence of a causal link between digital technology and TFP. The main hurdle facing empiricists is the likely presence of endogeneity bias. Firms do not haphazardly decide to adopt ICT, but make the decision to invest in the technology understanding the performance potential of the investment (Brynjolfsson and Hitt, 2003; Aral et al. 2006). For example, the management ability of a business appears to be important both in terms of implementing new ICT as well as obtaining greater effects from the technology. Bloom et al (2012) for example suggests that in the UK, more highly qualified managers have a greater likelihood to implement new technology. The use of superior management techniques and subsequent change of the organisational structure has been found to be an important channel to obtain productivity effects from ICT (Bresnahan et al 2002 Hubbard, 2003; Bartel et al., 2007; Brynjolfsson et al., 2008; Giacarno and Heaton, 2010; Giacarno, 2010; Bloom et al., 2012). As a result, the effects of ICT on productivity are likely to be influenced by an omitted variable such as the quality of management and organisational change within the firm.

In addition, the literature also implies that the short-run effects of ICT may be biased downwards in standard OLS estimation because of adjustment costs.[13] For example, previous work suggests that investment in ICT represents a small proportion of costs associated with adjustment to the investment including retraining workers, hiring consultants, additional management and so on (Draca et al 2006). Brynjolfsson et al (2002) suggest that $1 of investment in ICT is associated with $9 of total investment. The presence of such adjustment costs may somewhat conceal the effects of ICT in the short-run, an issue discussed by Brynjolfsson and Hitt (2003) and assessed by Stiroh (2002a), Wolff (2003), Basu et al. (2004) and Leung (2004).

Using the same firm level dataset from Bloom et al (2012) and employing an instrumental variable approach the main contribution from this chapter is to examine the extent to which ICT is causally related to firm productivity. The first instrument is firm access to the ADSL broadband infrastructure. The construction of our instruments exploits the rollout of the ADSL broadband around the beginning of the 20th century, which resulted in spatial and temporal variation in access to a superior form of internet technology. The delivery of ADSL exploits the Public Switched

[13] For additional information on adjustment costs see Draca et al. (2006).

Telephone Network. Access to the technology therefore required equipment upgrades to the telephone exchange box which firms were already connected to. As a result, supply-side constraints and the number of exchanges throughout the UK network meant that the rollout of ADSL occurred over a number of years, 1999 to 2007. Installation of ADSL provides firms connected to an activated exchange access to faster internet speeds than those that were connected to non-enabled exchanges. Other papers have used cross-time and spatial variation in broadband as instruments such as Abramovsky and Griffith (2006) and Akerman et al. (2015). Unlike this chapter which exploits firm level availability, previous studies rely on temporal changes in the proportion of households with broadband subscriptions as instruments in the UK and Norway, respectively.

In addition to enablement, the proximity of the firm to their telephone exchange box influences their connection speed since ADSL is a distance dependent technology (connection speeds begin to deteriorate rapidly around 2,000 meters). We therefore exploit this aspect of the technology and construct a second instrument, based on firm distance from the telephone exchange. While distance from the exchange also impacts the quality of a telephone call, connection deterioration occurs at greater distances than ADSL (for telephones around 16 kilometres) since loading coils can be used within the telephone infrastructure to boost line quality. However, loading coils are not compatible with ADSL. To our knowledge, this is the first time in the literature an empirical strategy exploits access to the broadband infrastructure and firm distance from the exchange as instrument variables for ICT. The effect of the instrument captures the local average treatment effect, where access to the broadband infrastructure impacts firm productivity by inducing ICT upgrading due to access to an improved external communication infrastructure.

From a technical perspective, ADSL availability as an instrument appears theoretically likely to fulfil the exclusion restriction assumption, that is to say broadband impacts the performance of the firm only through their ICT. This is because internet technology is not operable without at least a computer equipped with basic communication and operating system software. In addition, firms connected to an exchange that was upgraded from dial-up to ADSL gain access to a superior telecommunication technology and likely increase the rate of return on investment in ICT. The historical evidence suggests that the rollout of broadband from 1999 to 2002 was driven by supply side constraints given the number of exchanges across the UK

and the limited number of engineering technicians (BBC 1999a). Furthermore, since the locations of the boxes are determined by the pre-existing telephone infrastructure (in some cases since the 19th Century) firm distance to the exchange and hence their approximate broadband speed is plausibly exogenous to the performance of the firm.

The paper will continue as follows. Section 2 reviews the evolutionary progress of the literature on ICT and productivity. Section 3 briefly explains the data, evaluates the descriptive statistics and discusses the instruments. Section 4 presents the empirical strategy while section 5 discusses the results. Finally section 6 provides a summary along with some closing comments.

Literature Review

For decades, researchers have carried out substantial analysis regarding the economic implications of ICT. Much of our understanding on the effects of ICT and productivity as well as the historical path of the literature has been driven by data availability. Early studies tend to assess the economic contribution of ICT at the macro level using growth accounting techniques. The sectoral origin of the ICT contribution within the economy was later identified from more disaggregated industry level data. A large body of work at the micro level also identifies complementarities to ICT, channels through which the technology influences aggregate productivity, as well as the effects of specific types of ICT such as broadband. While our understanding of ICT continues to improve, endogeneity remains an issue given the difficulty in finding an appropriate natural experiment. Therefore evidence regarding causal links between digital technology and efficiency remain mute (Draca et al 2006; Kretschmer 2012; and Cardona et al 2013)

Growth Accounting and Aggregate Studies

Initially, empirical research found sparse evidence for a positive correlation between ICT and productivity (Thurow 1987; Kemerer and Sosa 1990; and Roach 1989), despite the fact that firms were increasing investment in hardware and computing equipment. In the US for example, from 1960 to 1990 real purchasing of computers rose by more than 200%, yet the gains from these investments were not clear. Robert Solow famously stated in 1987 that “you can see the computer age

everywhere except in the productivity statistics."[14] This phenomenon became known as the "computer paradox" which was the inability to detect the contribution of ICT to productivity growth.[15] It was later pointed out that the inability to detect productivity effects of ICT was due to the fact that the amount of ICT stock at the time was too modest for identification in earlier studies (Schreyer 2001).

However, the resurgence of the US economy coinciding with high rates of investment in ICT provided some indication regarding a positive contribution from ICT to aggregate productivity (Draca et al 2006). When comparing output growth between 1974-90 and 1995-1999, Jorgenson and Stiroh (2000) found that in the earlier period, annual growth was roughly 3.13% of which the contribution from ICT was roughly 10%. From 1995-99 however, output growth rose to around 4.76%, 20% of which was the result of ICT contribution. In addition, during these two sample periods a rise occurred in TFP growth from around 0.3% to close to 1%, where much of the rise in TFP occurred in the ICT producing sectors.

As well as accounting for a significant part of the growth in TFP, efficiency gains obtained in the ICT producing sector (in particular the production of semi-conductors) led to a considerable decline in the price of hardware and ICT technology inputs (Jorgenson and Stiroh 2000). Consequently, investment in IT assets increased dramatically resulting in capital deepening within sectors which used ICT intensively. This was confirmed by Stiroh (2002) who found that ICT contribution to growth came not just from the ICT producing sector but also the ICT using sector. In addition, Oliner and Sichel (2002) found that deepening in ICT capital represents around three-fifths of the growth in labour productivity and also found that reductions in the price of semiconductors contributed to the growth in multifactor productivity, providing further evidence of possible performance effects from digital technology.

Correspondingly, work by Jorgensen, Ho and Stiroh (2008) suggests that the engines of productivity growth changed twice after 1995. From 1995 until 2000, productivity growth was mostly facilitated by the ICT producing sectors in addition to investments made by the ICT intensive using industries. After 2000 however, much of the growth originated from the ICT using sector, enhanced competition, cyclical factors and productivity growth from other sectors.

[14] Solow, R. (1987). *New York Times Book Review*, July 12, p. 36

[15] For recent reviews of the literature on ICT and productivity see Draca et al (2006); Syverson (2011) Kretschmer (2012) and Cardona et al (2013)

Gordon (2003) however was somewhat sceptical of the idea that ICT substantially contributed to the growth of the US economy. Aside from growth obtained in the ICT producing sectors, Gordon (2000) suggests that the rise in productivity in other areas of the economy was cyclical. While this argument, may have been valid in the 1995-2000 period, it seems somewhat unlikely post 2005, given the continued productivity growth after the dot com bubble, 9/11 the Iraq and Afghanistan wars and so on (Draca et al 2006).

While ICT stock appeared to provide considerable contribution to the US economy, its effects were less pronounced in the European Union. The EU for example experienced slower productivity growth coincided by less investment in digital technologies. Colecchia and Schreyer (2002) suggest that the EU did not witness the same resurgence of growth because of lower investment rates in ICT. Viyselaur and Albers (2004) on the other hand, find evidence of output growth for the ICT production sector however given the small size of this sector its impact on aggregate growth is quite limited. In later years, from 2000 to 2005, the contribution of ICT was similar in magnitude between the US and EU, yet the EU obtained much lower productivity growth (Timmer et al 2003).

Van Ark and Inklaar (2005) suggest that the increased divergence between US and EU productivity growth provides some notion that ICT is a General Purpose Technology (GPT).[16] Their work highlights a "U-shaped pattern" for ICT productivity gains for France, Germany, the Netherlands and some evidence in the U.S. and UK. This pattern is consistent with the literature on GPTs where early returns from ICT investment result in normal returns in IT producing and using sectors. This period is then followed by negative productivity growth as firms invest in complementary inputs such as human capital, organizational structure and various tangible and intangible assets. This requires time for trial and error and then productivity growth increases later. The authors therefore imply that during this period, Europe was in the complementary investment and learning stage. Moreover, the authors suggest that European labour and product market regulations may be impeding the transition of complementary investment and experimentation.

[16] GPTs are technologies used for production or invention which have far reaching influences throughout much of the economy and society (Javanovic and Rousseau 2005).

Similarly, Van Ark et al (2008) find that the divergence in productivity growth between Europe and the US is somewhat attributed to fewer ICT producing industries. Moreover, in terms of the ICT using sectors, not only did the US invest in more ICT but their firms were able to achieve greater productivity growth, potentially due to complementary organizational change. These results further suggest the potential beneficial effects from ICT, particularly when they are complemented with intangible inputs.

Micro analysis

In addition to the evidence found at the aggregate level, a number of micro studies during the same period also find evidence of positive effects from ICT (Lichtenberg 1995; Brynjolfsonn and Hitt 1994 Greenan and Mairesse 2000; Dewan and Min 1997). Furthermore, the use of micro data is beneficial when assessing the effects of ICT on productivity as it allows the researcher to identify potential heterogeneity in the investment of ICT and productivity. In addition, it enables the econometrician to potentially control for endogeneity bias such as issues with omitted variables through the use of firm level controls and firm level fixed effects.

One of the more robust early assessments of ICT and productivity was carried out by Brynjolfsonn and Hitt (1995). Employing firm fixed effects, the authors find that roughly half of the productivity benefits from ICT come from time invariant unobservable firm characterises. Moreover, the authors assess the robustness of the Cobb-Douglas TFP estimates by also using a translog production function to find similar sizes in the ICT coefficients. In terms of heterogeneity across sectors Brynjolfsonn and Hitt (1995) find little variation in ICT elasticities among manufacturing and services firms. Moreover, they discover that firms with no growing revenue compared to firms with growing revenue demonstrated similar ICT coefficient elasticities, suggesting that simultaneity between revenue growth and investment in IT does not appear to be driving the size and significance of the IT coefficients.[17]

A number of studies also provide empirical evidence regarding the importance of organizational complements for ICT on productivity. Bresnahan et al (2002) find

[17] On top of the growing literature on ICT and productivity in the private sector, evidence is also found in the public sector (Lehr and Lichtenberg 1999).

evidence of complementarities between ICT, firm reorganization, product and service innovations and productivity. In addition, firms implementing these three innovations usually employ more skilled employees. Bloom et al (2005) find some support for the importance of complementarities between ICT and organizational change, implying the reason American businesses utilize ICT more effectively both at home and abroad is because they are better managed and more decentralized. On the other hand, Caroli and Van Reenen (2001) do not find support for complementarity between ICT and organizational change while Black and Lynch (2004) find little evidence regarding complementarities between IT and organization restructuring.

Given the accumulating evidence regarding the effects of ICT and productivity across a number of aggregate and micro level studies, a number of papers began assessing the channels through which ICT enabled greater productivity growth. For example, Hubbard (2003) examines the impact of on-board computers for the trucking industry. The results indicate that on-board computer use increases capacity utilization where trucks with electronic vehicle management systems experienced an increase in their capacity utilization by 13%. Hubbard (2003) suggests that these achievements were most likely accomplished due to increased efficiency in logistical coordination. Overall, the use of on-board computers is believed to have increased overall industrial capacity utilization by 3% thereby saving the sector billions of dollars yearly.

Similarly, Bartel et al (2007) investigate the link between a specific ICT technology and productivity in valve manufacturing. In particular, the study examines the effects of computer numerical control machining centres (CNCMs) and automated devices on valve production and identifies three central channels through which these ICTs relate to productivity. One, plants which implemented the technology adjusted their corporate strategy and increased product specialization. Two, the CNCMs positively impacts valve production by decreasing the time needed for production preparation, manufacturing and product quality and process checks. Three, the technology raises the demand for skilled workers, in particular equipment operators, and employees with critical thinking and technical skills.

Brynjolfsson et al (2008) on the other hand investigate the relationship between the expansion of ICT and firm level adjustments. The results of which suggest that increased usage of ICT increases both turbulence and concentration for businesses. By analysing a number of case studies, the authors find three significant strands of evidence relating to ICT and firm performance: first, ICT allows firms to adopt enhanced business processes from other firms both faster and easier; second, the boundary of firms remains important, therefore businesses cannot replicate internal processes used in other branches of the firm or from different establishments instantaneously; third, businesses need to continue to innovate in order to compete with new firms and existing competitors in the market. Using industry level data, their empirical analysis also finds that ICT intensive industries have undergone greater turbulence and concentration than non-IT intensive industries, thereby influencing competition consistent with Schumpeterian theories on resource allocation and creative destruction.

Broadband and productivity

A branch of the ICT literature also provides some evidence regarding the effects of broadband internet on productivity.[18] Similar to the literature on ICT, the historical empirical path begins with more aggregate data assessing basic correlations to firm level data identifying mechanisms and attempting to understand potential causal links. Czernich et al. (2011) for example, finds a positive relationship between broadband internet penetration and economic growth rates for a number of OECD countries. Kolko (2012) also finds a positive and significant relationship between broadband and local economic growth in the US, where the greatest effects are found for industries who use ICT the most and in locations with lower population density.

Recently a number of studies assess the effects of broadband at the firm level. In Ireland, Haller and Lyons (2012) find that firms with higher productivity are more likely to use broadband however there appears to be no evidence that broadband adoption impacts firm productivity. Bertschek, Cerquera and Klein (2011) find no evidence for the effects of broadband on labour productivity in Germany but find

[18] A recent review on the economic effects of broadband was carried out by What Works Centre for Local Economic Growth (2015).

that firms with access to broadband appear to carry out more innovation. A recent paper by De Stefano Kneller and Timmis (2014) exploits a five year geographical discontinuity in the availability of ADSL broadband to study the causal effect of broadband on the performance of firms located outside of major urban localities. The results find that broadband has no statistically significant effect on the performance of firms, including labour productivity.

The main hurdle in assessing the extent to which a causal link exists between ICT and productivity is the presence of endogeneity bias. This chapter attempts to control for this bias by exploiting a brief period during the delivery of a new internet technology in the UK which led to regional and temporal variation in access to the ADSL infrastructure.

Data

Similar to chapter one, the main dataset used here is the ARD, the Capital Stock Dataset and the ICT Capital Stock Database to obtain the key firm level variables for the analysis.[19]

An additional data source used is the ADSL Broadband Database which outlines the geographic rollout of ADSL broadband across the UK. The ADSL dataset is quite rich in that it provides detailed time (by day) and geographic (by postcode) information regarding broadband activation. Given that the ARD provides firm location by postcodes, firms are matched by their postcode to the postcode of the nearest exchange box, using the eastings and northings. This allows us to identify when broadband became available to a specific firm and to estimate firm distance from the exchange, as the crow flies.

Descriptive Statistics

The firm-level datasets used in this chapter are the same as in chapter one, however the sample used here is different. Therefore, for completeness summary statistics are provided below. The unbalanced panel used in this chapter consists of 12,100

[19] The Business Structure Database and the National Statistics Postcode Directory datasets will be merged into the panel to provide additional control variables; firm age and urban/rural dummies respectively.

observations with a total of 7,426 single plant firms across all sectors (asides for finance industry) and for the years 2000 to 2003. All multi-plant firms are excluded from the sample on the assumption that ADSL enablement and firm distance from the exchange are most appropriate for single site entities. In addition, the selection of the sample period (differing from chapter one) is determined by a brief period of the ADSL rollout program (1999 and 2002) which enablement appears reasonable exogenous. In order to allow for the time needed for premise installation and for firms to adjust to the technology, we take the lagged form of the instruments, therefore the time period used in this chapter is actually 2000 to 2003.

Firms are medium size where the median business employs 127 workers while the mean business uses 234 labourers. Median gross output is £9.3 million and the mean gross output is £34.9 million. The average firm has £204,000 of ICT capital stock with the median firm employing £28,000 of ICT stock. In addition, during this period firms on average had accumulated more hardware than software stock with means; £184,000 and £112,000 respectively. Moreover, the average firm is roughly 1,370 meters as the crow flies from their exchange box.

Table 20

Summary Statistics of Single Plant Firms, 2000 to 2003

Variables	Mean	Median	Standard Deviation	Frequency
Gross Output	34,901	9,208	177,846	12,100
Gross Value Added	10,251	3,618	35,648	12,100
Labour	234	127	399	12,100
Capital Stock	37,906	5,735	326,247	12,100
Materials	7,759	1,254	46,918	12,100
Hardware Stock	184	24	1,588	6,427
Software Stock	112	16	565	11,494
ICT Capital Stock	204	28	1,516	12,100
Distance	1,370	1,200	1,149	12,100

Note: Note: All variables aside from Labour and Distance are in thousands represented in pound sterling (base year 2000). Labour represents employee headcount whereas distance is meters.

The majority of the observations are located in Greater London and the South East accounting for 27% of the sample. Wales makes up 15% whereas the West Midlands, Scotland and the North West each account for 9% of the sample. Next, York and Humberside have 8% of the observations and the South West and East Midlands each account for 7%. The North and East Anglia represent the smallest share of the sample

with 4% each. The regional variation of firm observations closely represents the population of the UK. For example, 27.5% of Great Britain's population resides in London and the South East whereas East Midlands and York and Humberside account for 7.4% and 8.6%; respectively. Similar to chapter one, the sample in this chapter appears to accurately represent the UK population (ONS 2012).

Table 21

Regional Dispersion of Observations from 2000 to 2003

Region	2000	2001	2002	2003	Total
Greater London & SE	28%	27%	27%	25%	27%
Wales	8%	15%	18%	18%	15%
West Midlands	11%	9%	9%	9%	9%
Scotland	10%	9%	9%	9%	9%
North West	10%	9%	9%	10%	9%
York & Humberside	9%	8%	7%	8%	8%
South West	8%	8%	6%	7%	7%
East Midlands	7%	7%	7%	7%	7%
North	4%	4%	4%	4%	4%
East Anglia	4%	4%	4%	3%	4%
Total	2,150	3,201	3,374	3,375	12,100

Table 22 demonstrates that a majority of the firms in the sample are located in urban settings, roughly 78%. An urban location is defined as a region with a population greater than 10,000 residents classified by National Statistics Postcode Directory (2013). The remaining firms, (22%) reside in more rural settings. Over the sample period, the distribution of firms across urban and rural settings has stayed relatively consistent.

Table 22

Proportion of Firms Residing in Urban and Rural Settings from 2000 to 2003

Firm Location	2000	2001	2002	2003	Total
Rural	19%	21%	23%	23%	22%
Urban	81%	79%	77%	77%	78%
Total	2,150	3,201	3,374	3,375	12,100

The sample contains close to the same proportion of service and manufacturing firms. Here service firms relate to businesses in the following industries; Catering, Motor Trade, Property, Retail, Wholesale, Construction and Other Services. Manufacturing firms on the other hand signify businesses which engage in the production. Out of 12,100 observations, on average 47% of are from service firms while 53% are

manufacturers. The proportion of service firms during this period has grown from representing 40% of the sample in 2000 to around 50% in 2003.

Table 23

Service and Manufacturing Observations from 2000 to 2003

Sector	2000	2001	2002	2003	Total
Services	41%	46%	49%	50%	47%
Manufacturing	59%	54%	51%	50%	53%
Total	2,150	3,201	3,374	3,375	12,100

The majority of firms in our sample are owned by a domestic proprietor. 82% are run by domestic holders whereas roughly 11% and 6% are controlled by non-US multinationals and US multinational firms, respectively. The proportion of non-US foreign and US owned firms are quite consistent over the sample period altering no more than a few percentage points each year in comparison to the total time period.

