OECD *Economic Studies* No. 38, 2004/1

THE ICT PRODUCTIVITY PARADOX: INSIGHTS FROM MICRO DATA

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INTRODUCTION

Empirical analysis of economic growth and productivity typically distinguishes three effects of information and communications technology (ICT). First, investment in ICT contributes to capital deepening and therefore helps raise labour productivity. Second, rapid technological progress in the production of ICT goods and services may contribute to growth in the efficiency of capital and labour, or multifactor productivity (MFP), in the ICT-producing sector. And third, greater use of ICT throughout the economy may help firms increase their overall efficiency, thus raising MFP. Moreover, greater use of ICT may contribute to network effects, such as lower transaction costs and more rapid innovation, which should also improve MFP.

These impacts can be examined at different levels of analysis, *i.e.* with macroeconomic data, with industry data or with data at the level of individual firms or establishments. Several studies have already examined the impact of ICT at the macroeconomic level (*e.g.* Colecchia and Schreyer, 2001; Van Ark, *et al.*, 2003; Jorgenson, 2003; Schreyer, *et al.* 2003). These studies show that ICT investment contributed to capital deepening and growth in most OECD countries in the 1990s, though with considerable variation across countries.[1] Several studies have also been undertaken at the industry level (Van Ark, *et al.*, 2002; Pilat, *et al.*, 2002; O'Mahony and Van Ark, 2003; Inklaar, *et al.*, 2003; Pilat and Wölfl, 2004). These show that the ICT-producing manufacturing sector contributed substantially to labour productivity and MFP growth in certain OECD countries such as Finland, Ireland and Korea, and that the US benefited more from the ICT-producing manufacturing sector than the European Union (O'Mahony and Van Ark, 2003). They also showed that ICT-using services in the United States and Australia experienced an increase in labour and multi-factor productivity growth in the second half of the 1990s, which seems partially associated with their use of ICT.[2] Few other countries have thus far experienced similar productivity gains in ICT-using services (OECD, 2003). Moreover, the European Union lags behind the United States in experiencing an increase in productivity growth in ICT-using services (O'Mahony and Van Ark, 2003).

The aggregate and industry-level evidence provides helpful insights in the impacts of ICT on productivity, but also raises new questions, notably as regards the conditions under which ICT investment becomes effective in enhancing productivity.[3] Moreover, the aggregate and industry-level evidence points to very limited productivity impacts of ICT in many countries, despite substantial investment in ICT. This would suggest that computers are still not visible in the productivity statistics of several OECD countries, *i.e.* Solow's productivity paradox may still not be solved for some countries (Solow, 1987). Firm-level data may help in understanding why investment in ICT has not yet led to greater productivity impacts, as it can point to factors influencing the impacts of ICT that can not be observed at the aggregate level, *e.g.* organisational factors or the availability of skills.[4] Firm-level data can also point to dynamic and competitive effects that may accompany the spread of ICT, such as the entry of new firms, the exit of firms that failed, and changes in market share of existing firms. Confronting firm-level and more aggregate evidence may thus enhance our understanding of the ways in which ICT affects productivity and can contribute to solving some of the questions that still surround the impacts of ICT on productivity.

Firm-level evidence on the uptake of ICT is now available for many OECD countries. This is because over the past years, much progress has been made in developing statistics on the use of various ICT technologies in the economy (OECD, 2002).[5] Most OECD countries now collect information at the firm level on ICT investment or the uptake of specific technologies. In addition, many countries have developed databases that provide detailed and comprehensive data on the performance of individual firms. Combining these sources can help establish a link between firm performance and their use of ICT. Moreover, providing that these databases cover a large proportion of the economy, or are sufficiently representative for overall performance, they may help in linking the performance of individual firms to that of the economy as a whole.[6]

The paper first discusses some of the measurement issues related to firm-level data, since better data have made an important contribution to quantifying the impacts of ICT. Next, it summarises the empirical evidence on the impacts of ICT that emerge from firm-level studies. This is followed by a discussion of the main factors that complement the successful uptake of ICT. These sections point to evidence on how ICT may raise productivity that does not emerge from studies at a more aggregate level. The discussion does not provide a complete review of the literature, however, but primarily points to work that was carried out in the context of a recent OECD project on ICT, productivity and economic growth (OECD, 2003; 2004). The penultimate section of the paper returns to a key theme of the paper, namely why the spread of ICT may not yet have lead to clear evidence of higher productivity growth in many OECD countries and why firm-level evidence may lead to different findings from evidence extracted at a more aggregate level. A short final section concludes.

MEASUREMENT ISSUES

Improvements in measurement have played an important role in strengthening the evidence on the impacts of ICT.[7] Much of the early work with firm-level data on ICT and productivity was based on private data. For example, Brynjolfsson and Hitt (1997) examined more than 600 large US firms over the 1987-94 period, partly drawing on the Compustat database, while Bresnahan, Brynjolfsson and Hitt (2002) examined over 300 large US firms from the Fortune-1000 database. Similar studies with private data exist for other countries. Studies based on such private data have helped to generate interest in the impacts of ICT on productivity and have given an important impetus to the development of official statistics on ICT. However, private sources suffer from a number of methodological drawbacks. First, private data are often not based on a representative sample of firms, which may imply that the results of such studies are biased. For example, studies based on a limited sample of large firms may be biased since large firms may benefit more from ICT than small firms. Moreover, studies based on a fixed sample of firms will tend to ignore dynamic effects, such as the entry of new firms or the demise of existing firms, which may accompany the spread of ICT. Second, the quality and comparability of private data are often not known, since the data do not necessarily confirm with accepted statistical conventions, procedures and definitions.

Over the past decade, the analysis of firm-level impacts of ICT has benefited from the establishment of longitudinal databases in statistical offices. These databases cover much larger and statistically representative samples than private data, which is important given the enormous heterogeneity in plant and firm performance (Bartelsman and Doms, 2000). These data allow firms to be tracked over time and can be linked to many surveys and data sources. Among the first of these databases was the Longitudinal Research Database of the Center of Economic Studies (CES) at the US Bureau of the Census (McGuckin and Pascoe, 1988). Since then, several other countries have also established longitudinal databases and centres for analytical studies with these data. Examples include Australia, Canada, Finland, France, the Netherlands and the United Kingdom. The data integrated in these longitudinal databases differ somewhat between countries, since the underlying sources are not the same. However, many of the basic elements of these databases are common. The basic sources for such databases are typically production surveys or censuses, *e.g.* the US Annual Survey of Manufactures. These data typically cover the manufacturing sector, although longitudinal databases increasingly cover (parts of) the service sector as well.