Table 24

Domestic, non-US foreign and US owned from 2000 to 2003

Year	2000	2001	2002	2003	Total
Domestic	84%	81%	82%	82%	82%
Non-US Foreign	10%	12%	11%	12%	11%
US	5%	7%	7%	6%	6%
Total	2,150	3,201	3,374	3,375	12,100

Firm age varies from 0 to 32 years old. 17% of businesses are 5 years old or less, with 19% being between the ages of 6 to 10. Firms aged from 16 to 20 and 21 to 25 years old make up the smallest portion of the sample at 11% and 8%; respectively. In addition, the age group which makes up the largest percentage of the sample is 23 to 32 years old.

Table 25

Firm Age Distribution, 2000 to 2003

Age	Frequency	Percentage	Accumulation
0 to 5 years old	1,904	17%	17%
6 to 10 years old	2,694	19%	38%
11 to 15 years old	2,147	19%	56%
16 to 20 years old	1,306	11%	67%
21 to 25 years old	902	8%	74%
26 +	3,147	26%	100%
Total	12,100	100%	

Table 26 assesses the presence of firms residing either in knowledge intensive or low-knowledge intensive sectors. For a discussion on how firms are allocated into high and low knowledge intensive sectors, please refer to the data section in chapter one. Roughly 19% of the sample consists of firms in a knowledge intensive sector representing 2,262 observations. The remaining firms around 81% reside in low-knowledge intensive sectors, 9,838 observations. The proportion of knowledge intensive firms rose only slightly from 17% to 19% from 2000 to 2003.[20]

Table 26

Firms in Knowledge Intensity Industries from 2000 to 2003

Knowledge Intensive Sector	2000	2001	2002	2003	Total
low-KIS	83%	81%	81%	81%	81%
KIS	17%	19%	19%	19%	19%
Total	2,150	3,201	3,374	3,375	12,100

Empirical Strategy

Equation 1 illustrates the assumed relationship between ICT capital stock and productivity. tfp_{it} signifies the productivity of firm i at time t. The TFP measure used in this chapter is estimated in the same manner as chapter one.[21] ict_{it} refers to the ICT capital stock, X_{it}represents a vector of control variables also believed to be correlated with productivity such as firm age and ownership as well as controlling for year, sector and regional variation. Distance to the telephone exchange is also added in case it has any relationship with TFP outside of enabled exchanges. Finally, μ_{it} represents the error term.

$$tfp_{it} = \beta_0 + \beta_1 ict_{it} + \beta_2 X_{it} + \mu_{it} \quad (1)$$

As a robustness test we also use the Levinsohn-Petrin (2003) (Lev Pet) estimate of TFP which attempts to overcome endogeneity biases from input decisions by proxing

[20] Although differences exist in the percentage of firms in knowledge intensive sectors between chapter one and chapter two, it is important to note that chapter two examines single plant firms, while chapter one assess both single and multi-plant firms.

[21] Additional estimates of TFP are also used in order to assess the robustness in the effects of ICT. These include TFP estimations including 3-digit sector intermediate input interactions terms as well as a semi-parametric estimation.

unobserved productivity shocks with intermediate inputs. By relying on intermediate inputs rather than investment as in Olley Pakes (1996), more observations can be retained since most firms' are more likely to list positive use of intermediates for each year allowing the monotonicity condition to hold. This chapter therefore decides to use Lev Pet TFP estimate since it retains observations with zero investment values and since the TFP estimates between these two measures are found to be similar in Van Beveren (2012).

Instrumental Variable Approach

The literature suggests that ICT technology impacts productivity by allowing firms to communicate more effectively, restructure their organization more appropriately, improve scheduling of purchasing and sales and so on. However one of the difficulties in estimating the effects of ICT on performance in an OLS framework, illustrated in Equation 1 is that it is likely to be bias by the correlation between ICT use and productivity. For example, while ICT may lead to great efficiency it may also be that only productive firms can afford emerging technology such as IT and therefore the model contains simultaneity bias. In addition, the literature has long suggested that management (Bartel et al., 2007; Brynjolfsson et al., 2008; Giacarno and Heaton, 2010; Giacarno, 2010; Bloom et al., 2012) may be an important factor enabling greater gains from investment in IT and thus the model suffers from omitted variable bias. The chapter therefore also uses an instrumental variable approach in order to control for potential endogeneity bias and provide insights into potential causal links between ICT and TFP.

The estimation procedure used is a *Two Stage Least Squares* framework as illustrated in Equations 2 and 3, where the parameter of interest is β_1 which captures the estimated impact of ICT capital stock on TFP signified by tfp_{it}. The instruments ADSL availability and the ADSL distance interaction term are reflected by $adsl$ and $adsl * distance$ and a vector of control variables consistent with Equation 1 is signified by X_{it} .

$$tfp_{it} = \beta_0 + \beta_1 ict_{it} + \beta_2 X_{it} + \mu_{it} \quad (2)$$

$$ict_{it} = \alpha_0 + \alpha_1 adsl_{it-1} + \alpha_2 adsl_{it-1} * distance + \alpha_3 X_{it} + \mu_{it} \quad (3)$$

The construction of the instruments is the following: $adsl_{i,t-1}$ takes the value of 1, when a plant connected to a telephone exchange becomes enabled during wave one of the BT ADSL rollout and 0 for the years prior to enablement for these exchanges enabled from 1999 to 2002. Given that we are taking the lagged form of the instruments this means that $adsl = 1$ in time $t-1$. The reason for lagging the instruments is due to the time needed for installation as well as the time taken by firms to invest in additional ICT, after gaining access to ADSL broadband. $adsl_{it-1} * distance$ is the interaction between the $adsl_{it-1}$ dummy and the distance between the premise and the telephone exchange. Mentioned earlier, distance is estimated as the crow flies, using the easting and northings of both the firm and telephone exchange postcodes. The instrumental variable analysis relies for the most part on stage one of the rollout (asides for some robustness checks) and therefore the time period for most of the analysis is 2000 to 2003.

Although broadband has been shown to be an important source of internet technology for many firms, it is not likely to be relied upon by all firms. Large multi-plant firms with many users, various sites and greater bandwidth requirements would more likely rely on a leased line internet for their communication needs (Mitchell 2014). As a result, the specified instruments above are likely to be less relevant for multi-plant firms.[22] Small firms however are more likely to depend on ADSL and less likely to use leased-line broadband given the substantial cost of the service; the monthly cost during this period was around $1,000 to $1,500 per month (Howstuffworks, 2000). Multi-plant firms are therefore excluded from the analysis, aside for an instrument validity test later on in the study.

What is ADSL

Until recently, the two main options for internet connection was either dial-up or Asymmetric Digital Subscriber Line (ADSL) broadband. Unlike dial-up which offered

[22] From the data location information is at the plant level whereas ICT and TFP are at the firm level.

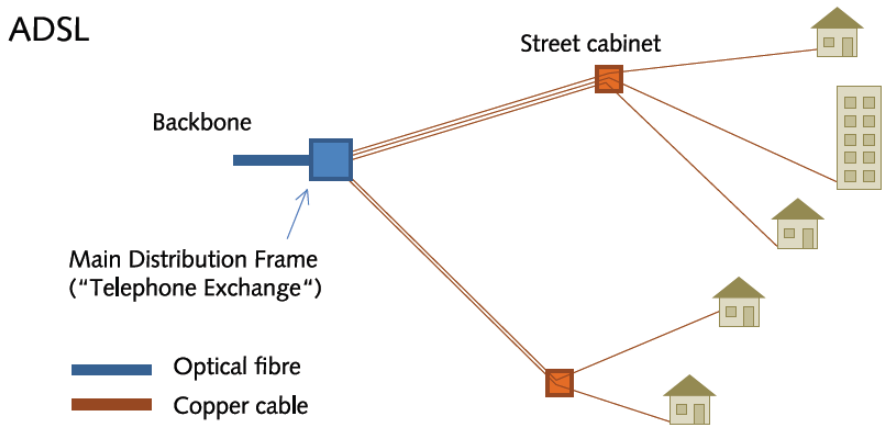
connection speeds of roughly 64 kbps (Bit Tech 2013), ADSL broadband offered speeds as high as 8000 kbps (Ofcom 2015). Since the delivery of ADSL utilizes the Public Switched Telephone Network (PSTN) relatively minimal infrastructure adjustments are required by the telecommunications providers. As a result, this form of broadband has been the internet technology of choice for many countries around the world. For example, the ONS (2013) finds that in 2012, ADSL was the most used form of broadband where 55% of homes and 85% of businesses in the UK had an ADSL connection.

Illustrated in Figure 1, the delivery of ADSL broadband is through the pre-existing telephone infrastructure, the same network used for the delivery of dial-up internet. Every firm or household in the UK is connected to a pre-determined telephone exchange by a cooper cable which runs between the premise and the local street cabinet. Each cabinet is then connected to a main distribution frame which in turn makes up key hubs within the fibre optic backbone of the UK telecomm infrastructure. On average, a UK telephone exchange services around 250 firms and 4,700 households.

The installation of these exchanges originates from the establishment of the telegraph network back in the 19th century in addition to network upgrades and expansion post World War II. In total, the UK telephone network is made up of close to 5,630 exchange boxes, most of which are operated by British Telecom aside for 37 exchanges in and around Hull which are serviced by Kingston Communications.[23] Unlike many European countries, the UK had a monopoly provider of ADSL broadband services, British Telecom. Other telecom companies in the UK were not able to install their own ADSL infrastructure (called local loop unbundling) until 2005, where in this year less than 2% of exchanges had been unbundled (Cadman 2005).

[23] Firms connected to these 37 exchanges are dropped from the analysis.

Figure 1 Telephone Infrastructure in UK



Broadband as an instrument for ICT

Broadband appears to be an appropriate instrument for ICT for several reasons. From a technical perspective, broadband itself is inoperable without at least a computer and a combination of operating and communicating software (Ofcom 2015). Therefore, broadband availability alone does not affect the productivity of a firm directly, only through the employment of both hardware and software of the establishment. One way in which broadband may result in greater use of ICT is by increasing the rate of return of investment in digital technology. For example, a business connected to a street cabinet which changes from delivering narrow broadband (dial-up) to ADSL broadband, experiences a substantial increase in the amount of data that can be uploaded and downloaded. This may induce firms to invest in new ICT, since having access to a superior form of telecommunication, enables them to obtain higher performance out of their investment than previously possible with dial-up internet. Moreover, switching from dial-up to ADSL broadband may lead to increased usage of ICT due to hardware and software requirement as a result of greater bandwidth and information flow (BT 2015).

Within the literature, there is some evidence regarding the effects of broadband on ICT usage. Varian et al (2002) for example find that firms in the US, Germany and the UK employing the internet tend to also use hardware and software more intensively. In addition, results from Forman (2005) and Forman et al (2005) also find a positive correlation between internet usage and the amount of hardware and software within

establishments. More recently the OECD (2016) finds evidence of a positive relationship between broadband penetration and ICT use. This indicates that firms in regions with greater proportions of broadband users invested in more ICT.

The Rollout of ADSL

The rollout of ADSL broadband occurred between November 1999 and September 2007. The way in which broadband was enabled across the UK suggests that initial timing of enablement was difficult for firms and consumers to anticipate. For example, BT began testing ADSL as early as 1994, but due to various technical and regulatory issues the enablement was continuously delayed for 5 years (BBC 1999b). The rollout eventually commenced in July 1999 however as of February 1999, BT still had not informed the public of any plans for broadband service (BBC 1999a). Even when it was announced that a region was to be enabled, it was not clear when consumers could start accessing services, since BT insisted on using its own engineers for line modification and equipment installation (BBC 1999a).

Upgrading an exchange to provide ADSL broadband required some technical investment such as air conditioning units, continuous electricity, and connection to the backbone. Moreover, initially each household or firm also required the installation of broadband splitters and modems (Guardian 2002). As a result, even after the rollout commenced, both the technical requirements at each exchange and premise and a limited supply of BT engineers, resulted in temporal and regional variation in access to ADSL technology persistent during the enablement period.

Ideally one would like to exploit variations in broadband availability throughout the entire rollout period, however given the context of BTs rollout strategies, this chapter only uses the initial period of the enablement, 1999-2002. Figure 2 illustrates the rollout of the ADSL infrastructure which occurred from November 1999 to September 2007. The figure also illustrates three breaks in the enablement program, the first of which was in the middle of 2002 and the second in 2005. During this chapter we will refer to these three phases of the rollout as, wave one (occurring between 1999-2002), wave two (2003-2005) and wave three (2006-2007). The first break, announced in November 2001 occurred as a consequence of the poor take-up of

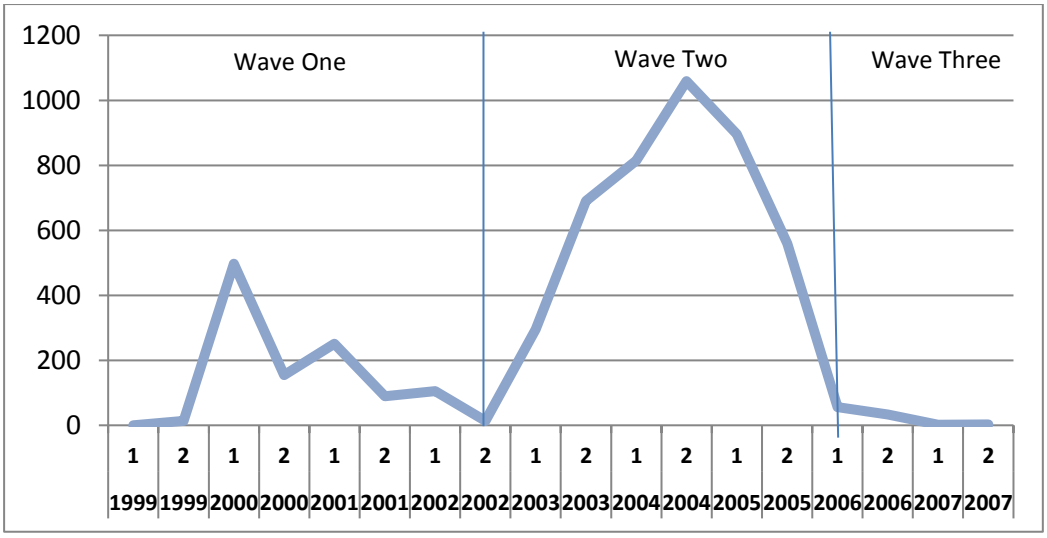
broadband internet by households.[24] The first break of the rollout was not planned by BT and thus unlikely that firms and households anticipated this.

The second stage of the rollout resumed in July 2003 where BTs plan of enablement was based on consumer demand, a procedure known as the pre-registration scheme (Department for Business Innovation and Skills 2004). For an exchange to receive authorization for enablement, consumers had to first confirm their willingness to purchase the service by subscribing on BT's website (Ofcom, 2002). In order for installation to take place, the number of potential subscribers would need to reach a particular threshold. [25] Once, the threshold was met and confirmed, the rollout began (broadband4wroxton, 2002). During the third stage (2006-2007), BT shifted rollout procedures to one of universal enablement, with the objective of providing ADSL access to 99.6% of households. Therefore during wave three many exchanges enabled were in rural and remote locations.

Since the enablement procedure in stage two was based on consumer demand, (including demand from firms) the use of ADSL availability as an instrument after wave one may not be appropriate since installation is not likely to be exogenous and is therefore excluded from the analysis.[26] Even though firms tend to make up just a small part of those connected to an exchange, regions experiencing a positive economic shock may be more likely to purchase technology and experience higher productivity, generating a positive correlation between enablement and firm productivity. Also, since firms enabled in stage three are mostly located in more remote locations wave three is also excluded.

[24] Less than expected up take was likely due to the high subscription costs, wholesale prices were £40-£150 per month.
[25] The subscription threshold was determined by the cost of upgrading a particular exchange box.
[26] Stage two is however used later on in the thesis as a robustness test.

Figure 2 Exchanges Enabled per Half Year



Throughout wave one, exchange enablement increased from 0% to 20.34%. Enablement began slowly with only 14 exchange boxes in 1999, accounting for only 0.25% of the total exchange boxes. An additional 651 boxes were enabled in 2000 followed by 340 more in 2001. In 2002, the number of enabled exchanged increased by an additional 119 boxes. Wave two commenced in 2003 and finished in 2005. 2003 saw roughly a nine fold increase of enablement with 985 additional exchanged. The years 2004 and 2005 experienced the greatest number of exchanges enabled with 1,873 and 1,451 boxes activated, respectively. The remaining 94 boxes were enabled by 2007 at which point roughly all exchange boxes in Great Britain were ADSL activated.

Table 27:

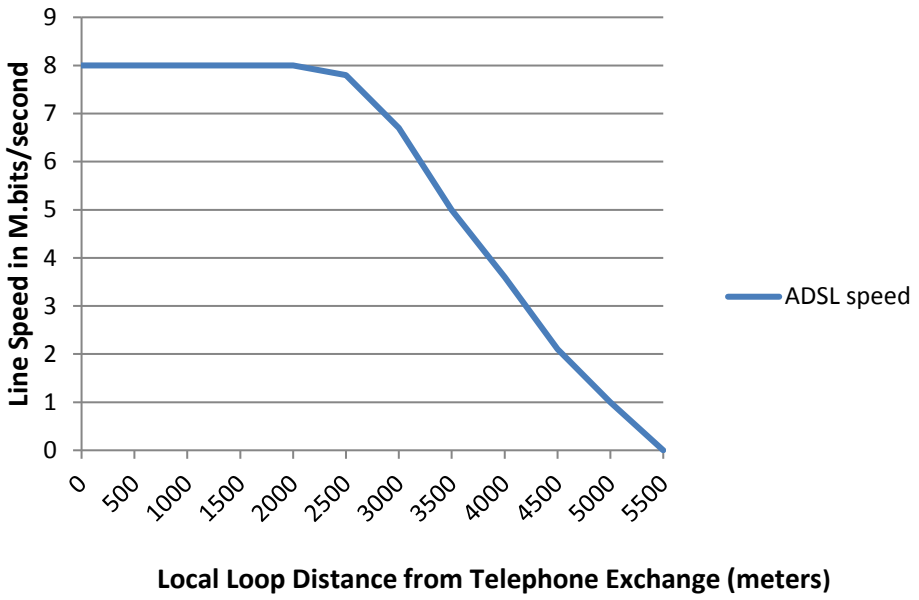
Exchange Enablement by Year from 1999-2007

Year	Number of Exchanges	Percentage	Accumulation
1999	14	0.3	0.3
2000	651	11.8	12.0
2001	340	6.2	18.2
2002	119	2.2	20.3
2003	985	17.8	38.2
2004	1,873	33.9	72.1
2005	1,451	26.3	98.3
2006	89	1.6	99.9
2007	5	0.1	100.0
Total	5,527	100.0	

The table excludes 37 Kingston communication exchanges enabled between 1999 and 2000. Northern Ireland exchanges are also excluded due to data issues between the ARD and the broadband dataset. Another 9 exchanges are excluded due to incomplete activation dates

As highlighted briefly above, the technical limitations of ADSL technology can also be further exploited as an instrument for ICT. ADSL broadband is a distance dependent technology, therefore the farther one is away from an exchange box the slower internet speeds become (BT, 2009). Figure 3, below illustrates how internet speed deteriorates the greater the distance between the telephone exchange and the premise. Engineering tests show that from 2,000 meters away, connection speed decreases quite rapidly. Firms more than 4,000 meters from the exchange could expect speeds half that of the maximum 8 megabits per second. In practice, firm distance from the exchange is not a precise threshold for speed deterioration. Other relevant factors include the width of the cable, the quality of the copper used in the cable and so on. Firms for example connected by an older and/or thinner cable laid in less optimal terrain with different wear and tear may experience speed deterioration at shorter distances than say longer thicker cable in optimal environments of relatively new condition (confirmed by David Cleevely and David Clarkson).

Figure 3: Distance and ADSL Speed Deterioration



(Heath 2012)

Firm distance from the exchange box is likely to be exogenous to firm performance and also a potential determinant of ICT use. As mentioned earlier, the location of the telephone exchanges was based on the pre-existing telephone infrastructure dating back in some cases as far as the 19th century. The main purpose of the telecomm

network was originally to enable the population to use a telephone. Importantly, through the use of load coils the technology allows phone calls to maintain acceptable quality at distances anywhere between 5 kilometres to as far as 16 kilometres (Macassey 1985). Load coils however are not compatible with ADSL. Distance from the exchange was therefore less of an issue for the previous technology than for ADSL. Firms born before the development of ADSL would not have chosen an optimal location to the exchange based on a technology that had yet to be invented. Cost restrictions and technical aspects prevented BT from digging up parts of the network to move existing cooper cables and exchanges closer to certain premises. Moreover, limited inter-connections of the fibre backbone prevented consumers from switching to a different telephone exchange.

Table 28 highlights the distribution of firm distance from their exchange. For the sample, we find that more than 75% of the firms are within the 2,000 meter of their telephone exchange box. 25% of the firms in our sample are 665 meters or less away from the exchange. Less than 25% of the firms however are more than 2,000 meters away from their exchanges. Given that distance is measured as the crow flies, they are likely to underestimate the distance of the local loop cable running between the premise and the exchange box, since cables do not always travel in a straight line.

Table 28

Firm Distance from Exchange	
Frequency	**Meters**
1%	76
5%	234
10%	362
25%	665
50%	1,198
75%	1,888
90%	2,531
95%	2,921
99%	3,985

Alternative Broadband Options

Cable broadband and for larger firms leased-line connections were the main alternatives to ADSL. Cable broadband relies on the cable infrastructure initially

rolled out to deliver cable television, which occurred in the UK in the early 1990s with some additional enlargement ending in 1998. After this time, the localities in which cable was available did not change (Oftel 2001). Leased line operates differ from ADSL in that it uses an independent fibre-optic cable between the establishment and the local exchange. ADSL on the other hand utilizes the pre-existing telephone copper wiring used previously for the telephone connecting the premises to the exchange. Given the cost of installing and connecting a fibre cable, leased line broadband tends to be used more by the largest firms. Leased line technology has existed since the 1990s and therefore was not introduced at the same time that ADSL was implemented (Oftel 2001).

Empirical Results

The first step in the empirical analysis is to examine whether ICT capital stock and TFP are positively related. A standard OLS technique is employed regressing ICT capital stock on our TFP estimate. Various control variables thought to influence TFP are included. These include 2 digit sector dummies to control for variation across sectors (Stiroh 2002a), year dummies are added to adjust for economy wide shocks and regional dummies are added to control for the variation across geographic locations. As documented in the literature, foreign owned firms, in particular those owned by US firms tend to be more productive and invest much heavier in IT than domestic firms (Bloom et al 2012). As a result foreign and US owned dummies are also included to control for the difference in productivity. Finally, firm age is included due to empirical evidence suggesting differences in performance across younger and old firms (Jensen et al 2001; Huergo and Jaumandreu 2004).

OLS Baseline Results:

From Table 29 we find that a positive relationship exists between ICT capital stock and TFP. The results are relatively stable across models with coefficients ranging from 0.098 to 0.081, all of which are statistically significant at the 1% level of significance. This suggests that a 10% increase in ICT capital stock relates to a 9.8% to 8.1% increase in TFP. The size of the ICT coefficients are a bit larger than the average coefficient found in the literature at roughly 0.06 (Kretschmer 2012). Moreover the coefficient size is larger than what is found in the first chapter however this may be

driven by the sample restriction to single plant firms used in this chapter. Firms owned by a foreign proprietor, including those owned by US proprietors exhibit higher TFP than domestic firms. In addition, the age of the firm appears to be negatively correlated with productivity.

Table 29

OLS Estimation: IT Effects on TFP, 2000 to 2003

Dependent Variable: TFP	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
ICT	0.099***	0.099***	0.091***	0.087***	0.090***	0.090***	0.084***	0.082***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Distance		-0.008	-0.011*	-0.013**	-0.012**	-0.012**	-0.009	-0.023***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	0.00
Foreign			0.344***	0.373***	0.374***	0.373***	0.378***	0.200***
			(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
USA				0.327***	0.332***	0.330***	0.339***	0.216***
				(0.03)	(0.03)	(0.03)	(0.03)	(0.02)
Age					-0.052***	-0.053***	-0.050***	-0.093***
					(0.01)	(0.01)	(0.01)	(0.01)
Additional Controls								
Year						✓	✓	✓
Region							✓	✓
2-digit Sector								✓
Adjusted R^2	0.0590	0.0590	0.0820	0.0830	0.0850	0.0850	0.0930	0.4940
Observations	12,100	12,100	12,100	12,100	12,038	12,038	12,038	12,038

Note: Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

Instrument Relevance:

The main objective of this research is to identify potential causal links between ICT and firm performance. To do so, an instrumental variable technique is employed using the rollout of the broadband infrastructure and firm distance to the telephone exchange as instruments. While it seems plausible that access to ADSL increases ICT usage by increasing the rate of return on digital technology investment, it is important to statistically assess both the relevance of the instruments to ICT and whether evidence suggests that the instruments fulfil the exclusion restrictions assumption.

In order to assess the relevance of the instruments, the statistical relationship between access to the broadband infrastructure/firm distance to the telephone exchange and ICT stock is examined. The results in Table 30 suggest this is the case. In particular, firms connected to an exchange that is ADSL enabled use more ICT than those connected to non-enabled exchanges. Moreover, the further a firm is away from an enabled exchange the less ICT is used. The signs are consistent with our assumption about differences in internet connection speeds and the instruments maintain their statistical significance at the 1% level. In addition, the strength of the instruments remains robust to the inclusion of additional control variables from Model 2 to Model 8. Both foreign and US owned firms appear to use more ICT than domestic firms while older firms appear to use more ICT capital stock than younger firms.

So how big are the effects of enablement and firms distance from the exchange on ICT use? Using Model 8 in Table 30 as a baseline, we find that firms that have access to the ADSL infrastructure broadband at a mean distance (1,370 meters) uses 29% more ICT than those who are not connected to an enabled exchange.[27] To put this effect into perspective, the ICT capital stock of the mean firm is £204,000.

[27] The mean firm is 1,370 metres from their telephone exchange. The 29% effect for the mean firm is calculated in the following manner $29\% = \exp(1.144 - 0.123 * \ln(1370)) - 1.$

Table 30

First Stage Results: Effects of Instruments on ICT, 2000 to 2003

Dependent Variable: TFP	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
ADSL	0.922***	1.482***	1.511***	1.507***	1.511***	1.617***	1.071***	1.144***
	(0.18)	(0.22)	(0.22)	(0.22)	(0.22)	(0.22)	(0.21)	(0.21)
ADSL*distance	-0.053**	-0.134***	-0.138***	-0.140***	-0.142***	-0.144***	-0.112***	-0.123***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Distance		0.081***	0.072***	0.065***	0.059***	0.060***	0.051***	0.043**
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Foreign			1.077***	1.156***	1.112***	1.117***	1.063***	0.920***
			(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
USA				1.080***	1.019***	1.027***	0.945***	0.779***
				(0.08)	(0.08)	(0.08)	(0.08)	(0.07)
Age					0.354***	0.358***	0.323***	0.289***
					(0.02)	(0.02)	(0.02)	-0.02
Additional Controls								
Year						✓	✓	✓
Region							✓	✓
2-digit Sector								✓
Adjusted R^2	0.0170	0.0190	0.0590	0.0590	0.0780	0.0800	0.1340	0.1950
Observations	12,100	12,100	12,100	12,100	12,038	12,038	12,038	12,038

Note: Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

While the instruments appear to be relevant for ICT capital stock (measured as an aggregate sum of hardware stock, purchased software stock and in-house software stock), next we assess the extent to which ADSL access and firm distance from the exchange is related to alternative measures of ICT. While all ICT variables within the ARD and ICT Capital Stock dataset tend to be broad measures of digital technology, there is some information on investment in telecom software and computer services. The results in Table 31 find a positive and significant relationship between enablement and other types of ICT investment or service. The results suggest that the instruments predict all these measure of ICT strongly and the coefficients are quite similar. For example, both instruments exhibit the strongest explanatory power on ICT stock, and computer services at the 1% level with coefficients of 1.114 and 1.097 for enablement and -0.123 and -0.128 for firm distance, respectively.

Table 31

First Stage Results: Effects of Instruments on Various ICT Measures, 2000 to 2003

Dependent variable: ICTs	IT Stock	Hardware Stock	Software Stock	Telecomm	Computer Service	Software Service
ADSL	1.144***	0.907***	1.036***	1.000***	1.097***	0.825***
	(0.21)	(0.27)	(0.21)	(0.14)	(0.17)	(0.25)
ADSL*distance	-0.123***	-0.096**	-0.116***	-0.112***	-0.128***	-0.095***
	(0.03)	(0.04)	(0.03)	(0.02)	(0.02)	(0.04)
Distance	0.043**	0.031	0.035**	0.033***	0.025*	0.040*
	(0.02)	(0.03)	(0.02)	(0.01)	(0.01)	(0.02)
Foreign	0.920***	0.614***	0.772***	0.844***	1.030***	0.710***
	(0.06)	(0.07)	(0.06)	(0.04)	(0.05)	(0.07)
USA	0.779***	0.439***	0.667***	0.893***	0.904***	0.623***
	(0.07)	(0.08)	(0.08)	(0.05)	(0.06)	(0.09)
Age	0.289***	-0.068**	0.217***	0.276***	0.340***	0.333***
	(0.02)	(0.03)	(0.02)	(0.01)	(0.02)	(0.03)
Adjusted R^2	0.1910	0.1470	0.1440	0.2710	0.2840	0.1560
Observations	12,038	6,419	11,434	11,967	11,472	9,344

Note: All models include year, region and sector controls. *** represents 1%, ** 5% and * 10% levels of significance

After assessing the relevance of the instruments, the next step is to assess the exclusions restrictions assumption i.e., the instruments only impact firm TFP through ICT stock. One potential threat to this assumption is if the telecomm provider (BT) targeted exchanges that larger and more productive firms were connected to, in anticipation for greater up-take. If this was the case, then the exclusion restriction assumption is likely to be invalid.

In order to assess this, we examining the relationship between exchanges enabled in wave one or at various periods throughout wave one and ex-ante firm characteristics such as TFP, employment and whether the firm was owned by a foreign proprietor for years just before the start of the rollout (1997-1998). If a positive and significant relationship exists, it may suggest that BT targeted exchanges connected to higher performers. The results in Table 32 find no relationship between being enabled in wave one with firm efficiency, size of the firm or their ownership in 1997 and 1998. These results also hold when assessing firms that were enabled at the beginning of wave one, 1999-2000. The results therefore provide some evidence to suggest that BT was not targeting exchanges connected to large, productivity and foreign owned firms.[28]

Table 32

Effects of ex-ante Characteristics on 1999-2002 and 1999-2000 ADSL enablement

Dependent Variable: Timing of Enablement	Wave One	Wave One	Wave One	1999-2000	1999-2001	1999-2002
TFP 1997-98	0.033			0.008		
	(0.06)			(0.06)		
Employment 1997-98		0.040			-0.010	
		(0.03)			(0.03)	
Foreign 1997-98			-0.025			0.076
			(0.08)			(0.07)
Adjusted R^2	0.1010	0.1080	0.1040	0.1630	0.1640	0.1670
Observations	261	261	261	261	261	261

Note: All models include year, region, sector, foreign USA and age controls. *** represents 1%, ** 5% and * 10% levels of significance

Instrumental Variable Estimation

After assessing both the relevance and validity of the instruments, the chapter next employs an instrumental variable approach in order to control for endogeneity between ICT and productivity and examine the extent to which a causal link exists between IT capital stock and TFP. Both instruments are lagged one year to allow for the time needed to adjust to the availability of the technology. Theoretically, we expect our instruments to be most appropriate for wave one as opposed to wave two given the difficulty of anticipation at the start of wave one and the fact that wave

[28] Additional instrument validity tests will also be presented in chapter three.

two of the rollout was driven by consumer demand. In addition, multi-plant firms are excluded from the analysis since they are more likely to rely on leased line broadband rather than ADSL.

The results in Table 33 provide some preliminary evidence that ICT capital stock is causally related to TFP, however the results need to be interpreted with care. The same control variables used in the OLS baseline estimates are incrementally added to the IV model. The empirical results support the claim that ADSL enablement and firm distance from the exchange are relevant instruments. The first stage results for both instruments show the expected signs and are significant at the 1% level. As discussed earlier, firms that have access to the ADSL broadband infrastructure at a mean distance (1,370 meters) uses 29% more ICT than those who are not connected to an enabled exchange. In addition, ADSL enablement and firm distance from the exchange appear to be strong instruments. The F statistics ranges from 33.03 to 33.27 which are greater than the Stock-Yogo critical value of 19.93 (Stock and Yogo 2005). This means that at approximately a 5% level of significances, the maximum bias level is at least close to 10%.

The ICT coefficients are positive and statistically significant at the 1% as well as being relatively stable to the inclusion of a number of control variables ranging from 0.311 to 0.313. The estimates imply that firm access to ADSL infrastructure, results in considerable productivity gains. Similar to what is found within the ICT literature, our ICT coefficients are larger when using an instrumental variable approach as opposed to an OLS framework (Cardona et al 2013). As discussed previously this is likely reflecting the expected downward bias of the OLS results if for example adjustment costs are required with ICT stock. Moreover, since we use two instruments, we also test for over-identification test using the Hansen J statistic. The *p* values of the Hansen J statistics however are small questioning the exogeneity of the instruments.

Table 33

IV Estimation: Impact of ICT on TFP, 2000-2003

Dependent Variable: TFP	Model 4	Model 5	Model 6	Model 7
Second Stage				
ICT	0.312***	0.312***	0.311***	0.313***
	(0.06)	(0.06)	(0.06)	(0.06)
First Stage				
ADSL	1.176***	1.156***	1.157***	1.144***
	(0.27)	(0.27)	(0.27)	(0.26)
ADSL*distance	-0.127***	-0.124***	-0.124***	-0.123***
	(0.04)	(0.04)	(0.04)	(0.04)
Control Variables				
Distance	✓	✓	✓	✓
Foreign		✓	✓	✓
USA			✓	✓
Age				✓
Cragg-Donald Wald F-Statistic	33.03	33.13	33.27	33.14
Hansen J Statistic	0.0551	0.0551	0.0542	0.0402
Observations	12,100	12,100	12,100	12,038

Note: all models also include sector, region and year control variables. In addition, models 4, 5, 6 and 7 include the additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

Robustness tests

To assess the robustness of the baseline IV results in Table 33 alternative TFP measures are used as second stage dependent variables. Here TFP1 represents our baseline measure highlighted in the methodology section. TFP2 builds on the baseline model by including 3 digit sector factor input interaction dummies to control for the differences in input usage across sectors. Lev Pet is estimated with the Levinsohn-Petrin algorithm using deflated gross value added as the dependent variable and materials as the proxy variable to control for endogeneity of input usage.

The results in Table 34 suggest that a likely causal link exists between ICT and efficiency, regardless of how it is measured. When controlling for differences in input usage across sectors, the effects of ICT on TFP2 remain significant at the 1% level where the size of the coefficients are slightly smaller than the baseline estimates at 0.271 and 0.274. In addition, with Lev Pet, the ICT coefficient remains positive and significant at the 5% level however the values are smaller 0.162. The first stage

results also demonstrate their expected signs with ADSL values of 1.157 and 1.144 and firm distance from the exchange coefficients varying from -0.124 and -0.123.

The F statistics are sufficiently larger than the Yogo-Stock critical values suggesting that the instruments are strong. The use of alternative measures of TFP also provides some reassurance that the instruments are exogenous with *p* values ranging from 0.1195 and 0.0941 and 0.9614 and 0.9143 for TFP2 and Lev Pet, respectively. These results therefore appear to be much more reliable.

Table 34

IV Estimation: Impact of ICT on various TFP measures, 2000-2003

Dependent Variables	TFP1		TFP2		Lev Pet	
	Model 4	Model 5	Model 4	Model 5	Model 4	Model 5
Second Stage						
ICT	0.311***	0.313***	0.271***	0.274***	0.162**	0.162**
	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
First Stage						
ADSL	1.157***	1.144***	1.157***	1.144***	1.157***	1.144***
	(0.27)	(0.26)	(0.27)	(0.26)	(0.27)	(0.26)
Distance*ADSL	-0.124***	-0.123***	-0.124***	-0.123***	-0.124***	-0.123***
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Control Variables						
Distance	✓	✓	✓	✓	✓	✓
Foreign	✓	✓	✓	✓	✓	✓
USA	✓	✓	✓	✓	✓	✓
Age		✓		✓		✓
Cragg-Donald Wald F-Statistic	33.27	33.14	33.27	33.14	33.27	33.14
Hansen J Statistic	0.0542	0.0402	0.1195	0.0941	0.9614	0.9143
Observations	12,100	12,038	12,100	12,038	12,100	12,038

Note: TFP1 is estimated as our baseline estimate, TFP2 includes sector*factor input interaction dummies to the baseline estimate, and Lev Pet is estimated with via the Levinsohn-Petrin algorithm using gross value added. All models include sector, region and year control variables. Models also additional controls as listed.

In order to assess both assumptions made in the empirical strategy as well as the extent to which the results are driven by the instruments rather than some underlying factor, additional robustness tests are carried out. First, to verify the assumption that ADSL is appropriate for single plant firms, IV estimations are conducted for multi-plant firms only. Second, we assess the possibility that

unobservables related to the location of the firm influence the use of ICT and firm performance. For example, firms residing in urban regions as opposed to rural locations may use more ICT and achieve greater performance due to agglomeration economies (Combes et al 2012). We therefore add a dummy variable indicating if firms are located in urban areas. In addition, the nature of the rollout of ADSL across the UK may have targeted some regions with greater users of ICT in hopes of higher subscriptions. Postcode area dummies are added as an additional robustness test.

In order to assess the assumption that access to the ADSL infrastructure is most relevant for single plant firms, the same baseline IV framework is used, however now for multi-plant firms. The results in Table 35 appear to confirm the original assumption that the instruments are most relevant for single plant firms. For example, when restricting the sample to only multi-plant firms, the instruments exhibit substantially less explanatory power than for the sample of single plant firms. The F statistics now range from 10.43 and 9.18 as opposed to 33.27 to 33.03 in the baseline estimates, below the critical value (19.93 for 10% maximum level of bias). In addition to the F statistics, the first stage results are considerably weaker than for the sample of single plant firms. Firm distance is now only statistically significant at the 10% level while ADSL enablement significant at the 5% level. Moreover the sizes of the coefficients in the first stage are smaller, roughly half the size found in the baseline results.

Table 35

IV Estimation: Impact of IT on TFP Multi Plant firms, 2000-2003

Dependent Variable: TFP	Model 4	Model 5	Model 6	Model 7
Second Stage				
IT	0.219**	0.217**	0.218**	0.221**
	(0.09)	(0.10)	(0.10)	(0.10)
First Stage				
ADSL	0.568**	0.552**	0.531**	0.533**
	(0.24)	(0.24)	(0.24)	(0.24)
ADSL*distance	0.057*	-0.058*	-0.056*	-0.056*
	(0.02)	(0.03)	(0.03)	(0.03)
Control Variables				
Distance	✓	✓	✓	✓
Foreign		✓	✓	✓
USA			✓	✓
Age				✓
Cragg-Donald Wald F-Statistic	10.43	10.06	9.23	9.18
Hansen J Statistic	0.3146	0.3123	0.3158	0.3167
Observations	16,249	16,249	16,249	16,230

Note: all models include sector, region and year control variables. Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

Literature on the agglomeration economies has long inferred that urban areas are more productive than non-urban areas. For example, agglomeration economies appear to influence the use of emerging technologies (Kelley and Helper 1999; No 2008; Haller and Seidschlag 2011) and also appear to exhibit greater management abilities (Glaeser and Resseger, 2010; Puga, 2010). As a result, an urban dummy is added to control for variation between cities and rural areas. The definition used for urban location represents a locality with a population of 10,000 or greater as defined by the National Statistics Postcode Directory (2013).

In order to assess the potential effects of agglomeration economies, an urban dummy variable is included to the baseline models. Controlling for firms located in urban locations does not substantially influence the results in comparison to the baseline estimates. The ICT coefficients are all statistically significant at the 1% level where the size of the coefficient ranges from 0.388 to 0.385. Importantly, the instruments in the first stage are comparable to the baseline coefficients both in

terms of the size of the coefficients and their statistical significance at the 1% level. While the instruments appear to be somewhat weaker with F statistics ranging from 21.62 and 22.46, the F statistics remain above the Yogo-Stock (2005) critical value of 19.93, suggesting that the instruments are sufficiently strong. Moreover when testing for overidentifying restrictions (Hansen J-statistic) the results provides further support that the instruments are exogenous. Therefore, we cannot reject the null hypothesis that the instruments are jointly valid, i.e. uncorrelated with the residual.

Table 36

IV Estimation: Impact of IT on TFP, 2000-2003 with Urban Control

Dependent Variable: TFP	Model 4	Model 5	Model 6	Model 7
Second Stage				
IT	0.387***	0.386***	0.385***	0.388***
	(0.09)	(0.09)	(0.09)	(0.09)
First Stage				
ADSL	1.090***	1.089***	1.078***	1.068***
	(0.27)	(0.27)	(0.27)	(0.26)
ADSL*distance	-0.123***	-0.122***	-0.121***	-0.119***
	(0.04)	(0.04)	(0.04)	(0.04)
Urban	0.180**	0.176**	0.167**	0.159**
	(0.07)	(0.07)	(0.07)	(0.07)
Control Variables				
Distance	✓	✓	✓	✓
Foreign		✓	✓	✓
USA			✓	✓
Age				✓
Cragg-Donald Wald F-Statistic	21.62	22.46	22.22	22.38
Hansen J Statistic	0.1805	0.1767	0.1748	0.144
Observations	12,100	12,100	12,100	12,038

Note: All models include sector, region and year control variables and urban controls. Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance.