In recent years, longitudinal databases have increasingly been linked to data on firm use of ICT; the linked data can subsequently be explored in analytical studies. The first studies in this area were typically based on ICT data derived from technology use surveys, such as the Survey of Manufacturing Technology in the Netherlands or the United States, and the Survey of Advanced Technology in Canada.[8] Other studies used data on IT investment derived from production or investment surveys. In recent years, more data on ICT have become available, *e.g.* from surveys of ICT use and e-commerce undertaken in many OECD countries.

Moreover, innovation surveys, such as the European Union's Community Innovation Survey, often include some questions on computer use that can, in principle, be used for empirical analysis. In addition, several countries have other statistical surveys that provide data on ICT use by firms. In principle, such data can all be used for firm-level analysis.

Firm-level studies of ICT's impact on economic performance require that researchers and statisticians link data for the same firms derived from different statistical surveys, *e.g.* data from a production survey and from a survey on ICT use. Other types of data can be integrated too, which is important since empirical studies suggest that the impact of ICT depends on a range of complementary investments and factors, such as the availability of skills, organisational factors, innovation and competition (OECD, 2003). Examining the impacts of ICT in isolation may thus be of limited use.

Unlike the analysis of economic impacts of ICT at the aggregate and sectoral level, analysis at the firm-level is characterised by a wide range of data and methods (Table 1). This variety is partly linked to differences in the basic data, but also

Table 1. **Approaches followed in some recent firm-level studies of ICT and economic performance**

Study	Countries	Survey covering ICT	Method	Economic impacts
Arvanitis (2004)	Switzerland	Survey of Swiss business sector	Labour productivity regressions	Labour productivity and complementarities
Atrostic *et al.* (2004)	Denmark, Japan, United States	US Computer Network Usage Survey, Denmark survey of ICT use, Japan survey of IT workplaces	Labour productivity regressions	Labour productivity (US, Japan), Multi-factor productivity (Japan)
Baldwin and Sabourin (2002)	Canada	Survey of Advanced Technology	Labour productivity and market share regressions	Market share, labour productivity
Clayton *et al.* (2003)	United Kingdom	ONS e-commerce survey	Labour productivity and TFP regressions	Labour productivity, TFP, price effects
Crepon and Heckel (2000)	France	BRN employer file	Growth accounting	Productivity, output
Criscuolo and Waldron (2003)	United Kingdom	Annual Respondents Database	Labour productivity regressions	Labour productivity

Table 1. **Approaches followed in some recent firm-level studies of ICT and economic performance** (*cont.*)

Study	Countries	Survey covering ICT	Method	Economic impacts
De Gregorio (2002)	Italy	Structural business survey	Multivariate analysis	IT adoption, e-commerce, organisational aspects
De Panniza *et al.* (2002)	Italy	E-commerce survey	Principal components	Labour productivity
Doms, Jarmin and Klimek (2002)	United States	Asset and Expenditure Survey	Labour productivity and establishment growth regressions	Labour productivity, establishment growth
Gretton *et al.* (2004)	Australia	Business longitudinal survey, IT Use Survey	Labour productivity regressions	Labour productivity, MFP, IT adoption
Haltiwanger *et al.* (2003)	Germany, United States	US Computer Network Usage Survey, German IAB establishment panel	Labour productivity regressions	Labour productivity
Hempell (2002)	Germany	Mannheim innovation panel	Regressions based on production function	Sales, contribution of ICT capital, innovation, labour productivity
Hempell *et al.* (2004)	Germany, Netherlands	Innovation surveys, structural business statistics	Regressions based on production function	Value added, contribution of ICT capital, innovation, labour productivity
Hollenstein (2004)	Switzerland	Survey of Swiss business sector	Rank model of ICT adoption	ICT adoption
Maliranta and Rouvinen (2004)	Finland	Internet use and e-commerce survey	Labour productivity regressions, breakdown of productivity growth	Labour productivity, productivity decomposition
Milana and Zeli (2004)	Italy	Enterprise survey of economic and financial accounts	Malmquist indexes of TFP growth, TFP correlations	TFP growth
Motohashi (2003)	Japan	Basic survey on business structure and activities (BSBSA); ICT Workplace Survey	Production function, TFP regressions	Output, TFP, productivity

Source: See OECD (2003; 2004).

reflects that a wide range of methods can be applied to firm-level data. To some extent, this variety is desirable, since the empirical evidence on impacts is stronger when it can be confirmed by different methods.

On the other hand, cross-country comparisons require common methods and comparable data. Some researchers have recently engaged in cross-country comparisons (*e.g.* Atrostic, *et al.*, 2004; Hempell, *et al.*, 2004; Haltiwanger, *et al.*, 2003), and the methods used in these studies are increasingly also being adopted by other countries. For example, the approach followed by Atrostic, *et al.* (2004) was also applied by Criscuolo and Waldron (2003), and, to some extent, by Gretton, *et al.* (2004).

EVIDENCE ON THE IMPACTS OF ICT AT THE FIRM LEVEL

A number of studies have summarised the early literature on ICT, productivity and firm performance (*e.g.* Brynjolfsson and Yang, 1996). Many of these early studies found no, or a negative, impact of ICT on productivity. Most of these studies also primarily focused on labour productivity and the return to computer use, not on MFP or other impacts of ICT on business performance. Moreover, most of these studies used private sources, since official sources were not yet available. The limited impacts of ICT found in such early studies contributed to the so-called "productivity paradox" (Box 1).

Box 1. **The productivity paradox**

Many studies in the 1970s and 1980s showed negative or zero impacts of investment in ICT on productivity, a situation which led economist Robert Solow to state that "computers were everywhere but in the productivity statistics" (Solow, 1987). Many of these early studies focused on labour productivity, which made the findings surprising as investment in ICT adds to the productive capital stock and should thus, in principle, contribute to labour productivity growth. Later studies found some evidence of a positive impact of ICT on labour productivity, however. Some also found evidence that ICT capital had larger impacts on labour productivity than other types of capital, suggesting that there might be spill-overs from ICT investment or that ICT might have positive impacts on MFP growth. More recent work for certain OECD countries, *e.g.* the United States and Australia, has more conclusively shown how ICT may enhance labour and multi-factor productivity (Gretton, *et al.*, 2004; Bosworth and Triplett, 2003).

Studies over the past decade have pointed to several factors that contributed to the productivity paradox. First, some of the benefits of ICT were not picked up in the productivity statistics (Triplett, 1999). A key problem is measuring productivity in the service sector, the part of the economy where most ICT investment

Box 1. **The productivity paradox** (*cont.*)

occurs. For instance, the improved convenience of financial services due to automated teller machines (ATMs) is only counted as an improvement in the quality of financial services in some OECD countries. Similar problems exist for other activities such as insurance, business services and health services. Progress towards improved measurement has been made in some sectors and in some OECD countries, but this remains an important problem in examining the impact of ICT on performance, notably across countries.

A second reason for the difficulty in finding hard evidence on ICT's impacts is that the benefits of ICT use took a considerable time to emerge, as did the impacts of other key technologies, such as electricity. The diffusion of new technologies is often slow and firms can take a long time to adjust to them, *e.g.* in changing organisational arrangements, upgrading the workforce or inventing and implementing effective business processes. Moreover, assuming ICT raises MFP in part via the networks it provides; it takes time to build networks that are sufficiently large to have an effect on the economy. ICT diffused very rapidly in many OECD countries over the 1990s and recent empirical studies typically find a larger impact of ICT on performance than studies that were carried out with data for the 1970s or 1980s. However, such impacts have not been observed in equal measure in all countries, and are more visible in the United States than in any other country. This may suggest that other countries are still adjusting to the diffusion of ICT.

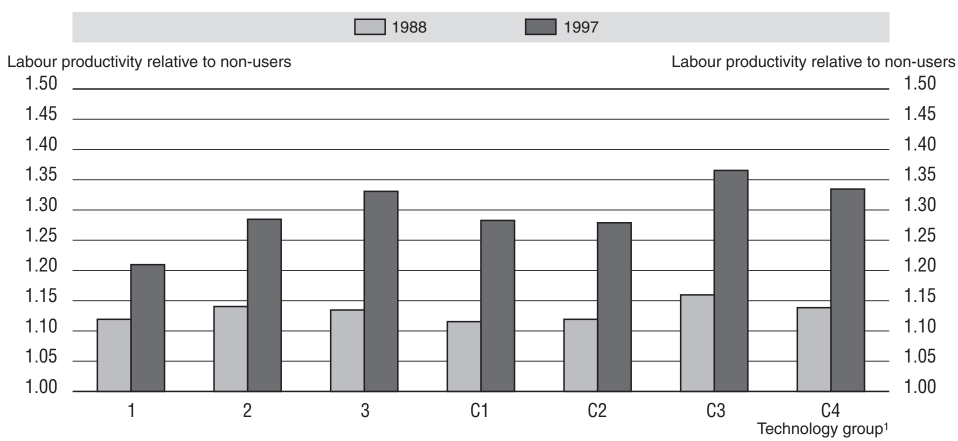
A third reason is that many early studies that attempted to capture the impact of ICT at the firm level were based on relatively small samples of firms, drawn from private sources. If the initial impact of ICT on performance was small, such studies might find little evidence, as it would easily get lost in the econometric "noise". It is also possible that the samples were not representative, or that the data were of poor quality. Moreover, several studies have suggested that the impact of ICT on economic performance may differ between activities, implying that a distinction by activity is important for the analysis. More recent studies based on large samples of (official) data and covering several industries are therefore more likely to find an impact of ICT than earlier studies. Much progress has been made in recent years in measuring ICT investment and the diffusion of ICT technologies, implying that the range of available data is broader, more robust and of greater quality than previous data.

Recent work by researchers and statistical offices, using official data, has gone beyond the early work on ICT and has provided many new insights in the role of ICT. Over the past years, OECD has worked closely with a group of researchers and statisticians from 13 OECD countries to generate further evidence on the link between ICT and business performance (OECD, 2003, 2004). Some of the findings of this group are discussed below.

Links between ICT *and firm performance*

Recent firm-level studies provide evidence that ICT use can have a positive impact on firm performance. The findings of these studies vary. Figure 1 illustrates a typical finding from several studies showing that ICT-using firms tend to have better productivity performance. It shows that Canadian firms that used either one or more ICT technologies had a higher level of labour productivity than firms that did not use these technologies.[9] Moreover, the gap between technology-using firms and other firms increased between 1988 and 1997, as technology-using firms increased their relative productivity compared to non-users. The graph also suggests that some ICT technologies are more important in enhancing labour productivity than other technologies; communication network technologies being particularly important.

Figure 1. **Relative labour productivity of advanced technology users and non-users**
Manufacturing sector in Canada, 1988 *versus* 1997



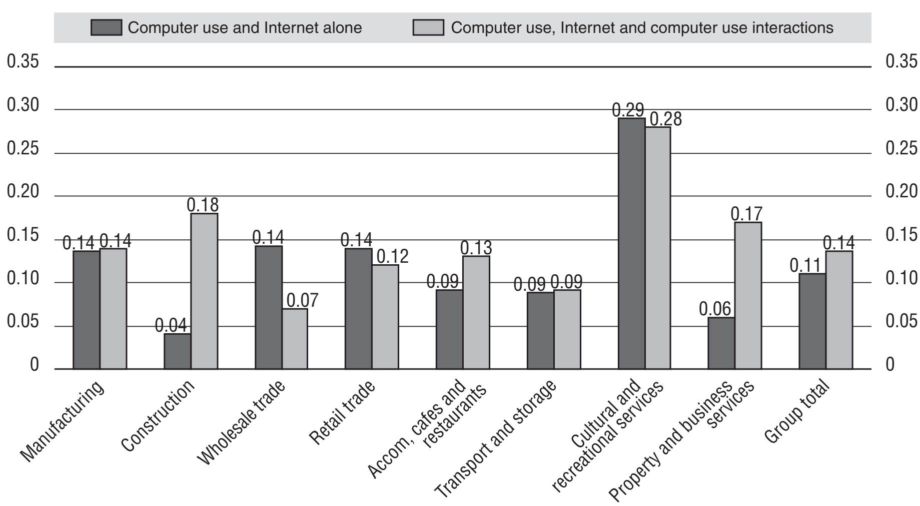
Note: The following technology groups are distinguished: Group 1 (software); Group 2 (hardware); Group 3 (communications); Group C1 (software and hardware); Group C2 (software and communications); Group C3 (hardware and communications); Group C4 (software, hardware and communications).
1. The graph shows the relative productivity on technology users compared to groups not using any advanced technology.
Source: Baldwin and Sabourin (2002).

Figure 2 is based on a study with Australian firm-level data (Gretton *et al.* 2004). Australia is typically considered as an OECD country where ICT already has had considerable impacts.The paper finds through aggregate growth accounting and the aggregation of firm-level results that ICTs and related effects raised Australia's annual MFP growth by around two-tenths of a percentage point. This contribution is significant, although it is a relatively small part of Australia's MFP growth in the 1990s, which amounted to 1.8 per cent a year. The use of computers thus already affected

Australian MFP growth in the mid-1990s, *i.e.* before the peak in ICT investment Moreover, this effect is over and above the substantial contribution of ICT to overall capital deepening, which was estimated at 1 per cent annually over the 1990s. Importantly, the firm-level econometric analysis, which controls for other influences, found positive links between ICT use and productivity growth in all industry sectors that were examined. The analysis also found that the productivity effects of ICT tapered off over time; the ultimate productivity effect from adoption of (a type of) ICT is thus a step up in levels, rather than a permanent increase in the rate of growth.