Next, postcode area dummies are added to the baseline models which are presented in Table 37. The inclusion of the regional postcode area controls does not appear to weaken either the second or the first stage results. The ICT coefficient remains positive and significant at the 1% level with the size of the coefficient ranging from 0.244 and 0.252 as opposed to the baseline results of 0.311 and 0.313. In the first stage, both ADSL and firm distance from the exchange are significant at the 1% level

with magnitudes close to the baseline estimates. The strength of the instruments appears to be strong with the F statistics ranging from 24.35 to 23.29. However for the instrument exogeneity, the *p* values from the Hansen J statistic are much smaller 0.0188 to 0.0127 bringing into question the exogeneity of the instruments when including postcode controls.

Table 37

IV Estimation: Impact of ICT on TFP, 2000-2003 with Postcode Controls

Dependent Variable: TFP	Model 4	Model 5	Model 6	Model 7
Second Stage				
IT	0.243***	0.244***	0.244***	0.242***
	(0.07)	(0.07)	(0.07)	(0.06)
First Stage				
ADSL	0.932***	0.940***	0.938***	0.938***
	(0.26)	(0.25)	(0.25)	(0.25)
ADSL*distance	-0.094***	-0.095***	-0.095***	-0.095***
	(0.04)	(0.04)	(0.04)	(0.04)
Control Variables				
Distance	✓	✓	✓	✓
Foreign		✓	✓	✓
USA			✓	✓
Age				✓
Cragg-Donald Wald F-Statistic	23.29	24.13	23.99	24.35
Hansen J Statistic	0.0188	0.0187	0.0185	0.0127
Observations	12,100	12,100	12,100	12,038

Note: All models include sector, region and year control variables and postcode area fixed effects. Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

Heterogeneity in the effects of ICT

The results throughout the empirical section provide some preliminary evidence of a causal link between ICT stock and TFP. An additional question however is the extent to which the causal link between ICT and TFP differences across various types of firms. The analysis in chapter one finds that the gains from ICT are heterogeneous across various firm characteristics, including foreign ownership and whether or not a

firm is located in a knowledge intensive sector.[29] This chapter extends this analysis to an instrument variable frame work to examine if the gains from ICT across knowledge intensive KIS and low-knowledge intensive and foreign and domestic owned firms are heterogeneous.

Before assessing causal links, we start first by examining the relationship between ICT and TFP for firms in KIS sectors in an OLS framework. The results in Table 38 suggest that single plant KIS firms obtain larger effects from ICT than the effects found for the general sample of single plant firms in Table 29. The effects of ICT amongst firms in KIS sectors range from 0.134 to 0.150 whereas in Table 29 the magnitudinal effects of ICT from our baseline sample vary from 0.090 to 0.082.[30]

Table 38

OLS Estimation: IT Effects on TFP, High Knowledge Sector Firms, 2000 to 2003

Dependent Variable: TFP	Model 4	Model 5	Model 6	Model 7
ICT	0.143***	0.139***	0.134***	0.150***
	(0.01)	(0.01)	(0.01)	(0.01)
Distance	-0.049***	-0.049***	-0.050***	-0.058***
	(0.01)	(0.01)	(0.01)	(0.01)
Foreign		0.146***	0.200***	0.159***
		(0.05)	(0.05)	(0.05)
USA			0.363***	0.359***
			(0.06)	(0.06)
Age				-0.261***
				(0.02)
Adjusted R^2	0.2080	0.2210	0.2220	0.2820
Observations	2,262	2,262	2,262	2,251

Note: All models include sector, region and year controls *** represents 1%, ** 5% and * 10% levels of significance

Next we assess the potential causal links between ICT use and TFP amongst firms in high-KIS and low-KIS by employing the same IV framework used in Table 30 but now the samples are restricted to samples of firms either in knowledge intensive or in low-intensive sectors. The control variables used here are consistent with those used in models 6 and 7 in Table 30.

[29] Firms in knowledge intensive sectors are defined as being in an industry in which 33% of total employment received tertiary education (Eurostat 2014).

[30] As a robustness test, we also assess and confirm that the effects of ICT are statistically different between knowledge intensive and low-knowledge intensive firms.

The results in Table 39 interestingly find that the ICT coefficients are larger for low-knowledge intensive firms than knowledge intensive firms where the coefficients are 0.338 and 0.269 respectively. While the statistical significance of the coefficients in the second stage are significant at the 1% level, the instruments exhibit different explanatory power across the two samples. For both KIS and low-KIS, being attached to an enabled exchange is correlated with greater ICT use, however enablement appears to result in more ICT use by KIS. Distance from the telephone exchange however appears to be less relevant for KIS firms than for low-KIS firms. For example the distance coefficient for low-KIS is significant at the 1% level while for KIS significant only at the 10% level. Moreover the F statistics suggest that our instruments are stronger for low-KIS than KIS with statistics ranging from 19.66 and 15.72, respectively. The *p* values from the Hansen J statistics also suggest that the instruments are exogenous for both samples. It is not entirely clear why low-KIS firms appear to gain more from ICT than KIS firms, in addition the literature does not offer much advice on this.

Table 39

IV Estimation: Impact of ICT on TFP, High/Low Knowledge Sector Firms, 2000-2003

Dependent Variable: TFP	KIS	low-KIS	KIS	low-KIS
Second Stage				
ICT	0.229***	0.341***	0.269***	0.338***
	(0.09)	(0.09)	(0.09)	(0.09)
First Stage				
ADSL	1.777***	0.991***	1.722***	0.979***
	(0.65)	(0.29)	(0.63)	(0.29)
ADSL*distance	-0.178*	-0.108***	-0.173*	-0.106***
	(0.09)	(0.04)	(0.09)	(0.04)
Control Variables				
Distance	✓	✓	✓	✓
Foreign	✓	✓	✓	✓
USA	✓	✓	✓	✓
Age			✓	✓
Cragg-Donald Wald F-Statistic	16.85	19.44	15.72	19.66
Hansen J Statistic	0.1393	0.1414	0.1804	0.1036
Observations	2,262	9,838	2,251	9,787

Note: all models include sector, region and year control variables. Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance.

Next we assess the effects of ICT on foreign owners, first in an OLS framework followed by IV estimation. Note that Table 40 only contains two models since the sample restriction is done by foreign ownership thereby eliminating Model 5 and Model 6. In terms of firm ownership, the OLS results do not suggest that single plant foreign firms obtain greater effects than a general sample of single plant firms. The ICT coefficients range from 0.073 and 0.074 whereas the baseline OLS results from Table 29 vary from 0.090 to 0.082.

Table 40

OLS Estimation: IT Effects on TFP, Foreign Firms, 2000-2003

Dependent Variable: TFP	Model 4	Model 7
ICT	0.073***	0.074***
	(0.01)	(0.01)
Distance	-0.036**	-0.035**
	(0.02)	(0.02)
Age		-0.046**
		(0.02)
Adjusted R^2	0.4660	0.4670
Observations	2,148	2,148

Note: Models 4 and 7 include sector, region and year controls, Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance

Moving on to the instrumental variable estimation we find that the link between ICT and TFP by ownership provides somewhat ambiguous results. While the ICT coefficient is positive and significant at the 1% level for domestic firms, the results are insignificant for foreign owned firms. This appears to be driven by the fact that the instruments are not relevant to foreign firms. While ADSL enablement and firm distance from the telephone exchange exhibit their expected signs and are significant at the 1% level, the strength of the instruments appear to be weak with the F statistics for foreign firms range from 4.21 and 4.42. For domestic firms, the first stage results also reflect their expected signs with the statistical significance being at the 1% and 5% level of significance for enablement and firm distance from the exchange respectively. The F statistics for domestic firms are substantially larger than those found for foreign firms ranging from 31.30 and 30.24, comfortably above the Yogo-Stock critical value. In addition, the sizes of the *p* vales of the Hansen J statistic are substantially different across ownership. For foreign firms, the *p* values range from 0.5900 and 0.6120 whereas for domestic firms vary from 0.0126 and 0.0089.

Table 41

IV Estimation: Impact of ICT on TFP for Foreign and Domestic Firms, 2000-2003

Dependent Variable: TFP	Foreign	Domestic	Foreign	Domestic
Second Stage				
ICT	0.152	0.303***	0.147	0.310***
	(0.16)	(0.06)	(0.15)	(0.07)
First Stage				
ADSL	1.670***	1.017***	1.701***	0.985***
	(0.54)	(0.30)	(0.54)	(0.29)
ADSL*distance	-0.225***	-0.096**	-0.228***	-0.093**
	(0.08)	(0.04)	(0.08)	(0.04)
Control Variables				
Distance	✓	✓	✓	✓
Age			✓	✓
Cragg-Donald Wald F-Statistic	4.21	31.3	4.42	30.24
Hansen J Statistic	0.5900	0.0126	0.6120	0.0089
Observations	2,148	9,952	2,148	9,890

Note: all models include sector, region and year control variables. Additional controls listed. *** represents 1%, ** 5% and * 10% levels of significance.

Conclusion

While the literature has provided substantial evidence regarding a positive correlation between ICT and productivity, less is known as to whether this relationship is causal (Cardona et al 2013 Draca et al 2006). The present chapter attempts to identify the extent to which these two variables are causally related through the use of an instrumental variable approach. The instruments here exploit spatial and temporal variation in access to a superior form of internet infrastructure at the turn of the century known as ADSL broadband. The delivery of ADSL relies on the pre-existing telephone network where the enablement of a telephone exchange required technology upgrades both to the exchange and the premise. As a result, supply-side constraints due to the limited number of engineers and the size of the telephone network meant that the rollout occurred in a staggered manner. The construction of the instruments is based on the context of the rollout procedures used by BT, focusing on a narrow time frame of the implementation thought to be exogenous to firms; wave one from 1999 to 2002. The first instrument therefore uses

the timing in which firms receive access to the ADSL infrastructure. The second instrument, firm distance from the exchange, exploits the distance dependence of ADSL in which internet connectivity decreases with distance. To our knowledge, this is the first time access to internet infrastructure and firm distance from the exchange has been used as instruments for ICT technology.

The results find that firms connected to a part of the enabled ADSL infrastructure use more ICT than firms connected to a non-enabled section. This is similar to earlier studies which find a positive correlation between internet and ICT use (Varian et al 2002; Forman 2005; and Forman et al 2005). At the same time, firm distance from the enabled exchange is related to less ICT use, consistent with our assumption on connection speed and technology use. In particular, the results suggest that firms connected to the enabled part of the ADSL infrastructure at firm mean distance use 29% more ICT than those connected to non-enabled exchanges. In addition to the relevance of the instruments, the timing of enablement does not appear to be correlated with ex ante firm characteristics such as employment, TFP and ownership, providing some reassurance regarding the instruments validity. In addition, the estimates confirm our assumption that ADSL and firm distance from the exchange are most appropriate instruments for single plant firms.

The second stage estimates from our instrumental variable approach provide some preliminary evidence of a causal link between ICT and productivity. The increase in ICT use induced by access to the ADSL infrastructure results in large productivity gains. Similar to other studies, we find that the ICT coefficients obtained from IV estimation are considerably larger than those from OLS estimates. The literature suggests that this may be explained by a downward bias in the OLS results, due to the likely presence of considerable adjustment costs which coincide with IT investment (Brynjolfsson and Hitt 2003; Wolff 2002; Basu et al. 2004). While initial estimates question the exogeneity of the instruments from the Hansen J *p* values, the use of different productivity measures as well as controlling for urban and rural locations provides some reassurance regarding the validity of the instruments.

The chapter also contributes to the literature by assessing heterogeneity both in terms of the strength of the instruments and the effects of ICT across various firm

characteristics. Building off of chapter one, we start by examining the effects of ICT between firms in low and high knowledge intensive sectors. The IV results suggest that firms in low-KIS obtain greater gains from their ICT than firms in high-KIS sectors. At the same time the instruments appear to be stronger for firms in non-KIS sectors, potentially implying that high-KIS firms may require greater bandwidth and connectivity speed and therefore rely more on leased-line broadband. In terms of ownership, the instruments are substantially stronger for domestic owned firms as opposed to foreign owned entities. While the first stage results for foreign firms show their expected signs and significance their F statistics are substantially smaller than for domestically owned firms, proposing that access to the ADSL infrastructure and firm distance are less relevant to foreign firms.

While access to the ADSL infrastructure appears to induce greater ICT use, which in term leads to greater productivity, it is not clear from this study which types of ICT are being used. The ICT variable employed in this chapter as well as by Bloom et al (2012) is an aggregate sum of both hardware and software thus masking which specific types of digital technologies are compatible with ADSL. It is likely for example that certain types of ICT are likely to be more complementary with communication technology such as website software and PCs as opposed to other technologies like mainframe computers. Building off of this work, the next chapter will use the same instrument variables to assess heterogeneity in ICT use and examine the extent to which various types of ICT impact productivity differently. Moreover, additional robustness tests of the instruments will be undertaken to further assess their validity.

Chapter Three

Broadband Enablement, Heterogeneity in ICT use and Firm Performance

Introduction

Over the last two decades the economic literature has found empirical evidence to suggest that ICT is economically beneficial and can be considered a general purpose technology (Jovanovic and Rousseau 2005). The continued development of ICT has allowed firms to more effectively process, send and store information leading to the production of new knowledge. At the same time, ICT has enhanced a firm's ability to coordinate production and logistical processes thereby influencing their organizational structure. Within the empirical literature, ICT is found to reduce production time, increase innovation and specialization, improve accuracy, allow firms to replicate processes faster and lead to productivity dispersion (Bresnahan et al 2002; Bloom et al, 2005; Hubbard 2003; Bartel et al 2011, Brynjolfsson et al 2008 Draca et al 2006). Moreover, the evidence suggests that divergence in productivity growth across countries is partially determined by differences in IT usage. Van Ark, et al (2008) for example finds that the productivity gap between Europe and the US is partly explained by the slower arrival of the knowledge economy to Europe. Not only did the US invest in more IT but their firms were able to achieve greater productivity growth, potentially due to complementary organizational change. As a result, a pressing issue facing many policy makers is to ensure that firms are continually adopting emerging technologies, such as ICT.

Many countries have rolled out various programs aimed at inducing greater ICT usage with the objective of narrowing the productivity gap with frontier countries. A survey carried out for the *OECD Digital Economy Outlook 2015* found that 27 of the 34 participating countries currently have a central national digital strategy. Some of these policies look to enhance technology usage by providing various financially incentives such as direct tax credits and subsidizes (Warda 2010). Other policies important for technology adoption are more indirect, such as loosening employee protection regulation, increasing competition and providing training, and education for ICT installation and use (Conway et al 2007, Bartlesman 2013 and Digital Technology Adoption Pilot Program 2015).

A key pillar for most of these digital strategies involves expanding and enhancing broadband infrastructure (OECD 2015). The motivation for the substantial focus in this area comes from the belief that access to broadband can enable communication

and facilitate new organizational strategies as a result of greater interconnectedness both at home and abroad. At the same time, firms with access to a superior form of telecommunication may lead to the adoption of new process innovation, develop new goods, access larger markets, greater creation of knowledge and easier access to global value chains (Varian et al., 2002; Antras et al., 2006; Abramovsky and Griffith, 2006, OECD, 2008). Therefore businesses which have access to broadband are expected to increase revenue, expand their size and increase efficiency.

One way through which broadband may also enhance productivity and sales is through the types of ICT technologies used within the firm. The results from chapter two provide the first evidence for this view; firms with access to ADSL broadband were found to own greater ICT capital than those with access to dial-up internet. Enhanced information exchange that follows from greater bandwidth requires firms to upgrade their hardware and software technologies or that access increases the rate of return for new ICT investments. This connection between ICT use and broadband availability has been previously overlooked in the economic and policy literature.

Although the evidence from chapter two shows that the availability of ADSL broadband in the UK appears to have led to an increase in hardware and software capital stock, it is unclear what particular types of ICT firms were induced to invest in. This is the focus of chapter three and represents a key contribution of this study.

Unbundling the aggregate ICT used by firms is not only important in assessing the effects of ADSL enablement on technology usage, but also to examine the potential heterogeneous effects of various types of ICT on firm performance. Recent work by Garicano and Rossi-Hansberg (2006), Bloom et al (2013b) and Garicano and Heaton (2010) indicate the value of such an approach. For example, as their results suggest, enterprise resource planning software (an information processing technology) encourages a decentralized organizational structure whereas intranet systems (a communication technology) induce more hierarchical structures. Therefore, relying on a homogenous measure of ICT may mask the likely heterogeneous effects of the technology on the firm.

While the emerging literature provides evidence on the effects of communication and information processing technologies on firm organizational structure, less is known regarding their impact on firm performance. As a result, this chapter assesses

heterogeneity in the effect of various types of ICT in particular, communication-ICT on labour productivity, representing the second main contribution of the paper.

In order to address these questions empirically, this chapter will use a new panel dataset known as the Ci Technology Database (CiTDB) produced, by the Aberdeen group, formally known as Harte Hanks.[31] This dataset is unique in that it provides very detailed information on specific types of digital technology usage at the establishment level. Importantly, the CiTDB contains plant postcodes, allowing us to continue to use similar instruments employed in chapter two, ADSL enablement and distance to the local telephone exchange box.

By employing a new dataset on detailed plant level usage of ICT and exploiting a particular period during the expansion of the ADSL infrastructure in the UK, this chapter attempts to contribute to the literature by: first, providing further assessment regarding a relatively unexplored determinant of ICT usage, access to broadband; second, understand the extent to which the effects of broadband availability are heterogeneous across a wide range of digital technologies; and third, examine whether these various types of ICT are causally linked to firm performance.

The extent to which access to the ADSL infrastructure and firm distance from the exchange induces greater use of various types of technology will be assessed using both OLS and Logit estimations. Data on ICT usage within the CiTDB is given as either a technology total (i.e. a count) or whether or not a plant uses a specific type of IT (0, 1 dummy scenario). Therefore, OLS will be used when ICT is a continuous variable and Logit will be employed when ICT is a dummy variable. In addition, the potential causal relationship between ICT and plant performance will be examined within an instrumental variable estimation framework. Similar to chapter two, the instruments are the broadband enablement dummy and the firm distance from the telephone exchange interacted with the enablement dummy. Rather than calculating the distance variable as was done previously (as the crow flies), chapter three will exploit newly acquired data from *Point Topic* which contains information on the length of the local loop cable running between an establishment and their exchange box. Also now the endogenous x variable will be one of a number of ICT technologies found to be relevant to the instruments in the empirical analysis. Moreover, this chapter

[31] The CiTDB is used in a number of empirical papers regarding ICT and firm/industrial performance, such as Bresnahan et al (2002), Brynjolfsson and Hitt (2003) Bloom, Draca and Van Reenen (2011) and Bloom et al (2013a) Bloom et al (2013b) Forman et al (2014).

conducts a number of falsification tests in order to further assess the validity of the instruments in the same spirit of the previous chapter. These tests include assessing potential anticipation effects, the influence of agglomeration on ICT use and so on.

The rest of the chapter continues as follows: section 2 discusses the literature related to the determinants of ICT adoption as well as previous work on the heterogeneous effects of ICT on the firm. Section 3 will introduce the databases used in the analysis and discuss the descriptive statistics from the panel. Section 4 introduces the empirical strategy while section 5 presents and examines the results. Section 6 provides a brief summary and discusses the main results.

Literature Review

This chapter contributes to three separate branches of the ICT literature. First, this paper looks to provide additional evidence regarding a relatively unexplored determinant of ICT usage, in this case access to a superior form of internet technology infrastructure and spatial variation in the speed of the internet proxied by firm distance to the exchange. The second contribution of the paper is to address a more classical question of the literature, the potential causal link between ICT and productivity. Both of these aspects of the chapter are linked to a third branch of the ICT literature which has begun moving away from the traditional homogenous measure of ICT to explore heterogeneity from various types of ICT.

As a result, the first section of the literature review will discuss work related to various drivers of ICT investment. These determinants include firm characteristics (size, region, levels of human capital etc.) and direct/indirect policy regulations (tax credits, product market regulations, openness etc.). The second part of the literature provides a brief outline regarding the empirical evidence on the relationship between broadband and ICT use, and the third part will discuss recent work on the heterogeneous effects of distinct types of technology on the organization.

Determinants of ICT usage

Firm Characteristics

Firm size has been considered an important determinant of technology use in both the theoretical and empirical literature for many years. One of the reasons for this is because it is not difficult to observe and because firm size relates to a number of

factors which is also believed to impact technology use (Geroski 2000). For example, large firms are likely to have more knowledge based capital and more accumulated technology making it easier for them to adopt emerging technologies (Gibbs and Kraemer 2004). At the same time, larger firms are likely to experience larger adjustment costs when implementing ICT. Moreover large firms, given their size tend to be more isolated from market forces and therefore may be less incentivized to use the most recent technology in order to reap even higher profits (Oster 1982).[32]

Network effects are also known to influence the rate and type of technological usage. For example, the actions of firms in the surrounding area can influence whether or not another decides to use emerging technologies. Given the costs associated with ICT investment, firms may be more willing to use new technology if neighbouring firms have successfully adopted and implemented the new capital. Examples of these come from a number of early papers on the adoption of hybrid corn seeds which found that location and the interaction between users of new technology is important for implementation (Ryan and Gross 1943 & Griliches 1957). In addition, there is some evidence in the UK engineering and basic metals sectors, where firms located relatively close to those implementing the new capital early on, resulted in enhanced understanding of the technology and thus more adoption (Baptista 2000). Having close proximity to the producers of advanced technology is also likely to influence whether or not a firm implements new capital (Armbruster et al 2005). Gertler (1995) on the other hand finds that in addition to the role of geographical proximity, other similarities between producers and users of advanced manufacturing technology such as culture and organizational structure lead to greater technological adoption.