The results of Figures 1 and 2 are confirmed by many other studies that also point to impacts of ICT on economic performance. For example, Hempell, *et al.* (2004) find that ICT capital deepening raised labour productivity in services firms in both Germany and the Netherlands. Arvanitis (2004) found that labour productivity in Swiss firms is closely correlated with ICT use. A study for Finland, by Maliranta and Rouvinen (2004), also found strong evidence for productivity-enhancing impacts of ICT. It found that after controlling for industry and time effects as well as specific characteristics of the firm and workers using ICT, the additional productivity of ICT-equipped labour ranges from 8 per cent to 18 per cent, which corresponds to a 5 to 6 per cent elasticity of ICT capital. This effect was much higher in younger firms and in the ICT-producing sector, notably ICT-producing services.

Figure 2. **Estimated contribution of ICT to multifactor productivity growth in Australia**
1994-95 to 1997-98, in percentage points



Source: Gretton *et al.* (2004).

Baldwin, *et al.* (2004) found strong evidence for Canada that the use of ICTs is associated with superior performance. In particular, greater use of advanced information and communication technologies was associated with higher labour productivity growth during the nineties. In another study for Canada, Baldwin and Sabourin (2002) found that a considerable amount of market share was transferred from declining firms to growing firms over a decade. At the same time, the growers increased their productivity relative to the declining firms. Those technology users that were using communications technologies or that combined technologies from several different technology classes increased their relative productivity the most. In turn, gains in relative productivity were accompanied by gains in market share.

Clayton, *et al.* (2004) examined the economic impacts in the United Kingdom of on specific application of ICT, namely electronic commerce. It found a positive effect on firm's labour and multi-factor productivity associated with use of computer networks for trading. However, there was an important difference between e-buying and e-selling, with e-buying having positive impacts on output growth and e-selling typically having negative impacts. This is likely due to pricing effects, since at least part of the gain from investment in electronic procurement by firms comes from the ability to use the price transparency offered by e-procurement to secure more competitive deals. Part of this comes from efficiency gains, but part is likely to be at the expense of suppliers.

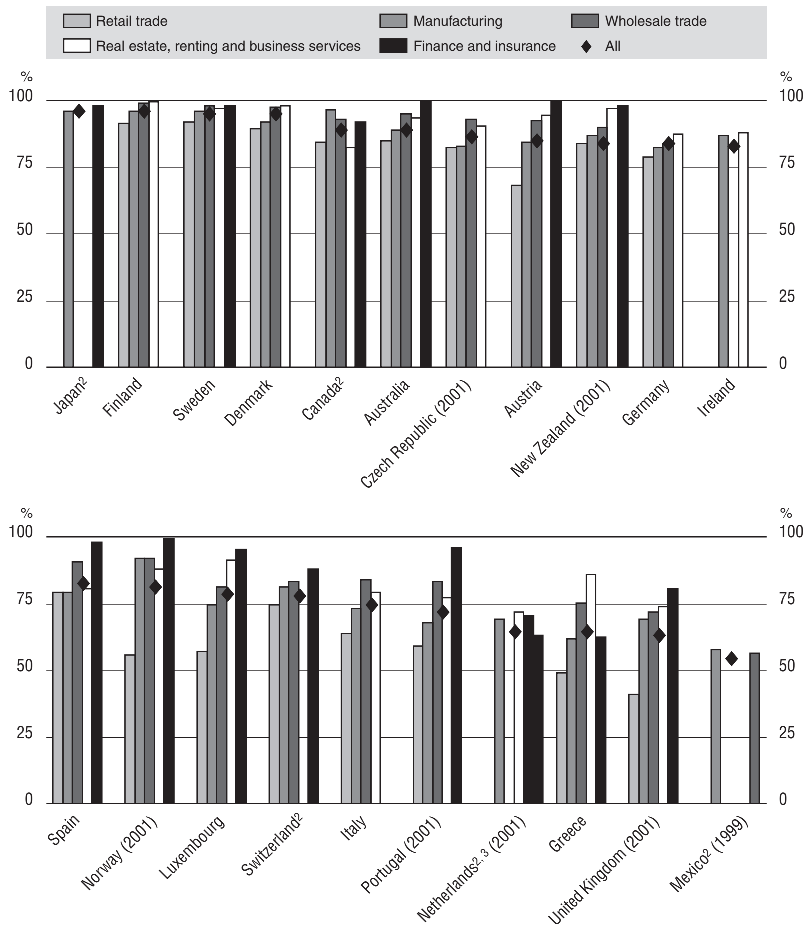
For the United States, Atrostic and Nguyen (2002) were the first in linking computer network use (both EDI and Internet) to productivity. The study found that average labour productivity was higher in plants with networks and that the impact of networks was positive and significant after controlling for several production factors and plant characteristics. Networks were estimated to increase labour productivity by roughly 5 per cent, depending on the model specification. Atrostic, *et al.* (2004) examined the impact of computer networks in three OECD countries, Denmark, Japan and the United States. For Japan, the study found that use of both intra-firm and inter-firm networks was positively correlated with MFP levels at the firm level, thus confirming the findings by Motohashi (2003). Positive and statistically significant coefficients were found for several types of networks, including open networks (the Internet), CAD/CAM technologies and electronic data interchange (EDI).

I*mpacts in services*

ICT use is more widespread in some parts of the services sector than in manufacturing (OECD, 2003). Moreover, not all sectors use the same technologies. In many countries, financial services are among the most ICT-intensive sectors (Figure 3). Evidence for the United Kingdom suggests that financial intermediation is also the sector most likely to use network technologies (OECD, 2003), and

Figure 3. **Internet penetration by activity, 2002**[1]

Percentage of all firms with ten or more employees using the Internet



1. In European countries, only enterprises in the business sector, but excluding NACE activity E (electricity, gas and water supply), NACE activity F (construction) and NACE activity J (financial intermediation), are included. The source for these data is the Eurostat Community Survey on enterprise use of ICT. In Australia, all employing businesses are included, with the exception of businesses in general government, agriculture, forestry and fishing, government administration and defence, education, private households employing staff and religious organisations. Canada includes the industrial sector. Japan excludes agriculture, forestry, fisheries and mining. New Zealand excludes electricity, gas and water supply, and only includes enterprises with NZD 30 000 or more in turnover. Switzerland includes the industry, construction and service sectors.
2. For Canada, 50-299 employees instead of 50-249 and 300 or more instead of 250 or more. For Japan, businesses with 100 or more employees. For the Netherlands, 50-199 employees instead of 50-249. For Switzerland, 5-49 employees instead of 10-49 and 5 or more employees instead of 10 or more. For Mexico, businesses with 21 or more employees, 21-100 employees instead of 10-49, 101-250 instead of 50-249, 151-1000 instead of 250 or more.
3. Internet and other computer-mediated networks.

Source: OECD, ICT database and Eurostat, Community Survey on ICT usage in enterprises 2002, May 2003.

also the sector to use combinations of network technologies. This indicates that this sector is an intensive user of information, and potentially the most likely to benefit from ICT.

Studies at the industry level provide only little evidence that ICT use has led to stronger productivity growth in the services sector, the United States and Australia being exceptions (OECD, 2004). Firm-level studies suggest that ICT can enhance the performance of the services sector, however, also in countries for which little evidence is available at the industry level. For Australia and the United States, firm-level studies confirm the evidence at the industry level. For example, Gretton, *et al.* (2004) found impacts of ICT on MFP growth in several services sectors. For the United States, Doms, Jarmin and Klimek (2002) show that growth in the US retail sector over the 1990s involved the displacement of traditional retailers by sophisticated retailers introducing new technologies and processes.

But impacts are also found in other countries. For Germany, Hempell (2002) showed significant productivity effects of ICT in firms in the German service sector. Moreover, experience gained from past process innovations helped firms to make ICT investments more productive. A comparative study for Germany and the Netherlands (Hempell *et al.* 2004) confirmed the link between ICT and innovation in the German service sector, and also found such a link for the services sector of the Netherlands. Moreover, the study found that ICT capital had a significant impact on productivity in the Netherlands' services sector.

For Finland, Maliranta and Rouvinen (2004) found that the higher labour productivity induced by ICT seemed to be somewhat greater in services than in manufacturing. Manufacturing firms benefit in particular from ICT-induced efficiency in internal communication, which is typically linked to the use of local area networks (LANs), whereas service firms benefit from efficiency gains in external (Internet) communication. For Switzerland, Arvanitis (2004) found that the use of Internet was less important for firm performance in the manufacturing than in the service sector, presumably because many manufacturing workers do not perform a desk job and are not equipped with a PC and an Internet connection.

FACTORS THAT AFFECT THE IMPACT OF ICT AT THE FIRM LEVEL

The evidence summarised above suggests that the use of ICT does have positive impacts on firm performance and productivity, even in countries and industries for which little evidence is available at more aggregate levels of analysis, *e.g.* Germany. However, the evidence also suggests that these impacts occur primarily, or only, when ICT investment is accompanied by other changes and investments. For example, many empirical studies suggest that ICT primarily affects firms where skills have been improved and organisational changes have been introduced. Another important factor is innovation, since users often help make investment in technologies, such as ICT, more valuable through their own experimentation and invention. Without this process of "co-invention", which often has a slower pace than technological invention, the economic impact of ICT may be limited. The firm-level evidence also suggests that the uptake and impact of ICT differs across firms, varying according to size of firm, age of the firm, activity, etc. This section looks at some of this evidence and discusses the main complementary factors that are associated with ICT investment.

Skills

A substantial number of longitudinal studies address the interaction between technology and human capital, and their joint impact on productivity performance (Bartelsman and Doms, 2000). Although few longitudinal databases include data on worker skills or occupations, many address human capital through wages, arguing that wages are positively correlated with worker skills. Many of these firm-level studies confirm the complementarity between technology and skills.

Studies for Canada, for example, have found that use of advanced technology is associated with a higher level of skill requirements (Baldwin, *et al.*, 1995). In Canadian plants using advanced technologies, this often led to a higher incidence of training. The study also found that firms adopting advanced technologies increased their expenditure on education and training. Baldwin, *et al.* (2004) found that a management team with a focus on improving the quality of its products by adopting an aggressive human-resource strategy – by continuously improving the skill of its workforce through training and recruitment – was associated with higher productivity growth.

For Australia, Gretton *et al.* (2004) found that the positive benefits of ICT use on MFP growth were typically linked to the level of human capital and the skill base within firms, as well as firms' experience in innovation, their application of advanced business practices and the intensity of organisational change within firms. The data for Australia also showed that the earliest and most intensive users of ICTs and the Internet tended to be large firms with skilled managers and workers.

For France, the data include details about worker characteristics, which allow more detailed analysis. Entorf and Kramarz (1998) found that computer-based technologies are often used by workers with higher skills. These workers became more productive when they got more experience in using these technologies. The introduction of new technologies also contributed to a small increase in wage differentials within firms. Greenan *et al.* (2001) examined the late 1980s and early 1990s and found strong positive correlations between indicators of computerisation and research on the one hand, and productivity, average wages and the share of administrative managers on the other hand. They also found negative correlations between these indicators and the share of blue-collar workers.

For the United Kingdom, Haskel and Heden (1999) used the UK's Annual Respondents Database (ARD) together with a set of data on computerisation. They found that computerisation reduces the demand for manual workers, even when controlling for endogeneity, human capital upgrading and technological opportunities. Caroli and Van Reenen (1999) found evidence for the United Kingdom that human capital, technology and organisational change are complementary, and that organisational change reduced the demand for unskilled workers.

A few studies have also looked at other worker-related impacts. For example, Luque and Miranda (2000) found that the skill-biased technological change associated with the uptake of advanced technologies also affects worker mobility. The larger the number of advanced technologies adopted by a plant, the higher is the probability that a worker will leave. Their interpretation is that workers at technologically advanced plants have greater (often unobserved) abilities, and therefore can claim a higher wage when they leave. The other mechanism at work is that less skilled workers tend to be pushed to plants that are less technologically advanced.

Organisational factors

Closely linked to human capital is the role of organisational change. Studies typically find that the greatest benefits from ICT are realised when ICT investment is combined with other organisational changes, such as new strategies, new business processes and practices, and new organisational structures. The common element among these practices is that they entail a greater degree of responsibility of individual workers regarding the content of their work and, to some extent, a greater proximity between management and labour. Because such organisational change tends to be firm-specific, empirical studies show on average a positive return to ICT investment, but with a large variation across organisations.

Several studies have addressed ICT's link to human capital, organisational change and productivity growth. Black and Lynch (2001), for example, found that the implementation of human resource practices is important for productivity, *e.g.* giving employees greater voice in decision-making, profit-sharing mechanisms and new industrial relations practices. They also found that productivity was higher in firms with a large proportion of non-managerial employees that use computers, suggesting that computer use and the implementation of human resource practices go hand-in-hand.