Geographic location has been found to not only influence technology usage within a country but also internationally. Cumin and Hobjin (2004) find evidence of "trickle down adoption", where technologies tend to be implemented first in advanced economies and used later in less developed economies. Therefore, emerging technology usage tends to be geographically concentrated both domestically and internationally. Kelley and Helper (1999) also find that both urbanization and

[32] Additional discussion on the effects of size as well as firm age on ICT use can be found in the first chapter.

regionalization lead to knowledge sharing and technology diffusion.[33] In addition, the results from No (2008) provides supportive evidence that advanced manufacturing technological diffusion occurs more within agglomerations, where the adoption within the clusters is influenced by early adopters.

In terms of geographic location and ICT usage, Armbruster et al (2005) find that firms who were located closer to the SAP headquarters (one of the first and largest producers of ERP software) exhibited a greater probability of using ERP applications. Cumin and Hobjin (2004) found that the trickle down adoption from advanced to less advanced economies occur across a range of technologies including textiles, steel production, transport, communication including ICT. Haller and Seidschlag (2011) find that firms exhibit a higher probability to use website technology when they are situated in the same sector and geographic area where a large share of website users resides.

Another characteristic believed to be correlated with ICT adoption is the level of human capital within the firm. Early work by Bartel and Lichtenberg (1987) propose that the cognitive ability of workers enables greater flexibility to the evolution of new technologies. Bresnahan et al (2002) show that businesses which employ more university graduates use a greater amount of IT than firms who hire more workers with just a high school education. IT technology is both a complement to higher trained workers and higher trained workers are more proficient at adopting IT.

Haller and Siedschlag (2011) illustrate that skill intensity leads to greater IT use but that the effects are different depending on the group of skilled workers and the type of technology. In particular, they find that management/technical and clerical workers both lead to a higher propensity to have a website, whereas only clerical workers statistically influence the propensity to accept online orders. Moreover, management/technical and clerical staff is positively related to IT intensity (computers per worker) but neither group appear to robustly influence turnover from online sales. More recently, the *OECD Digital Economy Outlook* (2015) finds that the use of cloud computing is greater amongst firms that also use other knowledge

[33] Here regionalization refers to the clustering of plants regionally within similar sectors why urbanization signifies both the diversity of sectors and the clustering of engineering educational institutions.

intensive ICTs which require substantial human capital, such as consumer resource management, finance and accounting software as well as computing power.

Foreign ownership has also been found to influence technology adoption. For example, a number of papers suggest that MNEs transfer emerging technology in addition to product and process innovation to newly acquired firms (see Teece 1977, Caves 1996 and Veugelers and Cassima 2004, Javoricik and Poelhekke 2014). Recently, Guadalupe, Kuzmina and Thomas (2012) show that although MNEs tend to obtain more productive domestic firms, however after acquisition the affiliate demonstrates higher levels of innovation, while at the same time adopting advanced capital, foreign technology and new organizational structures resulting in enhanced performance. In terms of digital technology, Haller and Siedschlag (2011) find that while foreign ownership is positively related with ICT intensity, it does not increase IT adoption, which may reflect cherry picking by the MNE rather than technology transfer.

Policy Environment

Another aspect which is likely to influence ICT usage is the policy environment in which a firm resides. For example, direct policy measures proposed by governments such as tax breaks for ICT investment may induce firms to adopt emerging technologies that they otherwise might not. Alternatively, regulatory and policy environments may indirectly induce ICT usage such as greater flexibility in the labour market, easier access to finance, a more open market enabling greater competition both from domestic and foreign competitors and so on.

Direct Policy Environment

Governments around the world have implemented numerous policies directly targeting firms with the objective of enhancing ICT adoption. For example, product market regulations that influence competition in the ICT producing sectors may result in an increase in the quality and a decrease in the price of technology, thereby inducing greater ICT adoption throughout the economy (Conway et al 2005). Other direct policies include tax credits, grants/subsidies procurement programmes, complementary ICT education, meant to directly incentivise adoption of ICT by the end user (Warda 2010). Empirical assessment into the effects of tax incentives has

been a long standing issue. Hall and Jorgenson (1967) find that tax regulation is strongly correlated with the amount and timing of investment. House and Shapiro (2008) assess a tax depreciation policy implemented in the US in 2002 and 2003 and find significant evidence regarding a positive effect on investment.[34]

In terms of ICT usage, recent empirical work by Gaggl and Wright (2015) assess the effects of a tax incentive programme in the UK from 2000 to 2004 which targets firms with 50 or less employees. Their results suggest that the tax incentive policy resulted in an increase ICT adoption for both hardware and software technologies. Using a difference-in-difference approach Cohen and Cummins (2006) however find little evidence in the success of partial expensing to investment in firm equipment and software.

Indirect Policy Environment

In terms of indirect policies, rigid employee protection regulations are shown to serve as a disincentive for firms adopting new uncertain technologies with implications for employment levels. This is because it is more expensive to shed workers in the event of poor economic performance (Bartelsman et al 2013). They also show that countries with stricter exit regulations have smaller IT producing sectors, which the authors argue are a key contributor to the disparity in IT intensity across countries. Similarly, Samaniego (2008) finds high costs associated with shedding works adversely impacts the profits of sectors with rapid technology change. Countries with high firing costs instead have a greater concentration of industries with slow technology change.

Policies which influence competitiveness within a country are also important drivers of technological adoption. Economic environments where firms face greater competition provide stronger motivation to use emerging technology whereas countries with low levels of competition may have less incentive to adopt new technology. For example, Bridgeman et al (2012) document how policies such as restricting the size of sugar cane farms in Puerto Rico stifled competition, hindering technology adoption and performance, until it was no longer profitable to produce sugarcane. The empirical evidence in terms of competition in ICT use is mixed.

[34] The policy-related variables are not covered in the empirics.

Dasgupta et al (1999) find that competition induces IT investment while Jeon et al (2006) and Thong (1999) find little or no effect of market competition on ICT usage.

Firms may also be induced to invest in new technologies in the presence of foreign competition from imports and/or foreign direct investment. Domestic businesses in open markets face competitive pressure both from imports and foreign direct investment and therefore experience pressure to either invest in innovative activities to improve efficiency, or chose to shrink or exit. Bertschek (1995) demonstrates that when firms face greater international competition (measured by the proportion of imports and inward foreign direct investment to the sum of domestic demand at the sectoral level) they exhibit a high propensity to undertake an innovative activity. In terms of ICT, international competitive pressure has been shown to increase the usage of business-to-business e-commerce technology (Bertschek and Fryges 2002).

Greater openness and trade liberalization can also induce technology adoption by allowing successful domestic firms to access a larger foreign market thereby inducing them to invest in advanced capital. Noted early on by Schmookler (1954), the profitability for businesses to implement efficiency improving technology increases the larger the market becomes. Exporting and investing are complementary activities, thus when the cost of exporting decreases firms are incentivized to both export and invest (Atkeson and Burstein 2007, Bustos 2008 and Constantini and Melitz 2008). In terms of ICT induced investment, Lileeva and Trefler (2010) find that Canadian firms that were incentivized to either begin exporting or increase export activities due to the elimination of US tariffs had higher adoption rates for advanced IT technologies (such as manufacturing information systems and inspection and communication technologies), experienced higher labour productivity and carried out more product innovation.

Even if firms are induced to invest in emerging ICT due to competitive market pressures, flexible employment regulation and greater foreign market access and so on, they require some access to formal credit. Given the considerable costs involved in adopting new technology, the presence of financial constraints within the economy can be a major deterrent to investment. Within the empirical literature, financial barriers are found to hamper research and development (R&D) and investment in firms (Hall 2002 and Lerner and Hall 2010). A recent study by Gorodnichenko and Schnitzer (2013) found that financial barriers substantially hinder

technological investment, where for example a modest increase in financial constraints reduced the probability of adopting emerging technology by 22%.[35] In addition, the authors imply that barriers to finance are one of the main reasons for the gap in productivity and innovation between domestic and foreign owned firms.

Broadband and ICT usage

A relatively unexplored determinant of ICT usage is the availability of broadband infrastructure. One way in which broadband may induce the usage of ICT is that greater internet speed may increase the rate of return on investing in other forms of digital technology. For example, a firm connected to a telephone exchange which switches from providing dial-up to ADSL broadband, experiences a substantial increase in the amount of external information that can be received or sent.[36] As noted earlier, this may induce firms to invest in new PCs and/or software, since having access to a superior form of telecommunication, enables them to obtain higher performance out of their investment than previously possible with dial-up internet. It is important to note however, this may not be the case for all ICT. In particular, ICTs which do not require or tend not to interact with external communication technology such as main frame computers, CAD/CAMs, printers and so on, may witness little change even after the internet infrastructure is upgraded.

Switching from dial-up to ADSL broadband may also lead to increased usage in other forms of ICT simply due to a technical requirement as a result of greater bandwidth and information flow. In fact, there are basic hardware and software requirements for consumers switching from narrow-broadband to ADSL. For example, BT suggests requirements for ADSL use such as PCs with a Pentium processor or faster with at least 150 MB of hard disk, a CD ROM, a minimum operating system being a Windows 98 SE/ME and so on (BT 2016). Thus plants attached to an exchange with pre-Pentium PCs, operating systems older than Windows 98 and so on, would require investment in new hardware and software. Moreover, investment in new ICT and the handling of more information due to the initial broadband requirements may also

[35] The modest increase in financial constraints here refers to an increase of one standard deviation.

[36] Dial-up only offered speeds up to 64Kbits/second (Bit Tech 2013) whereas ADSL technologies could deliver connections speeds up to 8,000Kbits/second (Ofcom 2015).

indirectly induce investment in complementary ICTs such as secondary storage devices, servers and so on.

Within the literature, there is only modest evidence regarding the effects of broadband on ICT usage. An exception being Varian et al (2002) which find that firms in the US, Germany and the UK using the internet tend to use hardware and software more intensively. In addition, results from Forman (2002) and Forman et al (2005) also report a positive relationship between internet usage and the amount of hardware and software within establishments. The results from chapter two of this thesis also finds evidence to suggest that firms connected to ADSL enabled exchanges used greater amounts of ICT capital stock than firms attached to non-enabled exchanges.

Heterogeneous effects of ICT and firm performance

The standard empirical estimation on the effects of ICT within the literature tends to rely either on an estimate of capital stock, usually treated as an aggregate sum of hardware and software (see Draca et al 2006), or alternatively use a specific technology within a specific firm/industry (Hubbard 2003). Recent empirical and theoretical research by Garicano and Rossi-Hansberg (2006), Bloom et al (2013b) and Garicano and Heaton (2010) suggests that treating ICT as an aggregate technology may overlook the likely heterogeneous effects of explicit forms of ICT.

Recently, Bloom et al (2013b) identify heterogeneous effects of ICTs on the structure of the firm. The paper disentangles ICT into its two main functions; first IT (information technology) which tend to deal with processing and storing of information and second, CT (communication technology) which enables communication amongst agents. Given that IT reduces the cost of information access while CT reduces the cost of communicating information, these technologies are expected to impact an establishment differently. In fact, the authors demonstrate that ERPs and CAD/CAM technologies which reduce the cost to access information leads to more decentralization, whereas technologies such as intranets that lower the cost of internal communication resulting in greater centralization.[37]

[37] The main ICT dataset used in Bloom et al (2013b) is the same used in this chapter.

Data

Chapter three utilizes data from three separate sources. The first dataset provides establishment level information on ICT usage in addition to data on sales and employment, which we use to calculate labour productivity; the second database contains information on the timing of enablement of ADSL at each telephone exchange in the UK; and the third dataset provides details on the length of the local loop running between a postcode and its respected telephone exchange box.

ICT Dataset

Detailed information on plant level ICT usage is available from the Ci Technology Database (CiTDB), produced by the Aberdeen Group, an information and international marketing company. The Aberdeen Group (formally known as Harte Hanks) gathers detailed information on ICT usage to sell to suppliers, and producers of IT goods and services such as IBM and Cisco. Firm establishments are surveyed annually, providing specific information on technology usage such as the number of computers and servers, various forms of software like business management systems, intranet infrastructure, IT personnel and so on. The dataset also provides descriptive information on turnover, employment, sector, number of plants in addition to its location given by the postcode. While the dataset provides substantial detail on ICT the CiTDB contains less information on firm characteristics including foreign ownership and age (which does not get introduced to the dataset until after our sample period).The CiTDB has been used in a number of empirical papers on ICT and firm and industrial performance such as Bresnahan et al (2002), Brynjolfsson and Hitt (2003) Bloom et al (2013a) Bloom et al (2013b) and Forman et al (2014).

Since the CiTDB is sold to large firms who in turn use the data for marketing purposes, Aberdeen Group has substantial market pressure to ensure that the quality of data accuracy remains high. To ensure that their data quality is high, the Aberdeen Group carries out random quality audits. Moreover, the Aberdeen Group guarantees the quality of its data, by promising to refund their customers if errors for any sample are greater than 5%.

The Aberdeen group has found no apparent bias in the survey responses across industries, regions and years, and suggests the sample is reasonably representative. However, the Aberdeen Group only surveys firms with 100 employees or more, which therefore unfortunately excludes the smallest firms. This sample restriction is

made at the firm level, thus the CiTDB does contain plants with less than 100 workers that are connected to a multi plant firm with more than 100 employees.

The CiTDB provides a unique opportunity to examine in detail, the benefits of ICT and identify which technologies firms are induced to use as a result of access to a superior telecommunication infrastructure. The types of ICT assessed within this chapter are classified based on the main function of the technology into four broad categories, *Personal Computers*, C*omputing Systems/Storage*, *Software* and *IT personnel*, illustrated in Table 42. The first category, *Personal Computers* covers the total number of PCs, desktops and laptops. Furthermore information is provided on the quality of the PC, listing the numbers of Pentium and non-Pentium computers. The next category, *computing and storage devices* include counts on mid-range computers (including a popular type of mid-range computer during this time, the AS400) and main-frame computers as well as secondary storage devices, Direct Access Storage Devices (DASDs) measured by gigabytes of storage space.

In order to assess the large varieties of software applications in the CiTDB, technologies are categorized based on their main technical function. In general, the software used in this chapter can be classified as software which enables either greater *internal communication* or *external communication,* in a similar manner to OECD (2016). Software classified as *internal communication* include technologies which carryout information allocation and data storage. Resource allocation software include ERPs, Inventory Management, Human Resource Management and Accounting software while data storage includes Database Management Systems. Given the perceived benefits of ERPs (Hitt and Zhou 2002) the analysis assesses all resource allocation software as well as ERP systems separately. *External communication* software on the other hand includes E-commerce, web design applications and email software.[38] The final category, *ICT personnel*, contains the numbers of ICT staff employed within the plant, in addition to the number of programmers.[39]

[38] It is important to note that some technologies such as ERPs can carry out both internal and external communicating functions. In such cases, the technology is classified based on their main function.

[39] The decision to limit the analysis to these categories was based on their being adequate and consistent coverage during the sample period.

Table 42

Technology and Classification Types

Personal Computers	Computing and Storage	Software	Personnel
Desktop	Mid-range computers	Internal Communication	IT staff
Laptop	-AS400s	-Resource allocation	Non-IT staff
Pentium	Main frame computers	-Data management	Programmers
Pre-Pentium	DASDs	External Communication	
		-Website	
		-Email	
		-E-commerce	

Broadband Enablement and Local Loop Length Data

The explanatory variables of interest, ADSL enablement and cable distance from the exchange are obtained from two separate datasets. First, the ADSL dataset containing information on the rollout of ADSL broadband across the UK comes from the Office of the Regulator for Telecommunications (OFCOM), which was introduced and discussed in the second chapter. This data is quite rich in that it provides exact location (by postcode) and the timing of enablement (by day) of each telephone exchange in the UK.[40]

The second dataset called *PointTopic* identifies the telephone exchange that each postcode in the UK is connected to and provides an estimate on the distance of the local loop (the cooper cable which runs between the establishment and the telephone exchange box). The *PointTopic* data is available for around 1.6 million postcodes in the UK[41] therefore allowing the chapter to identify when each plant in the sample obtained access to ADSL and their relative internet speed

The *Point Topic* data provides an alternative measure on the length of the local loop. In the second chapter distance from the exchange was calculated as the crow flies, however the cable between a premise and the exchange may not always travel in a straight line and can be determined by a number of factors (such as the geographic terrain, the layout of the streets pre-existing infrastructure and so on). The

[40] All but 37 of the telephone exchanges in the United Kingdom were enabled and operated by British Telecom. The remainder were serviced by Kingston Communication. Firms connected to these exchanges are dropped in this analysis.

[41] Postcodes in the UK typically relate to 14 domestic houses or a medium sized firm.

PointTopic data takes these issues into consideration when estimating the length of the loop which they have confirmed to BT.[42] Incorporating the new *PointTopic* data into chapter three provides an alternative and possibly more precise instrument. Including this data into chapter three also allows one to check the consistency of the effects of cable distance on ICT use.

Cleaning Data

Unlike the ARD used in the previous chapter, the CiTDB has a larger industrial coverage, including education, government, medical and agriculture sectors. Given that government and medical sectors are not for profit, the fact that education establishments use ICT differently (i.e. for student support services) and agriculture uses considerably lower levels of ICT, plants from these industries are dropped from the panel. In addition, observations with zero employment and revenue are removed since the CiTDB cannot confirm if these zeros are true values or missing.[43] Finally the first year of the sample is dropped when conducting most of the estimation due to the use of lagged enablement and the local loop enablement interaction term.[44] After cleaning and merging the datasets, we are left with an unbalanced panel of 35,377 observations for 9,363 plants across six years, from 2000 to 2005.

It might be argued that the availability of ADSL and length of the local loop have greater explanatory power for smaller and/or single plant firms given the cost of alternative forms of broadband such as leased line.[45] To deal with these issues, in chapter two, all multi plant firms were dropped from the analysis. Ideally, one would like to do the same in chapter three, however while a multi plant variable exists within the CiTDB, the method in which the variable is constructed is not clear. The multi plant variable is therefore not used to remove firms from the sample in this chapter and we choose instead to include this as a control variable in the estimation.

[42] It is important to note that the length of the distance is one aspect which influences ADSL connection speeds. Others include width of the cable, the quality of the copper used in the cable and so on (as confirmed by David Cleevely and David Clarkson).
[43] Resulting in a loss of 21,650 observations
[44] Firm characteristics in 1999 are used however later on in the chapter in a robustness test for the instruments.
[45] The average monthly cost of leased line internet during this time was around $1,000 to $1,500 (Howstuffworks, 2000).

In terms of regional dispersion, Greater London and the South East represent the greatest proportion of plants at 30% over the time period. Next are the West Midlands, the North West and East with 12%, 11% and 10% of the plants, respectively. Yorkshire, the East Midlands and the South West each have 8% of plants whereas Scotland has 7% of firms. The region with the fewest plants is Northern Ireland with only 1%.[46] For the most part, the regional dispersions are quite similar from 2000 to 2005. In addition, these proportions are relatively close to those found in chapters one and two of the thesis suggesting that the regional coverage is relatively consistent between the ARD and the CITDB.

Table 43

Regional Dispersion from 2000 to 2005

Region	2000	2001	2002	2003	2004	2005	Total
Greater London & SE	28%	30%	31%	30%	29%	29%	30%
West Midlands	12%	12%	11%	11%	12%	12%	12%
North West	11%	10%	10%	11%	11%	11%	11%
East	10%	10%	10%	10%	9%	9%	10%
Yorkshire & Humberside	8%	8%	8%	8%	8%	8%	8%
East Midlands	9%	8%	8%	8%	8%	7%	8%
South West	8%	8%	8%	8%	8%	8%	8%
Scotland	7%	7%	7%	7%	7%	8%	7%
North East	3%	3%	3%	3%	3%	3%	3%
Wales	3%	3%	3%	3%	3%	4%	3%
Northern Ireland	1%	1%	1%	1%	1%	1%	1%

In terms of sectoral dispersion, most of the plants in the sample are Manufacturers representing roughly 60% of the sample. Next are services and wholesale, transport, and finance with 15%, 13%, 7% and 4% of the plants, respectively. Unlike the ARD, the CiTDB contains financial plants, which are left in since the performance measure in chapter three is labour productivity rather than TFP, which can be difficult to estimate and interpret for financial businesses (Bloom et al 2012). Total services represent around 40% of the sample. Similar to regional dispersion, the proportion of plants across sectors is relatively consistent overtime. However, unlike chapters one and two, the sample here contains a greater proportion of manufacturing firms 60% as opposed to 50%.

[46] Note that Northern Ireland was excluded from chapter two, due to firm level data availability issues.