Several studies on organisational change are also available for European countries. For Germany, Falk (2001) found that the introduction of ICT and the share of training expenditures were important drivers of organisational changes, such as the introduction of total quality management, lean administration, flatter hierarchies and delegation of authority. For France, Greenan and Guellec (1998) found that the use of advanced technologies and the skills of the workforce were both positively linked to organisational variables. Organisations that enabled communication within the firm and that innovated at the organisational level seemed more successful in the uptake of advanced technologies. Moreover, such organisational changes also increased the ability of firms to adjust to changing market conditions, *e.g.* through technological innovation and the reduction of inventories.

Gretton, *et al.* (2004) on Australia also found significant interactions between ICT use and complementary organisational variables in nearly all sectors. The complementary factors for which data were available and which were found to have significant influence were: human capital, a firm's experience in innovation, its use of advanced business practices and the intensity of organisational restructuring. Computer use was also commonly associated with use of advanced business practices, the incorporation of companies and firm reorganisation.

Arvanitis (2004) found important complementarities for Switzerland. He found that labour productivity is positively correlated with human capital intensity and also with organisational factors such as team-work, job rotation and decentralisation of decision making. His study also found some evidence for complementarities between human capital and ICT capital with respect to productivity. However, he did not find evidence of complementarities between organisational capital, human capital and ICT capital, a combination that is found in some other studies.

Maliranta and Rouvinen (2004) find some evidence of complementarities for Finland, notably for human capital and organisational factors. Organisational factors appear important in Finland since the productivity effects of ICT in the manufacturing sector seem to be much larger in younger than in older firms. Some other studies have shown that the productivity of capital (primarily non-ICT) tends to be higher in *older* plants, which is possibly due to learning effects. While learning effects undoubtedly also exist with ICT, the finding for Finland is consistent with a view that it may be even more important to be able to make complementary organisational adjustments. Such changes are arguably more easily implemented in younger firms and even more so in new firms.

Innovation

Several studies point to an important link between the use of ICT and the ability of a company to innovate. The role of innovation was raised by Bresnahan and Greenstein (1996), who argued that users help make investment in technologies, such as ICT, more valuable through their own experimentation and invention. Without this process of "co-invention", which often has a slower pace than technological invention, the economic impact of ICT may be limited. For example, work for Germany, based on innovation surveys found that firms that had introduced process innovations in the past were particularly successful in using ICT (Hempell, 2002); the output elasticity of ICT capital for these firms was estimated to be about 12 per cent, about four times that of other firms. This suggests that the productive use of ICT is closely linked to innovation in general, and notably to process innovation. Studies in other countries also confirm this link. For example, Greenan and Guellec (1998) found that organisational change and the uptake of advanced technologies increased the ability of firms to adjust to changing market conditions through technological innovation.

Hempell, *et al.* (2004) points to the complementarity of innovation and ICT for both Germany and the Netherlands. They test the hypothesis that firms that introduce new products, new processes or adjust their organisational structure can reap higher benefits from ICT investment than firms that refrain from such complementary efforts. For both countries, the results indicate that ICT is used more productively if it is complemented by a firm's own efforts to innovate. These spillover effects are a particular feature of ICT capital, since no complementarities between non-ICT capital and innovation could be found in the study. The results also show that innovating on a more continuous basis seems to pay off more in terms of ICT productivity than innovating occasionally. This effect is found for product innovations (Germany) and non-technical innovations (Netherlands) and, to a much smaller extent, for process innovations. For Germany, they also find evidence for direct benefits from product and process innovation in services on multi-factor productivity (MFP). Service firms that innovate permanently show higher MFP levels. This positive direct effect of innovation on productivity, however, cannot be found for the Netherlands.

Baldwin, *et al.* (2004) finds that such characteristics are also important in Canada. The innovation strategy of a firm, its business practices, and its human-resource strategies all influence the extent to which a firm adopts new advanced technologies. A central theme emerging from the Canadian evidence is that a strategic orientation on high-technology is often the core of a successful firm strategy. The study also finds that firms that combined ICT with other advanced technologies do better than firms that only use one technology. Furthermore, the results emphasise that combinations of technologies that involve more than just ICT are important. For example, adoption of advanced process control technology, by itself, has little effect on the productivity growth of a firm, but when combined with ICT and advanced packaging technologies, the effect is significant. Similar effects are evident when firm performance is measured by market-share growth instead of productivity growth.

Competitive effects and the role of experimentation

In a competitive economy, the effective use of ICT may help efficient firms gain market share at the cost of less productive firms, raising overall productivity.

For example, Maliranta and Rouvinen (2004) point to the role of firm selection in Finland. While most of the increase in ICT use in Finland is driven by growth within firms, restructuring (the growth of some firms and decline of others) also plays an important role. This is notably the case among young firms, where some succeed and grow, and many others fail.

Several other studies point to the role of competition. A study by Baldwin and Diverty (1995) found that foreign-owned plants were more likely to adopt advanced technologies than domestic plants. For Germany, Bertschek and Fryges (2002) found that international competition was an important factor driving a firm's decision to implement B2B electronic commerce. These findings should be linked to the results of several firm-level studies that show that the implementation of advanced technologies can help firms to gain market share and may reduce the likelihood of plant exit (*e.g.* Doms *et al.* 1995; Doms, Jarmin and Klimek, 2002; Baldwin *et al.* 1995a; Baldwin and Sabourin, 2002).

A closely related issue is that of experimentation. This was raised in a recent comparison between the United States and Germany (Haltiwanger *et al.* 2003), that examined the relationship between labour productivity and measures of the choice of technology. The study distinguished between different categories of firms according to their total level of investment and their level of investment in ICT. It found that firms in all categories of investment had much stronger productivity growth in the United States than in Germany. Moreover, firms with high ICT investment had stronger productivity growth than firms with low or zero ICT investment. The study also found that firms in the United States had much greater variation in their productivity performance than firms in Germany.

These differences may occur because US firms engage in much more experimentation than their German counterparts; they take greater risks and opt for potentially higher outcomes (see Bartelsman, *et al.*, 2003). This may be related to differences in the business environment between the two regions; the US business environment permits greater experimentation as barriers to entry and exit are relatively low, in contrast to many European countries. Having scope for experimentation may be an advantage in times of great technological uncertainty, when firms need to learn in the market place about what works and what does not. The current period of ICT-driven growth might be such a period.