Table 44

Sectoral Dispersion from 2000 to 2005

Sectors	2000	2001	2002	2003	2004	2005	Total
Manufacturing	63%	59%	59%	60%	62%	60%	60%
Services	14%	16%	16%	15%	15%	16%	15%
Wholesale Resale	12%	13%	13%	13%	12%	13%	13%
Transport and Public Utility	7%	8%	8%	7%	7%	8%	7%
Finance Insurance and Real Estate	3%	4%	4%	5%	3%	3%	4%
Services	37%	41%	41%	40%	38%	40%	40%
Manufacturing	63%	59%	59%	60%	62%	60%	60%

Descriptive Statistics

Plants within the data employ on average 230 workers where the median number of employees is 140. In terms of revenue, the mean value is $81 million USD and the median revenue is $4 million USD. In general the establishments here are larger than those found in chapter two. This is explained by the combination of the restriction to use single-plant firms only in chapter two and that the CiTDB tends to sample larger firms. With regards to IT usage, the average firm location has 151 personal computers. The majority of these are desktops, (mean of 132) and laptops (mean of 28). The mean plant has 0.80 PCs per employee with on average employees 10 IT employees of which 5 are programmers. The average plant however has 2, 3, and 4 Main-frame, Mid-range and AS400s, respectively. Moreover there is substantial variation in the usage of Direct Access Storage Device (DASD), where the mean plant employees 250 and the median establishment 50 during this time period.

It is important to note that within the CiTDB, observations with zero values for hardware and plant characteristics such as total PCs and employment can either represent a true zero or missing. Since the empirical estimation is done within a log linearized model, these observations are dropped automatically. However in order to represent a sample consistent with the analysis in Table 45, observations with zero values are dropped here as well, which accounts for roughly 4,600 observations. In addition, given the differences in sampling of technology overtime, not all variables are present in the CiTDB throughout the entire sample, as listed below. It is important to note, that the issue with zero values only pertains to hardware

technology, employment and revenue. For software, the zero values represent true zeros.

Table 45

Summary statistics of key variables, 2000-2005

Variables	Mean	Median	SD	Count	Sample Period
Employment	231	140	296	35,377	2000 to 2005
Revenue	81	4	14,580	35,377	2000 to 2005
Total PCs	151	64	303	35,302	2000 to 2005
Total Desktops	132	56	265	35,072	2000 to 2005
Total Laptops	28	10	74	25,795	2000 to 2005
Total Pentium	135	58	278	31,722	2000 to 2004
Total Pre-Pentium	34	10	102	17,343	2000 to 2004
PC Intensity	0.8	0.58	2	35,302	2000 to 2005
IT Employee	10	2	39	30,689	2000 to 2005
Programmers	5	1	20	13,246	2000 to 2005
Total Main Frames	2	1	4	720	2000 to 2004
Total Mid-range	3	1	28	11,303	2000 to 2004
Total AS400	2	1	2	5,539	2000 to 2004
Total DASD	270	50	2,979	14,769	2000 to 2005
Distance (km)	3.1	3	1.33	35,377	2000 to 2005

Note: Revenue is in US millions with base year of (2000).

From 2000 to 2005 the proportion of firms using software increased. For example, the percentage of firms using internal and external software rose from 5% to 24% and 29% to 87%, respectively. At the same time, there is heterogeneity in the usage of software found between the classifications of external and internal software. In 2005, 10% of firms used data management, 10% employed resource allocation software while only 3% used ERP software. For external communication software, the most widely used technology is web services. Surprisingly the proportion of plants investing in email services is lower than one would expect, however this is likely driven by firms obtaining email technology through open source online providers such as Hotmail. In addition, email services are available for free on most operating systems installed on PCs, negating the need to separately invest in this technology. During the sample period the proportion of plants using E-commerce software is flat at around 1% each year.

Table 46

Proportion of Software Adoption by Classification from 2000 to 2005

Software Type	2000	2001	2002	2003	2004	2005
Internal	5%	9%	12%	16%	20%	24%
Resource Allocation	2%	3%	5%	6%	8%	10%
Data Management	3%	5%	7%	10%	13%	15%
ERP	0%	1%	1%	2%	2%	3%
External	29%	59%	72%	81%	88%	87%
Web Services	27%	57%	71%	79%	87%	86%
Email Services	2%	3%	5%	6%	7%	6%
E-Commerce	1%	1%	1%	1%	1%	1%

During the sample period, plants also increased their intensity of hardware usage of most technologies. For example, PCs per employment increased from 0.68 in 2000 to 0.85 by 2005. Growth in technology intensity however is not homogeneous across all types of ICT over the years. In terms of specific types of PCs, desktops and Pentium PCs experienced a larger in the number of units per employee (0.59 to 0.74 and 0.54 to 0.84) than laptops and pre-Pentium PCs (0.13 to 0.18 and 0.18 to 0.20). This may imply that plants favour more fixed forms of computing and PCs with greater processing power. IT Employee and Programmer intensity is flat from 2000 to 2005. At the same time however, there was a substantial increase in the intensity of secondary storage devices, (DASD/employee) from 0.71 to 2.56.

Table 47

Hardware and IT Employee Intensity from 2000 to 2005

Software Type	2000	2001	2002	2003	2004	2005
Total PCs Intensity	0.68	0.77	0.82	0.90	0.90	0.85
Desktops Intensity	0.59	0.67	0.69	0.69	0.78	0.74
Laptops Intensity	0.13	0.14	0.19	0.17	0.17	0.18
Pentium Intensity	0.54	0.66	0.75	0.85	0.84	n.a.
Pre-Pentium Intensity	0.18	0.19	0.16	0.19	0.20	n.a.
IT Employee Intensity	0.05	0.04	0.04	0.04	0.04	0.04
Programmer Intensity	0.01	0.01	0.01	0.01	0.01	n.a.
DASD Intensity	0.71	0.96	1.56	2.39	2.56	n.a.
The following intensity measures for hardware are calculated as total technology type / total employee.						

Table 48 illustrates the year and region plants received access to ADSL infrastructure throughout the rollout period. In 1999, the start of the rollout, around 1% of the

sample was connected to an exchange that was enabled for ADSL. This increased substantially where in 2000, roughly 40% of the sample gained access to broadband infrastructure. By the end of wave one, 71% of plants within our sample were connected to an exchange that was enabled. Most of the plants in the sample that gained access to the ADSL infrastructure in wave two occurred in 2003 and 2004. For a majority of regions, the greatest year of enablement was 2000 with the exception of Wales and the East Midlands.

Table 48

ADSL Enablement by Region from 1999 to 2007

Year of Enablement	East	East Midlands	London & South East	North East	North West	Northern Ireland	Scotland	South West	Wales	West Midlands	Yorkshire & Humberside	Total
1999	10	0	0	48	235	0	89	0	49	106	0	537
2000	1,406	662	8,122	545	1,850	152	838	678	150	1,592	1,202	17,197
2001	801	1,187	946	223	599	117	120	587	64	970	303	5,917
2002	142	122	348	22	36	9	98	267	61	285	160	1,550
2003	477	559	541	69	796	100	631	659	374	562	813	5,581
2004	432	257	318	216	176	88	578	386	341	550	225	3,567
2005	115	42	208	8	97	1	137	120	51	90	141	1,010
2006	0	0	6	0	0	0	0	4	0	2	0	12
2007	0	0	6	0	0	0	0	0	0	0	0	6
Total	3,383	2,829	10,495	1,131	3,789	467	2,491	2,701	1,090	4,157	2,844	35,377

Variations in the length of the local loop are illustrated in Table 49. Since the *Point Topic* data attempts to calculate the local loop length as oppose to the straight distance between the firm and the exchange, the distances are longer than in chapter two. The average plant is connected to an exchange with a cable length of 3.1 kilometres while the median loop is 3 kilometres long. Roughly 75% of plants are connected to a cable longer than 2,000 meters. It is important to note that the 2,000 meter distance is not a sharp cut-off for connectivity deterioration as discussed earlier; firms for example connected by an older and/or thinner cable laid in less optimal terrain with different wear and tear may experience speed deterioration at shorter distances than longer thinker cable in optimal environments of relatively new condition.

Table 49

Local loop length from exchange	
Frequency	Kilometres
1%	0.7
5%	1.1
10%	1.4
25%	2.1
50%	3.0
75%	4.3
90%	5.0
95%	5.3
99%	5.9

Empirical Strategy

The results in chapter two suggest that ADSL availability incentivizes firms to invest in ICT. In particular, firms with ADSL access increased investment in hardware and software stock. However what is unclear from chapter two is what specific types of ICT firms were investing in. By exploiting the detailed nature of the CiTDB, this chapter looks to provide a more thorough understanding regarding the particular types of ICT faster internet speeds induce firms to use.

The first part of the methodological strategy will start by exploring the relationship between ADSL availability/local loop length and IT usage relying first on a standard

OLS estimation then later Logit estimation. The reason for using both OLS and Logit in the first two sections is determined by the nature of the CiTDB. Information on technology usage within the CiTDB, is provided either as a technology total for hardware and staff, (such as the numbers of PCs, and IT personnel) or an indicator for software (such as whether or not a plant is using an ERP application). Thus, for ICT listed as technology totals, OLS will be used and when ICT is listed as binary variables, Logit estimation is used.

OLS and Logit Estimation

Equation 1 examines whether the relationship between ICT and broadband infrastructure enablement and local loop length differs across various technology classes from 2000 to 2005 within an OLS framework.[47] Here ict_{it} represents the use of a specific form of technology in plant i at time t. $adsl_{i,t-1}$ signifies the lagged dummy variable representing ADSL availability, taking the value of 1, when a plant is connected to a telephone exchange that is enabled and 0 for the years before enablement, thus $adsl = 1$ in time $t-1$. $adsl_{i,t-1} * localloop$ is the interaction between the $adsl$ dummy and the local loop length of the cable running between the premise and the telephone exchange. As in chapter two, the analysis does not include exchanges which were enabled after wave one (after 2002) since installations were driven by local demand and thus likely to fail the exclusion restriction. Thus the instruments are set to missing for plants connected to an exchange that was enabled after wave one.

δ is a vector of control variables also believed to be correlated with ICT adoption. A disadvantage of using the CiTDB data is the limit it places on the number and types of controls that can be included. We control for size, measured by whether or not a plant is connected to a multi-plant firm, year, region (indicated by the 11 major geographic regions of the UK) and industry (2-digit sic classification). At this stage it has not proved possible to merge the CiTDB with the ARD that might provide additional control variables. All continuous variables within the model are log

[47] Unlike chapter two, the empirical strategy starts by extending the time period in include years 2003 to 2005 in order to exploit the entire dataset and to assess not just the potential short term but also medium term effect of the instruments. The robustness of this decision is later assessed in the second section of the empirical strategy where the time period is again restricted from 2000 to 2003.

linearized.[48] When the dependent variable is binary, a standard Logit model is used. Thus instead of assessing whether access to ADSL broadband results in greater ICT usage, the Logit model equations will examine the probability of ICT usage, when connected to an enabled exchange.

$$ict_{it} = \alpha_0 + \alpha_1 adsl_{i,t-1} + \alpha_2 adsl_{i,t-1} * localloop + \alpha_3 \delta + \varepsilon_{it} \quad (1)$$

Instrumental Variable Estimation

The final part of the methodological strategy revisits the key objective of the second chapter which is to examine the extent to which a causal relationship exists between ICT and firm performance. In this chapter we extend this to assess the specific digital technologies plants were induced to use as result of access to ADSL broadband.

The estimation procedure will be a *Two Stage Least Squares* framework as illustrated in Equation (2) and (3), where the parameter of interest α_1 represents the estimated effects of a distinct ICT technology on the outcome, labour productivity signified by lp_{it}. The instruments ADSL availability and the ADSL local loop interaction term are reflected by $adsl_{it}$ and $adsl_{it} * localloop$ and a vector of control variables consistent with Equation 1 is signified by:

$$lp_{it} = \alpha_0 + \alpha_1 ict_{it} + \alpha_2 \delta + \varepsilon_{it} \quad (2)$$

$$ict_{it} = \beta_0 + \beta_1 adsl_{it} + \beta_2 adsl_{it} * localloop + \beta_3 \delta + \gamma_{it} \quad (3)$$

The key requirements for a valid instrument are that they are correlated with the endogenous variable and that they fulfil the exclusion restrictions assumption i.e. the instruments are correlated with the dependent variable only through the endogenous variable. Testing the relevance of the instruments on the endogenous x variable can be done either within a standard regression framework, or in the first

[48] As mentioned in chapter two, a common panel procedure used to potentially control for endogeneity bias is to employ firm level fixed effects. In this case however it is not because the instruments lack sufficient time series variation and arguably the instrument which is most plausibly exogenous, firm distance from the telephone exchange is time invariant.

stage results of the IV estimation, both of which are assessed in this chapter. The exclusion restrictions assumption cannot be directly tested for since the error term is unobservable to the econometrician however a number of falsifications tests are used to assess the extent to which this assumption holds.[49] Assuming that the assumptions of instrument hold, the results in the second stage can be interpreted as the local average treatment effect.[50]

Empirical Analysis

The empirical section starts by examining the extent to which access to the ADSL infrastructure and local loop cable are relevant to ICT. Next, a number of tests are undertaken to assess the validity of the instruments. After which, the effects of the instruments are examined across a range of digital technologies. Finally, the potential causal links between ICT and labour productivity are analysed within an instrumental variable framework.

Instrument Justification

First Stage

Before examining the heterogeneous effects of enablement and ICT usage, it is important to start by assessing both the relevance of access to ADSL broadband and local loop length as appropriate instruments. The chapter does this by first examining the relationship between the instruments and a general form of ICT, in this case totals PCs within an establishment.[51] The second step is then to ensure that our instruments are valid and that the instruments explain the variation in ICT usage and not some other unseen factor. This is tested by assessing whether other exchange level characteristics are driving differences in PC usage and if the timing of enablement and distance are correlated with ex-ante firm characteristics and PC usage.

[49] These will be assessed in more detail in the empirical section.
[50] For the estimation, the STATA command ivreg2 is used along with the robust and cluster commands to ensure robust statistics when heteroscedasticity and intra-group correlation exists.
[51] Total PCs represents the sum of all forms of PCs used within the plant, including desktops and laptops

The results within Table 50 assess the relationship between the instruments and total PC use where control variables listed within the table are incrementally added. Total PCs is positively correlated to ADSL enablement whereas the local loop interaction term is negatively related, consistent with the results found in chapter two. The signs and significance of the two parameters of interest remain significant at the 1% and 5% level after controlling for firm characteristics, time, regions and sectoral variation. Using model 6 as a baseline, we find that firms that have access to the ADSL infrastructure at a mean distance (3.1 kilometres) uses 0.8% more ICT than those who are not connected to an enabled exchange.[52] Moreover, the parameters of interest are quite stable after Model 2. As expected, the relationship between plants connected to a multi-plant firm and total PC usage is positive and significantly correlated at the 1% level in all models in which the variable is included.

Table 50

Effects of Enablement and Loop distance on Total PCs with Various Controls, 2000-2005

Dependent variable: Total PCs	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ADSL Enablement	0.832***	0.328***	0.295***	0.338***	0.286***	0.230**
	(0.05)	(0.11)	(0.10)	(0.11)	(0.11)	(0.10)
ADSL*Loop	-0.644***	-0.211**	-0.212**	-0.219**	-0.204**	-0.196**
	(0.04)	(0.09)	(0.09)	(0.09)	(0.09)	(0.08)
Distance		-0.432***	-0.417***	-0.407***	-0.234***	0.025
		(0.08)	(0.08)	(0.08)	(0.08)	(0.08)
Multi Plant			0.378***	0.378***	0.365***	0.353***
			(0.02)	(0.02)	(0.02)	(0.02)
Control Variables						
Year				✓	✓	✓
Region					✓	✓
2 digit sector						✓
R-squared	0.013	0.014	0.033	0.033	0.047	0.138
Observations	24,953	24,953	24,953	24,953	24,953	24,829

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

[52] The mean firm is 3.1 km from their telephone exchange. The 0.8% effect for the mean firm is calculated in the following manner $0.8\% = \exp(0.230 - 0.196 * \ln(3.1)) - 1$.

Instrument Validity

The results in Table 50 suggest that firms attached to enabled exchanges use more PCs. However, it is important to assess the robustness of the instrument before examining their effects on other forms of ICT. In particular, does the model fulfil the exclusion restriction assumption i.e. that the instruments only influence the outcome of the firm through the endogenous x variable (Angrist and Pischke 2009). Threats to the potential validity of the instrument are: an omitted variable related to the timing of enablement which also leads to greater ICT usage; the timing of the rollout is determined by firm performance such as employment or sales; the timing of enablement coincides with another factor which explains an increased use of ICT. In addition, although the results reflect the expected negative correlation between the length of the local loop and ICT, such differences may be explained by agglomeration economies (No 2008), as opposed to slower internet speeds.

Although ADSL enablement and firm distance from the exchange may be robust instruments for ICT usage, the results found in Table 50 may be influenced by other factors not included in the model. For example, there may be local characteristics in proximity to the exchange itself which may be correlated with ICT usage. The ADSL dataset includes some information on exchange level characteristics such as the size of the exchange, defined by the number of businesses and households attached to an exchange. Larger exchanges may exhibit some potential agglomeration effects therefore both the number of businesses and households connected to the exchange are added as control variables. Moreover, the local economic climate pertaining to the area close to the exchange, such as local unemployment may also influence ICT usage and is therefore also included as a control variable.[53]

The results within Table 51 use Model 6 in Table 50 as a baseline and incrementally add local unemployment (which refers to the proportion of unemployed in the ward where the telephone exchange resides) and the number of businesses and the number of households connected to the exchange (number of each entity connected to the respected telephone exchange). Total PC usage does not appear to be strongly influenced by the additional exchange level characteristics included. When comparing the size and significance of enablement and relative speed between

[53] Ward level unemployment data comes from Eurostat (2000).

Model 6 in Table 50 and model 4 in Table 51 we find quite similar results. The number of businesses and households attached to an exchange do not robustly explain PC usage alleviating some concerns regarding potential agglomeration economies. The economic prosperity of a local region proxied by the unemployment rate is negatively correlated with total PC usage suggesting that firms in more impoverished areas tend to employ less ICT. Again however this does not explain the correlation between ADSL enablement and cable distance.

Table 51

Effects of Enablement Total PCs with Exchange level Controls, 2000-2005

Dependent Variable: Total PCs	Model 1	Model 2	Model 3	Model 4
ADSL Enablement	0.230**	0.237**	0.223**	0.224**
	(0.10)	(0.10)	(0.11)	(0.11)
ADSL*Loop	-0.196**	-0.195**	-0.190**	-0.195**
	(0.08)	(0.09)	(0.09)	(0.09)
Distance	0.025	-0.017	-0.006	-0.061
	(0.08)	(0.08)	(0.08)	(0.09)
Multi Plant	0.353***	0.356***	0.356***	0.356***
	(0.02)	(0.02)	(0.02)	(0.02)
Unemployment		-0.069***	-0.076***	-0.083***
		(0.02)	(0.02)	(0.02)
Number of Businesses			0.024*	0.010
			(0.01)	(0.02)
Number of Houses				0.031
				(0.02)
Control Variables				
Year	✓	✓	✓	✓
Region	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓
R-squared	0.138	0.139	0.139	0.139
Observations	24,829	24,325	24,325	24,325

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Another potential threat to the validity of the instruments is if firms connected to exchanges that were enabled in wave one and those with shorter cable distances possess some unobservable firm characteristics that led them to be enabled earlier or be located closer to these exchanges. The standard method to deal with time invariant firm characteristics would be to add firm fixed effects. The time invariant nature of the cable distance instrument prevents this. If these are persistent

characteristics then one could expected a potential correlation between enablement and pre-ADSL characteristics.

In order to assess this, we examine the extent to which the timing of enablement in wave one is correlated with ex ante firm performance including sales and employment.[54] A positive and significant relationship between being enabled in wave one and ex-ante revenue and employment would suggest potential endogeneity in the rollout of ADSL in the first wave.

The results in Table 52 estimate the relationship between ex ante (1999) employment and revenue and different times of enablement during wave one (including, those connected to exchanges enabled in 2000 and exchanges enabled in 2001-2002). The results here do not directly suggest that BT first targeted exchanges which were connected to plants with greater sales or employment, similarly found in chapter two. In fact 1999 employment of firms enabled in 2000 is negatively correlated, suggesting that if anything firms attached to enabled exchanges in year 2000 were smaller in 1999 compared to those attached to exchanges later in wave one. At the same time, there is no correlation between being enabled in 2000 and revenue in 1999. Moreover, the relationship between being attached to an enabled exchange in 2001-2002 and employment and revenue is not statistically significant suggesting that the timing of enablement is not consistently correlated with ex-ante firm characteristics. From this we conclude that persistent unobserved firm effects that are correlated with the instrument and firm performance do not appear to be present.

[54] It is important to note that ADSL enablement began at the end of 1999 with the enablement of 15 exchanged. However, since, the CiTDB begins in 1999 it is not possible to explore the relationship with ex- ante firm characteristics (1998) and those that were enabled in 1999.

Table 52

Relationship between time of enablement in Wave One and Ex Ante (1999) Plant Employment and Revenue

Variables	2000	2001-2002	2000	2001-2002
Employment in 1999	-0.111***	0.045		
	(0.03)	(0.04)		
Sales in 1999			0.022	0.037
			(0.05)	(0.05)
Distance	0.055	0.047	-0.098	-0.094
	(0.09)	(0.09)	(0.13)	(0.14)
Control Variables				
2 digit sector	✓	✓	✓	✓
Region	✓	✓	✓	✓
R-squared	0.0900	0.0800	0.1100	0.1100
Observations	4,364	4,364	4,364	4,364

Note: The enablement variables refer to dummy variables which equal 1 for the said year or time period of enablement and zero otherwise. Models do not include multi plant covariate as this variable was not present in the CiTDB in 1999. All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Another potential threat to the validity of the instruments would be if there was an anticipation effect and firms began upgrading their ICT usage prior to the enablement of their exchange. Given the historical context it does not appear easy for firms to have anticipated when their exchange was going to be enabled. For example as noted in chapter two, ADSL enablement began in July 1999 however in February of that year, BT still had not issued a press release of any plans for broadband service (BBC 1999a). Moreover even when announcements were made as to when a certain region was to be enabled it was not explicit when broadband services would commence, since BT insisted on using its own engineers for line modification and equipment installation (BBC 1999a). However, one of the ways this can be tested is to assess the correlation between the timing of enablement and ex-ante ICT usage. If for example, an exchange which is enabled in 2000 is positively correlated with PC usage prior to enablement the validity of the instrument may be suspect.

Table 53 presents the results regarding the correlation between ex-ante (in 1999) ICT use and enablement at different times of the wave one rollout (2000, 2001-2002, anytime in wave one and anytime in wave two). We do not find evidence of a significant correlation between enablement and ex ante plant PC usage. The results

in the first two models are particularly important as they suggest that the effect of being connected to an exchange that is enabled in wave one on ICT is significant only after the date of enablement. This strongly suggests that the results found in the baseline estimation are driven by the rollout of ADSL in a way that is expected. The results also imply that either being attached to an enabled exchange during wave one or wave two is not correlated with plant level PCs usage in 1999. However, given the change in the rollout procedure between wave one and two as discussed in the second chapter, this chapter only focuses on firms connected to exchanges that were enabled in wave one.

Table 53

Relationship between timing of Enablement and Ex Ante (1999) ICT Usage

Variables: Total PCs	1999	1999	1999	1999
Enabled in 2000	-0.016			
	(0.04)			
Enabled in 2001 to 2002		0.012		
		(0.04)		
Enabled in Wave One			-0.007	
			(0.04)	
Enabled in Wave Two				-0.051
				(0.04)
Distance	-0.035	-0.036	-0.036	-0.039
	(0.10)	(0.10)	(0.10)	(0.10)
Control Variables				
2 digit sector	✓	✓	✓	✓
Region	✓	✓	✓	✓
R-squared	0.116	0.116	0.116	0.116
Observations	4,354	4,354	4,354	4,354

Note: The enablement variables refer to dummy variables which equal 1 for the said date and period of enablement and zero otherwise. The multi plant control is not included as this variable was not present in the CiTDB in that year. All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

One possible reason as to why we find a negative correlation between the loop length and PC usage within the baseline result may actually be explained by agglomeration economies rather than the relative speed of the available broadband. The literature suggests that urbanization and regionalization may influence technology adoption and knowledge diffusion (Kelley and Helper 1999 & No 2008). Given the fixed capacity of a telephone exchange, agglomeration may help to predict

short local loops and ICT use. Thus firms located close to the exchange may reside closer to urban centres or clusters of firms inducing ICT usage.

Table 54 assesses the validity of the second instrument by repeating the estimation method used in Table 53 however now the explanatory variable is the length of the local loop. The estimates here assess the relationship between ex ante ICT use (in the year 1999) with the local loop length of firms enabled in years within wave one and wave two (in particular: 2000, 2001 and 2002, all of wave one and all of wave two). The results in Table 54 do not provide consistent evidence of agglomeration effects when assessing the relationship of local loop distance and ex-ante total PC usage. For the first model, relationship between loop length and those attached to an exchange enabled in 2000 is negative and significant at the 10% level. However for those enabled in 2001 to 2002, the results are insignificant. There is no significant relationship between loop length and total PC usage in 1999 for those enabled in wave one. Furthermore, there is a positive and significant relationship between loop length and being enabled in wave two. Although the first regression finds a weak negative relationship between the cable length of firms attached to exchanges in 2000 and total PC usage in 1999, overall the results do not consistently suggest that the negative relationship we find for firm distance from the exchange and total PC usage considerably driven by an agglomeration economy effect.

Table 54

The relationship between the loop length of exchange enabled at different times and Ex Ante (1999) Total PC Usage

Variables: Total PCs	1999	1999	1999	1999
Loop: Enabled in 2000	-0.271*			
	(0.15)			
Loop: Enabled in 2001 to 2002		0.409		
		(0.28)		
Loop: Enabled in Wave One			-0.175	
			(0.13)	
Loop Enabled in Wave Two				0.367**
				(0.18)
Control Variables				
2 digit sector	✓	✓	✓	✓
Region	✓	✓	✓	✓
R-squared	0.128	0.164	0.119	0.127
Observations	2,011	1,001	3,012	1,289

Note: Distance represents the local loop length of the cable between the establishment and the exchange box for those connected to exchanges in the stated years. Distance is therefore not interacted with the enablement dummy. Models for year 1999 do not include multi plant as this variable was not present in the CiTDB in that year. All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Main Results

Heterogeneous Effects of ADSL Enablement on ICT Usage

Having undertaken a number of robustness tests which suggest that broadband enablement and the local loop length appear to be relevant and valid instruments, the empirical section will next assess whether the effects of the instruments are heterogeneous across a range of technologies, including various PCs, IT personnel, equipment/computing, external communication software and internal communication software.

Personal Computers

The following table assesses the effects of enablement and cable length on Pentium, non-Pentium, desktops, laptops and PC intensity (total PCs/employees) and Pentium intensity (total Pentiums/employees) usage. The control variables included in these models include distance, multi-plant, year, region and 2-digit sector, consistent with

Model 6 in Table 50. In terms of Pentiums and non-Pentiums, the results suggest that access to ADSL is correlated with greater Pentium usage but not for non-Pentium usage. The results suggest that access to ADSL may have led to greater ICT usage due to technology upgrade requirements. However, while the coefficient for Pentiums is positive and significant the results imply that having access to ADSL with an average local loop distance impacts Pentium usage by close to zero percent.

When examining the effects of enablement on both fixed and mobile PCs, the estimation finds that ADSL availability relates to greater desktop usage where cable distance results in less, both of which are significant at the 5% level of significance. The two instruments however do not exhibit statistically significant explanatory power on the usage of laptops. Therefore enablement appears to have induced greater use of more fixed forms of hardware as opposed to mobile forms like laptops. Finally, the estimation finds that access to more advanced telecommunication does not significantly correlate with greater numbers of PC intensity and Pentium intensity, implying that although, firms connected to enabled exchanges use PCs more than those connected to non-enabled exchanges it does not appear that this has lead them to use PCs more intensively. For all types of PCs, multi-plant firms appear to use these technologies more than single plants.

Table 55

Effects of Enablement and Local Loop Length on Personal Computer Usage, 2000-2005

Variables	Total PCs	Pentium	non-Pentium	Desktop	Laptop	PC Intensity	Pentium Intensity
ADSL Enablement	0.230**	0.221**	0.117	0.270**	0.167	-0.004	0.029
	(0.10)	(0.10)	(0.14)	(0.11)	(0.15)	(0.07)	(0.08)
ADSL*Loop	-0.196**	-0.196**	-0.048	-0.253***	-0.094	0.074	0.023
	(0.08)	(0.08)	(0.11)	(0.09)	(0.12)	(0.06)	(0.07)
Distance	0.025	0.043	0.061	0.069	0.149	-0.288***	-0.252***
	(0.08)	(0.08)	(0.11)	(0.09)	(0.11)	(0.05)	(0.06)
Multi Plant	0.353***	0.330***	0.315***	0.378***	0.214***	0.204***	0.225***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.01)	(0.01)
Control Variables							
Year	✓	✓	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓	✓	✓
R-squared	0.138	0.132	0.110	0.129	0.091	0.194	0.173
Observations	24,829	24,658	18,040	22,342	12,224	24,829	22,342

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

The rollout of ADSL broadband, in effect was an upgrade to the telecommunication infrastructure of the UK. Thus when an exchange box became activated, it allowed firms access to a superior form of external communication technology which likely induced investment in ICT that is compatible to broadband but potentially not for other forms of IT. In terms of PC use, faster internet speeds may have required consumers to invest in new PCs, with greater memory and processing capabilities. For example, BT suggests basic requirements for ADSL including PCs with a Pentium processor or faster with at least 150 MB of hard disk, a CD ROM, at least Windows 98 SE/ME and so on (BT 2015).

In addition, many PCs in the late 1990s early 2000s could not be simply connect to broadband but needed an Ethernet network adaptor, which required consumers to take their machines to a computer technician for the installation. As a result the mood during this time as suggested by Mark Vena from Compaq was “typically, people don't want to go through the hassle of taking an existing PC and adding the devices to it to make it broadband compatible, so they're buying new PCs with broadband connections on them”, such machines began coming onto the market during this time (CNN 2001).

The results in Table 55 which find that ADSL enablement and local loop are significantly correlated with total PC, desktops and Pentium PCs appear to be consistent with the idea that access to the ADSL infrastructure induced usage of certain types of PCs due to technical requirements. Moreover, the lack of a significant correlation between the instruments and non-Pentium PC provides some additional support of a likely technical upgrade mechanism through which ADSL access relates to investment in some kinds of PCs but not others.

In addition, it appears that broadband enablement led to differences in the use of PCs depending on their function such as in this case desktops and not laptops. Both desktops and laptops are a combination of hardware and basic operating software. However one difference is that desktops are a more fixed form of hardware whereas laptops are designed for mobility. One could assume that access to broadband as opposed to dialup may enable employees to carry out more complex tasks at home and elsewhere (Bauer et al 2002) and thus lead to greater laptop use. However during this time laptops with comparative performance capabilities to desktops were substantially more expensive given their size, weight, and space needed for a battery.

For example, the cost of a laptop with the minimal requirements for ADSL during this period was roughly $2,000 (PC Magazine 2010) which is substantially more expensive than the average cost of desktop around $846 (CNN 2001).

ICT Personnel

Given that access to broadband appears to result in greater numbers of total PCs, desktops and Pentium computers, this may also lead to an increase in the need for IT employees in order to install, maintain and organize the IT infrastructure of the plant. The next step of the empirical section examines the extent to which ADSL access at relative speeds is correlated with the numbers of general IT employees, programmers as well as IT employee and programmer intensity (IT employees per total employment and programmers per total employment) and the intensity of programmers out of IT staff (programmers per IT employees). Similar to the assessment on PCs, we look to assess whether the instruments affect both use and intensity.

The first model in Table 56 implies that the rollout of broadband and the local loop length are significantly correlated with the number of IT employees. In particular, being attached to a broadband enabled exchange at the average local loop length lead to roughly a 5% increase in IT employees. However, firms attached to enabled exchanges do not have higher IT employee intensity than those connected to a non-enabled exchange. Having access to ADSL to some extent may result in greater programmers however the coefficient for enablement is at the 10% level of significance. Moreover, the loop length interaction terms has no statistical effect on the number of programmers. Also, the two instruments exhibit no significant explanatory power on programmer intensity and programmer to IT employee intensity. The variable however which most consistently explains IT personnel use, IT intensity and programmers (aside from programmer intensity and programmer IT intensity) is multi-plant.

Table 56

Effects of Enablement and Local Loop Length on ICT Personnel, 2000-2005

Variables	IT Employees	IT Employee Intensity	Programmers	Programmer Intensity	Programmer IT Employee Intensity
ADSL Enablement	0.306***	0.129	0.265*	0.237	-0.220
	(0.11)	(0.10)	(0.16)	(0.16)	(0.28)
ADSL*Loop	-0.230**	0.007	-0.136	-0.016	0.219
	(0.09)	(0.08)	(0.13)	(0.13)	(0.23)
Distance	0.199**	-0.039	0.221*	0.161	-0.135
	(0.09)	(0.08)	(0.12)	(0.12)	(0.22)
Multi Plant	0.311***	0.179***	0.110***	-0.024	-0.158***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Control Variables					
Year	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓
R-squared	0.151	0.160	0.160	0.170	0.088
Observations	21,544	21,544	9,522	9,522	7,649

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Computing Equipment and Storage

The next step of the empirical analysis examines whether or not ADSL enablement and plant distance from the exchange is correlated with information processing and storage hardware. In particular, this section focuses on main frame computers, midrange computers (typically used as servers) and direct access storage devices (DASDs) measured by gigabytes of storage space. Unlike PCs these technologies, aside for DASDs tend to be used to process information.

For example, main frame computers are typically used by institutions that require substantially larger processing power in order to process very large flows of data (mainframes360.com 2015). Main frames tend to be used by highly profitable larger firms. For example around this sample period, IBMs more economical main frame models cost roughly $100,000 (New York Times, 2006). Midrange computers, offer substantially more processing power than a standard computer but less than a main frame computer and are usually used as network servers (WiseGeek 2015).The general function of mid-range computers is to share information either with other computers or itself. Examples of this include enabling files and folders to be shared within a department, host web based applications, and importantly provide

computing resources either as a location to store files or a central location for additional processing power (PC Mag 2015).[55] Given that these technologies tend to focus on the internal processing of data within the firm, a communication technology such as ADSL may not be complementary.

In addition to computing equipment, the CiTDB provides information on DASDs, a technology originally developed by IBM in the 1970s. The DASD allows users to store information under a specific location i.e. "unique address". This allows the user to access the saved information directly negating extensive searching, a requirement for alternative technologies (IBM 1975). Unlike information processing technology, access to ADSL may influence increased used of DASDs due to greater contact with external information and a need to more effectively save and access files.

The results in Table 57 find no statistically significant relationship between enablement and local loop length on information processing hardware. Neither main frames nor mid-range computers are significantly related with any of the instruments. In terms of mid-range computers (including AS400s), the estimation finds no statistical evidences of a correlation with access to broadband and relative internet speed. Therefore the instruments appear to be less relevant to information processing technology.

There does however appear to be evidence that ADSL enablement leads to greater use of external storage devices, whereas the length of the local loop appears to be less important as an explanatory variable. Unlike information processing hardware, access to broadband as opposed to dialup internet enhances a firm's ability to access external information requiring additional storage space to collate the data and increased use of DASD.

[55] Since CiTDB contains information on both general mid-range computers and a particular mid-range brand produced by IBM during this time called the AS400, both classifications are assessed below.

Table 57

Effects of Enablement and Local Loop Length on Computing/Storage, 2000-2005

Variables	Main Frame	Mid-Range	AS400	DASD
ADSL Enablement	-0.099	0.077	-0.010	0.437**
	(0.23)	(0.11)	(0.12)	(0.22)
ADSL*Loop	0.085	-0.086	-0.004	-0.352*
	(0.18)	(0.10)	(0.10)	(0.18)
Distance	0.449**	0.190**	0.239**	0.511***
	(0.19)	(0.09)	(0.10)	(0.17)
Multi Plant	-0.092*	0.047***	0.035**	0.248***
	(0.05)	(0.02)	(0.02)	(0.03)
Control Variables				
Year	✓	✓	✓	✓
Region	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓
R-squared	0.176	0.092	0.161	0.164
Observations	575	7,953	4,011	10,393

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

ADSL Enablement and Software Usage: Logit Estimation

After examining the effects of broadband enablement on various types of PCs, IT personnel and computing the next step will be to explore the extent to which the instruments relate to the use of software. Unlike the previous session where the dependent variable was a continuous variable, here due to the sampling method of the CiTDB, software is signified by a dummy (0, 1) yes or no response. For this analysis a logit model will be used.

In the analysis below, software technologies are categorized into two groups based on their function, *internal communication* and *external communication* software. *Internal communication* software refers to technology that predominately allows for the transfer and allocation of information and resources within the firm. This includes ERP technology, resource management, human resource management, accounting management and data storage/management software. *External communication* software, on the other hand, refers to software which enables plants to communicate externally including web related software, E-commerce, customer resource management, and Email applications.

Given that ADSL represents an advanced form of external communication, one would expect a significant relationship between broadband and other external communicating software such as E-commerce, electronic mail and website programs. In fact, a prerequisite for firms to effectively use such forms of software is a reliable broadband connection (WTO 2013). The importance of broadband for more internal facing technologies like ERPs, data management services is in comparison, less obvious. Broadband requirements of these technologies depend on how firms use such applications (Fresca 2010) including the number of users, the amount of data per dialog steps, the average number of dialog steps per minute and so on (Toolbox 2005). Thus small numbers of users may not need fast broadband whereas larger firms are likely to require greater bandwidth as well as faster upload and download speeds.

Despite the initial assumption that the availability of ADSL leads to increased probability of usage in external communication software given the compatibility of the technology, the results in Table 58 provide no evidence of this. For the aggregate measure, External software, as well as Web applications and E-commerce, the instruments lack adequate explanatory power. The only variable in the models which are correlated with a software technology is multi-plant, where plants attached to a multi-plant firm are more likely to use external and web software , but less likely to use E-commerce software. The explanation for a negative coefficient for E-commerce are at best speculative but may suggest that firms rely on more complex software that sync sales and production in a signal program such as ERPs.

For Email software, the enablement variable is negative and significant suggesting that attached to an ADSL enabled exchange results in less usage of Email programs. One of the difficulties of assessing email software is that such programs are available for free online and therefore may not be accurately present in the data. From the sample statistics we see that use of email software is one of the lowest proportions out of all other forms of software. Sillince et al (1998) however finds that even in the mid to late 1990s roughly 25% of firms sampled in the North East of the UK had adopted email. This suggests that the CiTDB may underestimate the number of plants using email technology.

Table 58

Effects of Enablement and Local Loop Length on External Communication Software, 2000-2005

Variables	External Software	Web Services	E-Commerce	Email
ADSL Enablement	-0.311	-0.270	-1.131	-0.857*
	(0.20)	(0.20)	(1.23)	(0.51)
ADSL*Loop	0.209	0.179	0.915	0.670
	(0.16)	(0.16)	(1.01)	(0.41)
Distance	-0.048	-0.010	0.036	-0.707*
	(0.15)	(0.15)	(0.92)	(0.40)
Multi Plant	0.670***	0.683***	-0.450***	0.066
	(0.03)	(0.03)	(0.17)	(0.07)
Control Variables				
Year	✓	✓	✓	✓
Region	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓
Observations	24,829	24,829	18,043	24,518

Note: External software refers whether a plant is using any one or more of the listed types of software. All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Table 59 contains estimates regarding the relationship between the instruments and internal communication software. Similar to external communication software, the relevance of the instrument to internal communication software also appears to be inconclusive. While the analysis finds expected signs of the instruments for internal software and Resource allocation neither of them are significantly correlated. Data management software is also insignificant and has the reverse relationship with the instruments. The estimation does provide some evidence of a potential link between enablement and ERP software, where enablement is significant at the 10% level and the distance interaction, significant at the 5%. The standard errors are however somewhat larger in comparison to the other regressions implying some weakness in the precision of the estimated model for ERP software.

Table 59

Effects of Enablement and Local Loop Length on Internal Communication Software, 2000-2005

Variables	Internal Software	Resource Allocation	Data Management	ERPs
ADSL Enablement	0.056	0.410	-0.119	2.387*
	(0.37)	(0.56)	(0.46)	(1.25)
ADSL*Loop	-0.102	-0.49	0.114	-2.087**
	(0.30)	(0.45)	(0.37)	(1.00)
Distance	0.254	0.913**	-0.12	2.902***
	(0.29)	(0.44)	(0.37)	(0.96)
Multi Plant	0.106***	0.100	0.069	0.102
	(0.04)	(0.06)	(0.05)	(0.13)
Control Variables				
Year	✓	✓	✓	✓
Region	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓
Observations	24,829	24,356	24,762	21,849

Note: Internal software refers whether a plant is using any one or more of the listed types of software. All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

It should be noted that assessing the effects of enablement on software usage faces several challenges due to the nature of the technology. Firstly, a number of software do not need to be purchased but are available free online, known as open sources software. One could expect a plant to use high quality open sourced technology when available. In fact, businesses are beginning to rely more on Linux software as opposed to traditional providers like Microsoft (PC World, 2011). Secondly, a substantial proportion of software used by firms is not just purchased or available free online, but developed in house. For example, in chapter one of the thesis some of the software used by firms is produced internally. Both of these issues highlight the possibility that the dataset may potentially underestimate the whole amount of software used within our sample.

Contemporaneous Enablement and Sample Restriction

The previous section provides preliminary evidence regarding the effects of enablement and relative internet speed across a range of ICT. In some ways, the results are consistent with what was found in chapter two, in that ADSL enablement is positively correlated with certain measures of ICT and the cable loop interaction term is negatively related. In addition, both instruments appear valid. Despite this

however, the explanatory power of the instruments in this chapter appear weaker than in chapter two. For example, for models in which the instruments are significantly correlated there is never an instance where the level of significance is at the 1% level for both instruments. In fact, only the relationship between desktops and the instruments, found in Table 55 does at least one of the instruments relate at the 1% level of significance. This indicates that the instruments are likely to be weak within an IV framework.