Firm size and age

A substantial number of studies have looked at the relationship between ICT and firm size, notably as regards differences in the uptake of ICT by size of firm. This question has been addressed in a large number of studies, most of which find that the adoption of advanced technologies, such as ICT, increases with the size of firms and plants.

Evidence for the United Kingdom, with 2000 data for a variety of network technologies used in different combinations, shows that large firms of over 250 employees are more likely to use network technologies such as Intranet, Internet or EDI than small firms; they are also more likely to have their own Web site. However, small firms of between 10 and 49 employees are more likely to use Internet as their only ICT network technology. Large firms are also more likely to use a combination of network technologies. For example, over 38 per cent of all large UK firms use Intranet, EDI and Internet, and also have their own Web site, as opposed to less than 5 per cent of small firms. Moreover, almost 45 per cent of all large firms already used broadband technologies in 2000, as opposed to less than 7 per cent of small firms.

These differences are partly due to the different uses of the network technologies by large and small firms. Large firms may use the technologies to redesign information and communication flows within the firm, and to integrate these flows throughout the production process. Some small firms only use the Internet for marketing purposes. Moreover, skilled managers and employees often help in making the technology work in large firms (Gretton *et al.* 2004).

There is also a question whether ICT has an effect on the size of firms or changes the boundaries of firms over time. This question is linked to the expectation that ICT might help lower transaction costs and thus changes the functions and tasks that should be carried out within firms and those that could be carried out outside the firm boundaries. This issue has been researched by only few firm-level studies, most of which use private data. For example, Hitt (1998) found that increased use of ICT was associated with decreases in vertical integration and increased diversification. Moreover, firms that were less vertically integrated and more diversified had a higher demand for ICT capital. Motohashi (2001) found that firms with computer networks outsourced more activities.

The link between size and age is also important, as it provides a link to firm creation. Dunne (1994) found that the impact of age on the likelihood of adopting advanced technologies was quite small. Luque (2000) confirmed this result, but found that age may have a role depending on plant size. Small new plants were more likely to adopt advanced technologies than small old plants. Maliranta and Rouvinen (2004) did find some impacts of firm creation for Finland, however, as part of the increase in ICT uptake was driven by the emergence of new firms and the demise of others.

Lags

Given the time it takes to adapt to ICT, it should not be surprising that the benefits of ICT may only emerge over time.[10] This can be seen, for example, in the relationship between the use of ICT and the year in which firms first adopted ICT.

Evidence for the United Kingdom shows that among the firms that had already adopted ICT in or before 1995, close to 50 per cent bought using electronic commerce in 2000 (Clayton and Waldron, 2003). For firms that only adopted ICT in 2000, less than 20 per cent bought using e-commerce. The evidence presented by Clayton and Waldron suggests that firms move towards more complex forms of electronic activity over time; out of all firms starting to use ICT prior to 1995, only 3 per cent had not yet moved beyond the straightforward use of ICT in 2000. Most had established an Internet site, or bought or sold through e-commerce. Out of the firms adopting ICT in 2000, over 20 per cent had not yet gone beyond the simple use of ICT.

The role of lags also emerges from analysis for Australia. Gretton *et al.* (2004) used firm level information on productivity growth and the duration of computer use to examine the dynamics of the impact of the introduction of computers. They found that computers had a positive effect on MFP growth that varied between industries and that the positive effect was largest in the earlier years of uptake but appeared to taper off as firms returned to "normal" growth after the productivity boost of the new technology. This indicates that the ultimate productivity effect from adoption of ICT is a step up in levels, rather than a permanent increase in the rate of growth. However, further technical developments can set further productivity-enhancing processes in motion.

FIRM-LEVEL EVIDENCE AND THE PRODUCTIVITY PARADOX

Examining the role of ICT at the aggregate, sectoral and firm level raises some difficult questions (see Gretton *et al.* 2004; OECD, 2004). The firm-level evidence suggests that ICT use is beneficial – though under certain conditions – to firm performance and productivity in all countries for which micro-level studies have been conducted. However, the aggregate and sectoral evidence is less conclusive about the impacts of ICT use. It shows that investment in ICT capital has contributed to capital deepening and growth in most OECD countries, and that the ICT-producing sector has contributed to productivity growth in some OECD countries. There is, however, little evidence that ICT-using industries have experienced more rapid labour or multi-factor productivity growth, the United States and Australia being the major exceptions. The discussion in the previous sections suggests that there are several reasons why this may be the case and why aggregate evidence may lead to an apparent productivity paradox whereas firm-level data provides little evidence for a paradox.

First, aggregation across firms and industries, as well as the effects of other economic changes, may disguise the impacts of ICT in sectoral and aggregate analysis. This is also because the impacts of ICT depend on other factors and policy changes, which may differ across industries. The size of the aggregate effects over time depends on the rate of development of ICT, their diffusion, lags, complementary changes, adjustment costs and the productivity-enhancing potential of ICT in different industries (Gretton *et al.*, 2004). Disentangling such factors at the aggregate or industry level is not straightforward.

Second, the firm-level benefits of ICT in many OECD countries may not yet be large enough to translate into better outcomes at the aggregate level. The firm-level benefits may be larger in the United States (and possible also in Australia) than in other OECD countries, and thus show up more clearly in aggregate and sectoral evidence. For example, Haltiwanger *et al.* (2003) suggest that the impacts of ICT are smaller in Germany than in the United States. Given the more extensive diffusion of ICT in the United States, and its early start, this interpretation should not be surprising. This is particularly the case if it takes time before the benefits from ICT become apparent, *e.g.* because of high costs of adjustment to the new technology. Moreover, the conditions under which ICT is beneficial to firm performance, such as having sufficient scope for organisational change or process innovation, might be more firmly established in the United States than in many other OECD countries. Small firm-level benefits in most OECD countries might thus lead to relatively small productivity benefits at the aggregate level.

Third, firms that are successful in implementing ICT may be better able to gain market share and grow in a competitive market such as the United States than in less competitive markets. This would contribute to greater overall impacts of ICT in the United States. For example, some of pick-up in US productivity growth over the second half of the 1990s can be attributed to the growth in market share of Wal-Mart, a company that replaced many less efficient retailers, partly owing to its effective use of ICT throughout the value chain. If the most efficient firms in Europe find it difficult to expand and gain market share, even if they do benefit from ICT, the overall impacts on productivity might be more limited than in the United States.

Fourth, measurement may play a role. The impacts of ICT may be insufficiently picked up in macroeconomic and sectoral data outside the United States, due to differences in the measurement of output. For example, the United States is one of the few countries that have changed the measurement of banking output to reflect the convenience of automated teller machines.[11] Since services sectors are the main users of ICT, inadequate measurement of service output might be a considerable problem.

Fifth, countries outside the United States may not yet have benefited from spill-over effects that could create a wedge between the impacts observed for individual firms and those at the macroeconomic level. The discussion above has already suggested that the impacts of ICT may be larger than the direct returns flowing to firms using ICT. For example, ICT may lower transaction costs, that can improve the functioning of markets (by improving the matching process), and make new markets possible. Another effect that can create a gap between firm-level returns and aggregate returns is ICT's impact on knowledge creation and innovation. ICT enables more data and information to be processed at a higher speed and can thus increase the productivity of the process of knowledge creation. A greater use of ICT may thus gradually improve the functioning of the economy. Such spill-over effects may already have shown up in the aggregate statistics in the United States, but not yet in other countries.

Finally, the state of competition may also play a role in the size of spill-over effects. In a large and highly competitive market, such as the United States, firms using ICT may not be the largest beneficiaries of investment in ICT. Consumers may extract a large part of the benefits, in the form of lower prices, better quality, improved convenience, and so on. In other cases, firms that are upstream or downstream in the value chain from the firms using ICT might benefit from greater efficiency in other parts of the value chain. In countries with a low level of competition, firms might be able to extract a greater part of the returns, and spill-over effects might thus be more limited. Further cross-country research may help to address these questions, and provide new insights in the extent of any ICT-related spill-overs.

CONCLUDING REMARKS

The studies discussed above demonstrate that the empirical evidence of the economic impacts of ICT is significantly improved from what it was only a few years ago. Many OECD countries now provide estimates of ICT investment that enable calculations of capital services and of the contribution of ICT capital to GDP growth (Schreyer, *et al.*, 2003). Data on the ICT industry and on those parts of the services sector that are intensive users of ICT are also available for many countries, permitting a breakdown of productivity growth by industry. Moreover, many countries now have regular business surveys of ICT use that provide an overview of ICT diffusion patterns. These surveys provide a wealth of information for empirical research.

The evidence from these surveys also suggests that turning investment in ICT into higher productivity is not straightforward. It typically requires complementary investments and changes, *e.g.* in human capital, organisational change and innovation. Moreover, ICT-related changes are part of a process of search and experimentation, where some firms succeed and grow and others fail and disappear. Countries with a business environment that enables this process of creative destruction may be better able to seize benefits from ICT than countries where such changes are more difficult and slow to occur.

The more solid evidence on the economic impacts of ICT and the conditions under which these impacts occur are important for policy, as it helps underpin evidence-based policies. For example, empirical analysis has demonstrated to policy makers that ICT does indeed matter for growth. Moreover, it has shown that ICT is no panacea and that there are large cross-country differences in the extent to which countries have thus far benefited from ICT.

Despite these achievements, further progress in both measurement and economic analysis is feasible and desirable. One important area concerns the measures of economic impacts that are available at the aggregate or industry level (see Ahmad, *et al.*, 2004; Pilat and Wölfl, 2004). This will require more comparable investment data, a greater use of quality-adjusted deflators and improved output measures for services. More analytical work would also be helpful, *e.g.* in linking ICT investment more systematically to economic impacts, for example through econometric analysis at the aggregate or industry level.

However, the largest potential for further work probably lies in further work with firm-level data. There are at least two aspects to this. First, cross-country studies on the impact of ICT at the firm level are still relatively scarce, primarily since comparable data sources are still relatively new. Some studies discussed above have already engaged in international comparisons (Atrostic, *et al.*, 2004; Hempell, *et al.*, 2004; Haltiwanger *et al.*, 2003). Understanding the reasons for the cross-country differences reported in such studies would benefit from further work, and could lead to helpful insights for policy.

Second, there are several key issues that remain poorly analysed and that offer scope for progress. For example, further work with firm-level data could provide greater insights into the contribution of firm dynamics to productivity gains, *e.g.* the role of new firms, the conditions that lead to successful survival and the factors determining firm exit. Moreover, the link between innovation and ICT has only been examined for some OECD countries. Understanding this link is of great importance as long-term growth largely depends on the future pace of innovation. Moreover, quantitative analysis of the price and productivity impacts of electronic commerce and e-business processes is still in its early stages, but is a promising area of further work, as suggested in a recent study for the United Kingdom (Clayton, *et al.*, 2004). Finally, while there is good evidence for some OECD countries that ICT can help transform the service sector and make it more innovative and productive, a good understanding of ICT's impact on the service sector is still lacking, partly because of some thorny measurement problems but also due to lack of cross-country empirical analysis.

Finally, the work discussed above also serves to highlight the importance of close interaction between statistical development and policy analysis. Many of the data used in the studies discussed above were not yet available 5 or 6 years ago; the bulk were developed in response to demands by policy makers for new and better data on ICT diffusion. The response of statistical offices to this demand has been quick and comprehensive. But this interaction also works the other way; effective use of the large amounts of data held by statistical offices can provide a wealth of policy-relevant information if the data is made accessible for research by academics and other analysts. This remains a challenge in several OECD countries.

NOTES

1. A large number of studies of ICT investment and impacts at the industry level are also available at the national level. These are not examined here; several are summarised in OECD (2003).
2. Gretton, *et al.* (2004) discuss the evidence for Australia in more detail, whereas Bosworth and Triplett (2003) provide a detailed account of the industry-level evidence for the United States.
3. The impacts of ICT on productivity can refer to both labour and multi-factor productivity, as discussed above. The literature examines both, as does this paper. Where relevant, a distinction is made in the text.
4. This section provides references to some of the available firm-level studies. The OECD work has benefited from close co-operation with researchers in 13 countries that were involved in the work with firm-level data. More detail on their work and other firm-level studies is available in OECD (2003) and OECD (2004).
5. Progress in this area owes much to the efforts of the OECD Working Party on Indicators for the Information Society, a group that was established in 1999 to develop and improve statistics on the information society.
6. Although aggregation across industries or firms does not have to lead to consistent findings between aggregate and disaggregated results (Fox, 2004).
7. This is also the case at the aggregate level. The introduction of hedonic price indexes in the national accounts of many OECD countries has helped to make the contribution ICT investment much more visible in productivity analysis and growth accounting.
8. Vickery and Northcott (1995) provide an overview of these technology use surveys.
9. Obviously, the graph does not demonstrate that ICT use caused higher productivity. More sophisticated econometric techniques can distinguish ICT's impact from other firm-level characteristics that may enhance productivity, *e.g.* the size or age of a firm, or a firm's investment in skills.
10. The existence of lags linked to the impacts of ICT is consistent with a view that ICT is a general purpose technology (GPT), a technology that requires a major redesign of existing ways of work (Lipsey, 2002).
11. Although better measurement does not necessarily lead to higher output or productivity growth.

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