In this section we consider the importance of the assumption that the effects of the instrument occur with a lag. In cases where the requirement to use ADSL necessitates either equipment upgrades or complete equipment replacement (as was the case for certain types of PCs), one may expect a stronger contemporaneous effect. The length of the time period of the analysis may also reduce the strength of the instruments, if for example the effects occur in the short term. In the above analysis we pool the data across 2000 to 2005. The data period therefore extends three years beyond the date in which the last exchange is enabled in wave one. This potentially weakens the power of the instruments.

Below we consider the instruments both in contemporaneous and lagged form, and restrict the sample period to 2000 to 2003. The lagged instruments now capture whether there was a different effect in ICT use in the period after enablement occurred. The results in Table 60 suggest that the explanatory power of the instruments are stronger contemporaneously, implying the effect of enablement and firm distance from the exchange appears more likely to occur in the year of enablement rather than in the subsequent year. For total PCs, desktops, laptops and Pentium PCs and Pentium intensity, both instruments exhibit the expected signs and are at the 1% level of significance.

Moreover the sizes of the effects are substantially larger than in those in Table 55. For example, the estimates suggest that being connected to an exchange for mean firm loop length results an in increase in total PCs by 6% as opposed to 0.8%. Similarly for desktops and Pentiums, the combined effect of the instruments (with the mean loop length) is now 5% and 6%, respectively. In particular, the instruments appear to be most relevant to laptops where being connected to the enabled infrastructure leads to an increase in laptop and Pentium use by 10%. As for Pentium intensity, the results suggest an 11.4% increase in Pentiums per employee of firms

connected to the ADSL infrastructure for firms at the mean local loop distance. In terms of the control variables, the multi plant variable is positive and significant similar to the previous results.

Table 60

Effects of Enablement and Local Loop Length on Personal Computer Usage, 2000-2003

Variables	Total PCs	Desktop	Laptop	Pentium	non-Pentium	PC Intensity	Pentium Intensity
ADSL_t	0.955***	0.862***	1.241***	1.267***	0.290	0.320*	0.659***
	(0.26)	(0.26)	(0.35)	(0.29)	(0.36)	(0.19)	(0.23)
$\mathrm{Loop} * \mathrm{ADSL}_t$	-0.796***	-0.722***	-1.007***	-1.069***	-0.242	-0.189	-0.487**
	(0.21)	(0.21)	(0.29)	(0.24)	(0.30)	(0.16)	(0.19)
ADSL_{t-1}	0.134	0.137	-0.008	0.129	0.208	0.011	-0.004
	(0.12)	(0.12)	(0.15)	(0.13)	(0.16)	(0.08)	(0.09)
$\mathrm{Loop} * \mathrm{ADSL}_{t-1}$	-0.113	-0.122	0.05	-0.131	-0.122	0.046	0.038
	(0.10)	(0.10)	(0.13)	(0.10)	(0.14)	(0.06)	(0.08)
Distance	0.689***	0.646***	0.930***	0.984***	0.298	-0.115	0.191
	(0.19)	(0.19)	(0.26)	(0.22)	(0.28)	(0.15)	(0.18)
Multi Plant	0.348***	0.328***	0.318***	0.374***	0.207***	0.210***	0.238***
	(0.02)	(0.02)	(0.03)	(0.02)	(0.03)	(0.02)	(0.02)
Control Variables							
Year	✓	✓	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓	✓	✓
R-squared	0.141	0.133	0.115	0.124	0.086	0.218	0.172
Observations	14,715	14,667	10,466	14,335	9,246	14,715	14,335

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

In terms of IT employees, the contemporaneous instruments have the expected signs and are significant at the 5% level. As for the lagged instruments only enablement is significant and at the 10% level with IT employees. In Table 56, the relationship between IT employees is somewhat stronger with enablement and cable distance being significantly different from zero at 1% and 5% levels of significances, respectively. However, now the combined effect of the instruments is stronger. For example, plant access to ADSL with an average cable length results in a 9% increase in IT employees as opposed to 5% found in Table 56. This may suggest that the explanatory power of the instruments is greater contemporaneously. Similar to Table 56, the instruments (contemporaneous or lagged) are not robustly correlated with IT employee intensity, the number of programmers, programmer intensity and programmer IT employee intensity.

Table 61

Effects of Enablement and Local Loop Length on ICT Personnel, 2000-2003

Variables	IT Employees	IT Employee Intensity	Programmers	Programmer Intensity	Programmer IT Employee Intensity
ADSL_t	0.538**	0.045	0.156	-0.317	0.770
	(0.24)	(0.24)	(0.30)	(0.36)	(0.67)
$\mathrm{Loop} * \mathrm{ADSL}_t$	-0.398**	0.078	-0.026	0.406	-0.631
	(0.20)	(0.20)	(0.25)	(0.30)	(0.55)
ADSL_{t-1}	0.243*	0.123	0.241	0.304*	-0.388
	(0.13)	(0.11)	(0.18)	(0.18)	(0.32)
$\mathrm{Loop} * \mathrm{ADSL}_{t-1}$	-0.175	0.000	-0.119	-0.086	0.355
	(0.11)	(0.09)	(0.15)	(0.15)	(0.26)
Distance	0.521***	-0.091	0.247	-0.176	0.358
	(0.17)	(0.18)	(0.21)	(0.26)	(0.49)
Multi Plant	0.276***	0.163***	0.077***	-0.036	-0.129***
	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)
Control Variables					
Year	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓
R-squared	0.132	0.160	0.154	0.176	0.090
Observations	12,573	12,573	6,074	6,074	4,221

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

Table 62 presents the results for computing and equipment. The instruments either contemporaneous or lagged are not significantly correlated with main frames, mid-

range computers or AS400s. In fact for main frame computers, the sign of the enablement coefficient is negative albeit insignificant. The results do however suggest that the effects of enablement and cable distance on DASD occur only with a lag. Here the result for storage is consistent with what was found in Table 57, however now the magnitudinal effect appears to be larger (an 8% increase) and the significance of the instruments are both at the 5% level.

Table 62

Effects of Enablement and Local Loop Length on Computing and Storage, 2000-2003

Variables	Main Frame	Mid-Range	AS400	DASD
ADSL_t	-0.116	0.263	0.255	0.584
	(0.43)	(0.36)	(0.31)	(0.92)
$\mathrm{Loop} * \mathrm{ADSL}_t$	0.139	-0.217	-0.224	-0.43
	(0.36)	(0.31)	(0.26)	(0.77)
ADSL_{t-1}	0.041	0.01	-0.09	1.128**
	(0.27)	(0.12)	(0.14)	(0.51)
$\mathrm{Loop} * \mathrm{ADSL}_{t-1}$	-0.039	-0.025	0.069	-0.926**
	(0.22)	(0.10)	(0.11)	(0.42)
Distance	0.311	0.363	0.414*	1.505**
	(0.31)	(0.29)	(0.24)	(0.67)
Multi Plant	-0.069	0.048**	0.026	0.249***
	(0.06)	(0.02)	(0.02)	(0.05)
Control Variables				
Year	✓	✓	✓	✓
Region	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓
R-squared	0.159	0.087	0.158	0.113
Observations	412	5,260	2,683	4,366

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

In terms of internal and external communication software, similar to Table 58 and Table 59 the instruments in Table 63 are not significantly correlated with any type of software use. The results therefore suggest that ADSL enablement and plant's local loop length are not important determinants for software usage. Plants connected to a multi-plant firm do however appear to use some types of software more likely than single plant establishments.

Table 63

Effects of Enablement and Local Loop Length on Internal and External Communication Software, 2000-2003

Variables	Internal Software	Resource Allocation	Data Management	ERPs	External Software	Web	E-Commerce	Email
ADSL_t	0.409	-1.338	1.779	1.502	-0.198	-0.161	-0.911	-0.565
	(1.03)	(1.62)	(1.21)	(3.67)	(0.52)	(0.53)	(2.41)	(1.78)
$\mathrm{Loop} * \mathrm{ADSL}_t$	-0.383	0.957	-1.442	-1.296	0.211	0.168	0.488	0.734
	(0.85)	(1.34)	(0.99)	(2.89)	(0.43)	(0.44)	(2.02)	(1.50)
ADSL_{t-1}	0.067	0.364	-0.066	2.171	-0.256	-0.190	-0.619	-0.901
	(0.41)	(0.65)	(0.50)	(1.44)	(0.22)	(0.22)	(1.57)	(0.56)
$\mathrm{Loop} * \mathrm{ADSL}_{t-1}$	-0.132	-0.415	0.021	-1.841	0.172	0.12	0.515	0.636
	(0.34)	(0.52)	(0.41)	(1.18)	(0.18)	(0.18)	(1.30)	(0.45)
Distance	0.593	0.017	1.211	4.011	-0.26	-0.198	-0.365	-1.097
	(0.79)	(1.26)	(0.92)	(2.70)	(0.40)	(0.41)	(1.62)	(1.44)
Multi Plant	0.158**	0.121	0.164**	0.346*	0.611***	0.633***	-0.344	0.022
	(0.06)	(0.10)	(0.08)	(0.21)	(0.04)	(0.04)	(0.24)	(0.10)
Control Variables								
Year	✓	✓	✓	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓	✓	✓	✓
Observations	14,637	14,209	14,524	10,918	14,715	14,715	10,138	14,274

Note: All controls used are listed in the table. Level of significance is as follows, *** 1%, ** 5% and * 10%. Robust standard errors in parenthesis.

IV Estimation: ICT usage and Labour Productivity, 2000-2003

The final part of the empirical strategy assesses the potential causal links between ICT usage and plant performance. The motivation for this analysis is driven by the results obtained in chapter two which found that enablement of broadband and distance to the telephone exchange induced greater use in ICT capitals stock. Moreover recent literature suggests the need for a more subtle approach to assessing the effects of information technology. Treating ICT as a uniform technology is likely to cloud the potential differentiating effects of various forms of ICT (Bloom et al 2013b).

This section therefore hopes to provide some additional insights regarding the extent to which various types of ICT causally related to labour productivity. Similar to chapter two, an instrumental variable approach will be employed. ADSL enablement and firm local loop length are used as instruments for ICT use. The results from the robustness tests suggest that ADSL enablement and cable length are valid instruments. The ICT technologies selected for the IV estimation are based on results from the previous section which identify a number of technologies that are statistically relevant to the instruments; these include total PCs, desktops, laptops, Pentium PCs, Pentium intensity and DASDs. The decision as to whether the instruments are used in lagged or contemporaneous form is also based on the results from the previous section. Therefore, the instruments are contemporaneous for total PCs, desktops, laptops, Pentium PCs and Pentium intensity and lagged for DASDs. Moreover, given that the effects of enablement appear to be the strongest in the short-term, the time period for the IV analysis is 2000 to 2003.

The results in Table 64 find evidence of potential causal links between certain types of ICT and labour productivity. The instruments are the strongest for Pentium PC intensity, where both enablement and local loop length are significant at the 1% level. Moreover the F statistic is 33.49 and is above the Yogo-Stock critical values of 19.93. In addition, for Pentium Intensity, the instruments also pass the overidentifying restrictions test, where the Hansen J Statistic *p* value is 0.439. Therefore, we cannot reject the null hypothesis that the instruments are jointly valid, i.e. uncorrelated with the residual for this model. Similarly, there is some evidence to suggest a positive causal link between laptop use and labour productivity. Both instruments exhibit

their expected signs and significance. The strength of the instruments are however somewhat weaker signified by an F statistic of 10.50. In terms of the overidentifying restrictions test, the instruments appear exogenous illustrated by a Hansen J *p* value of 0.8540.

For the remaining ICTs there is evidence of a positive relationship between these technologies and labour productivity, but the results need to be interpreted with care. The estimates from the first stage results for PCs, desktops and Pentiums show their anticipated signs and are statistically significant at the 1% level. Differences vary however in terms of the strength of the instruments for each kind of computer. For total PCs and Pentiums the F statistic is 13.70 and 13.40, respectively. For desktops, the F statistic is slightly smaller at 12.34. However the exogeneity of the instruments are questionable. For example, the Hansen J *p* value range from 0.0014 to 0.0366. In terms of DASDs, the instruments (in this model lagged) are even weaker where the F statistic is 2.82. The results therefore suggest that access to ADSL infrastructure and cable loop length are less appropriate instruments for storage devices and total PCs including desktops than for laptops and Pentium Intensity.

Table 64

IV Estimation: Impact of distinct forms of ICT and Labour Productivity, 2000-2003

Second Stage	Total PCs	Desktops	Laptops	Pentiums	Pentium Intensity	DASD
ICT	1.371***	1.360***	1.420***	1.264***	1.284***	0.017
	(0.37)	(0.40)	(0.39)	(0.35)	(0.23)	(0.40)
First Stage						
ADSL_t	0.614***	0.587***	0.487***	0.649***	0.623***	
	(0.12)	(0.12)	(0.15)	(0.13)	(0.10)	
$\mathrm{Loop} * \mathrm{ADSL}_t$	-0.482***	-0.467***	-0.329***	-0.510***	-0.435***	
	(0.10)	(0.10)	(0.12)	(0.10)	(0.08)	
ADSL_{t-1}						1.228**
						(0.52)
$\mathrm{Loop} * \mathrm{ADSL}_{t-1}$						-1.001**
						(0.43)
Distance	0.267***	0.272***	0.271***	0.295***	0.162**	1.150**
	(0.08)	(0.08)	(0.10)	(0.09)	(0.07)	(0.41)
Multi Plant	0.355***	0.334***	0.331***	0.372***	0.239***	0.248***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.05)
Cragg-Donald F Test	13.70	12.34	10.50	13.40	33.49	2.82
Hansen J Statistic	0.0043	0.0014	0.8540	0.0054	0.4391	0.0366
Control Variables						
Year	✓	✓	✓	✓	✓	✓
Region	✓	✓	✓	✓	✓	✓
2 digit sector	✓	✓	✓	✓	✓	✓
Observations	20,605	20,539	14,684	20,077	20,077	4,366

Note: All controls used are listed in the table. * p<0.10, ** p<0.05, *** p<0.01. Robust standard errors in parentheses.

Conclusion

This chapter first contributes to the literature by examining a relatively unexplored determinant of ICT use, broadband availability. The preliminary results from chapter two found that firms with access to the ADSL infrastructure use more ICT than firms connected to non-abled exchanges suggesting a relatively unexplored determinant of ICT use. What is unclear however is whether or not access to ADSL is correlated heterogeneously across all types of ICT. Using the CiTDB dataset which provided detailed information on ICT use at the plant level, we assess the extent to which the effect of access to the ADSL infrastructure and local loop length are heterogeneous across various types of ICT use.

Additionally, recent work by Garicano and Rossi-Hansberg (2006), Garicano and Heaton (2010) and Bloom et al (2013b) suggest that treating ICT as a homogenous technology hides the likely differentiating effects various digital technologies have on the firm. Therefore the second objective of this chapter is to contribute to this emergent branch of the literature by examining whether a range of hardware, IT personnel and software impact labour productivity differently. Similar to chapter two, we use firm access to the ADSL infrastructure as instruments for ICT.

Consistent with the previous chapter the instruments are relevant to ICT use, depending however of the type of technology. For example, the instruments exhibit significant explanatory power on certain kinds of ICT such as PCs and external storage devices. There is however little evidence to suggest that ADSL access and the local loop length are relevant to various types of software and some IT personnel. The results provide preliminary insights regarding technological complementarities between certain types of ICT and access to ADSL. Furthermore, this chapter also finds that the timing between telephone exchange enablement and investment in certain ICTs differ across technologies. Access to the ADSL infrastructure appears to induce investment in PCs contemporaneously whereas the effects between the instruments and DASDs occur in time t-1, suggesting additional time needed for firms to bring the investment to fruition.

Finally, the IV analysis finds heterogeneity in the effects of ICT on plant labour productivity. Pentium intensity and laptop use result in considerable labour productivity gains. In addition, the strength of the instruments for these technologies appear reasonably large as well as exogenous given the size of their F statistics (33.49 and 10.50) and Hansen J *p* values (0.4391 and 0.8540), respectively.

Given that our instruments used here are access and connectivity to a superior form of telecommunication, it is likely that we are capturing a communication-ICT effect. The estimates therefore suggest that communication technology not only influence organizational structures (as found in Bloom et al 2013b) but also the performance of the firm measured by labour productivity. One potential avenue for future work would be to assess differentiating effects from other technology relating to information processing such as servers, mid-range computers and mainframes on firm performance. The instruments used in this chapter however do not appear to be appropriate for such an endeavour.

Thesis Conclusion

The objective of this thesis is to provide greater understanding regarding ICT usage and its effects of firm productivity. The first chapter attempts to address the extent to which the productivity effects of ICT are heterogeneous across firm characteristics such as size, age and human capital. In the second chapter, we look to provide evidence regarding a causal relationship between ICT and productivity using the rollout of ADSL broadband as instruments for ICT. Finally, the last chapter assesses whether access to ADSL broadband heterogeneously impacts various types of ICT use in addition to whether these distinct types of digital technologies impact firm performance differently.

The productivity gains from ICT are found to differ across various types of firms. The effects of ICT are greater for larger firms than for smaller firms whereas young firms experience larger effects from their ICT than older firms. In addition, the effects of ICT across age-size cohorts are heterogeneous with no clear trend implying either a knowledge accumulation or an adjustment cost effect. Firms who employ educated workers more intensively appear to exhibit a productivity advantage with their ICT however importantly only for firms that are larger and more mature. Furthermore, amongst these cohorts, US firms in knowledge intensive sectors exhibit greater gains from ICT than non-US foreign and domestic owned firms.

Additionally the thesis provides some preliminary evidence regarding a causal link between ICT and TFP. Estimation is carried out using an instrumental variable framework where firm access to the ADSL infrastructure and distance to the telephone exchange are used as instruments for ICT. The instruments are relevant and the timing of enablement in wave one does not appear to be correlated with ex-ante firm performance and ICT use. In addition, the effects of the distance variable do not appear to be driven by agglomeration economies therefore suggesting that the instruments are valid. Within the second stage, evidence suggests a probable causal relationship between ICT and TFP, once controlling for firm urban/rural location or using other TFP measures.

Access to a superior form a telecommunication technology, in this case ADSL, appears to be an important determinant for ICT use. However, its effects are heterogeneous across a range of distinct technologies. For example, access to ADSL

results in increased usage of certain types of PCs such as (desktops, laptops and Pentium computers) as well as DASDs and IT employees. In addition, the thesis finds that the timing of these effects is heterogeneous across different types of technology. For example, the effects of the instruments exhibit greater explanatory power contemporaneously for PC use while for storage technology, after a year. Moreover, the results from IV estimation suggest that increased laptop and Pentium PC intensive use as a result of access to the ADSL infrastructure results to greater labour productivity. The results of which appear to be causal.

The key results from chapters two and three point to a likely causal link between digital technology and productivity. However since the instruments are constructed from the delivery of a telecommunication infrastructure, it is likely that we are capturing an effect of communication-ICT. This is further illustrated from the first stage results in chapter three, where the effects of the instruments are insignificant for technology related to information processing such as main frame computers and mid-range/server computing. Future work is therefore needed to identify the effects of information processing-IT on firm performance.

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Appendix

A1 pools the observations across all sizes and ages to assess extent to which results are driven by sectoral composition. For models 5 to 7, the ICT*KIS variable is positive and significant and the size of the coefficient stable. However when controlling for sector variation, ICT* KIS becomes negative and significant at the 1% level. Although the size of the coefficient is small, the results suggest that after controlling for industrial variation being a knowledge intensive firms exhibits less additional effect on the level of ICT use for the sample as a whole. A 10% increase in ICT stock results in an increase in TFP by 2.7% and 3.1% for firms in knowledge intensive and low-knowledge intensive sectors, respectively.

A1

Effects of ICT by High Knowledge Sector Firms, 2000-2005

Dependent Variable: TFP	Model 5	Model 6	Model 7	Model 8
ICT	0.033***	0.033***	0.031***	0.031***
	(0.00)	(0.00)	(0.00)	(0.00)
ICT*KIS	0.022***	0.022***	0.019***	-0.004***
	(0.00)	(0.00)	(0.00)	(0.00)
Multi Plant	-0.034***	-0.033***	-0.037***	-0.033***
	(0.00)	(0.00)	(0.00)	(0.00)
Foreign	0.048***	0.047***	0.043***	0.033***
	(0.01)	(0.01)	(0.01)	(0.01)
USA	0.075***	0.074***	0.071***	0.069***
	(0.01)	(0.01)	(0.01)	(0.01)
Age	-0.025***	-0.027***	-0.024***	-0.006***
	(0.00)	(0.00)	(0.00)	(0.00)
Additional Controls				
Year		✓	✓	✓
Region			✓	✓
Sector				✓
Adjusted-R^2	0.0700	0.0730	0.0880	0.3080
Observations	44,543	44,543	44,542	44,542

Note: ICT*KIS refer to ICT stock knowledge intensive sector interaction term. All models additionally include year, region and 2-digit sector control variables. *** represents 1%, ** 5% and * 10% levels of significance.