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Productivity, Technology Diffusion and Digitization

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INTRODUCTION

Digitization is everywhere, but productivity progress is not. Researchers are divided into techno-optimist and techno-pessimists fighting over whether or not productivity progress already kicked in, or whether there will be a great leap forward in the near future.

In order to identify the link between digitization and productivity, we analyse technology diffusion's development over time. We discuss the preconditions for technology take-up and their implications for productivity growth. To carve out the more specific relationship between digitization and productivity, we also zoom in on whether infrastructure, individuals or enterprises constitute the driving force behind productivity enhancing technological progress.

During the years after the financial crisis of 2008 many mature economies experienced a significant slowdown in GDP growth compared with the pre-crisis period (The Conference Board 2016). Economists are highly concerned with the countries' weak growth performance. Introducing the buzzword 'New Secular Stagnation', Summers (2014a) describes an economic situation where GDP deviates massively from its potential as investments fail to equal savings in the short run. In the post-crisis period extremely low interest rates are accompanied by a severe slump in investment which has plunged to a historical trough (Diermeier and Hüther 2015). What is more, with the increasing deflation risk, real interest rates are not expected to increase significantly in the near future (Demary and Hüther 2015). One of the main structural breaks in the economic environment now identified as triggering low returns and weak investments is the slowdown in technological growth: 'slower technological growth means a reduction in the demand for new capital goods to equip new or more productive workers' (Summers 2014b).

With lower technology growth, investments are held back, as investors prefer to wait for better opportunities in the future. Lower investment and R&D spending consequently hold back productivity progress and, ultimately, GDP growth (European Commission 2015; Andrews and Criscuolo 2013). Indeed, Total Factor Productivity (TFP) growth has been historically low or even negative after 2011 (The Conference Board 2016). During the 1990s and early 2000s, a co-movement of mature economies with relatively stable TFP contributions to GDP growth between zero and two percent can be identified. TFP growth drops after the financial crisis to a value around zero, and even becomes negative for Eurozone countries.

The productivity sceptics' godfather, Robert Gordon (2012), explains the current productivity slowdown with a lack of game-changing innovations and diminishing returns on innovation. Unlike the introduction of industrial electricity consumption that generated huge productivity leaps, this stream of literature doubts that recent information and communications technology (ICT) innovations had have a comparable impact on TFP – especially in Europe (Brasini and Freo 2012; Inklaa *et al.* 2005; van Ark *et al.* 2008).

TOTAL FACTOR PRODUCTIVITY IN THE AGE OF DIGITIZATION

TFP has enjoyed a bad reputation as the blind spot of economic models for a long time. Deducted as the residual between the growth rates of measurable GDP and the factor inputs capital and labour, TFP used to be the exogenous unexplainable void that was hard to interpret. Although it remained a vague concept, TFP became the most famous proxy for an economy's productivity. By representing the productivity of both labour and capital, TFP is more complex, but also more sophisticated, than simple labour productivity.

Finally, the most important determinant of TFP is the incorporation of a new technology into the production process, thereby yielding more output for the same input. Until recently, ICT technologies' impact on productivity was merely incorporated into economic models as inputs in the classical production function approach (van Reenen *et al.* 2007; OECD 2004). In recent years, growth accounting started to control for qualitative factors in capital and labour in order to reduce the residual and to make TFP a more adequate measure of technological progress (van Ark 2014). A major leap forward in growth accounting is the calculation of the contribution of ICT capital formation to GDP growth. By and large, ICT capital formation has a relatively small and volatile impact on GDP growth, and makes positive contributions even during the crisis years. What is more, ICT investments have resisted the general investment recession present in many countries during the post-crisis period (The Conference Board 2016).

Although many problems remain: in the age of digitization, pinning down the ICT sector's capital contribution to economic growth is a step in the right direction. The contribution of ICT capital in the United States accounts for 35 percent of GDP growth during the post crisis period – and in Germany this figure is even as high as 42 percent (The Conference Board 2016). Apart from ICT capital deepening, however, productivity progress from digitization could additionally be driven either by technological progress from the ICT sector itself; or by complementary innovations that exploit external effects from ICT technologies on production in other sectors.

With respect to TFP growth from the 1990s onwards, ICT-using industries experience stronger TFP growth than other sectors (Jorgenson *et al.* 2004). Additionally, van Ark (2014) underlines the importance of network effects in non-ICT sectors based on the use of ICT technology – a classical technological spill-over. Although the latter is much harder to quantify, techno-optimists usually assume the spill-over effect to be of very high importance. However, although consumers might be better off through an increased variety of goods and services, the national accounts may suggest a decrease in economic performance (see also Grömling 2016a and 2016b). This has two interesting implications: a flaw in GDP accounting goes hand in hand with an evident flaw in the TFP residual. If we believe GDP to be biased downwards, the same must hold for TFP. Additionally, it is possible that research and development with respect to 'Industrie 4.0' – the digitization of the entire value chain from raw material producer to retail consumer – have not effectively raised productivity yet, but are already paving the way for innovations that will enhance it in the future. Both implications stress the underestimated importance of TFP in the present due to advancing digitization. Therefore, the following section presents an analysis of digitization technologies and their possible impact on productivity.

IS DIGITIZATION SPECIAL IN THE HISTORY OF TECHNOLOGICAL PROGRESS?

To assess the potential productivity contributions of digitization, one should zoom in on the respective technologies and their diffusion. As explained above, technology and especially digitization are important driving factors of TFP. However, the digitization channel that finally triggers productivity remains unclear. Evangelista *et al.* (2014) identify access, usage and digital empowerment as transition mechanisms to productivity variables aggregated at the national level. Access in terms of infrastructure is certainly a necessary pre-condition for a successful adoption and application of technologies. By itself, however, it does not seem to be productivity enhancing (OECD 2004; NTATREP 2006; Fornefeld *et al.* 2008; Thompson and Garbacz 2007).

By grouping technologies into different categories and taking into account the actual technology's penetration and adoption rates, we will be able to narrow down the TFP black box. Using the European Commission's Digital Agenda Scoreboard (DAS), we determine the average use of technologies in relation to the technology leader – the country in the sample that uses the respective technology most. We call this ratio the technology penetration rate. By definition, this rate ranges between zero and one. The penetration rate is a common measure for technology diffusion. It is high if countries homogeneously apply a technology close to the technology frontier. The penetration rate is low if one country is far ahead of the other countries. We identify the following 15 technologies to be relevant ICT technologies divided into three subgroups: infrastructural pre-conditions, the application of digital technologies by enterprises and the application of digital technologies by individuals. The latter two will be named enterprises' ICT empowerment and individual ICT empowerment, respectively.

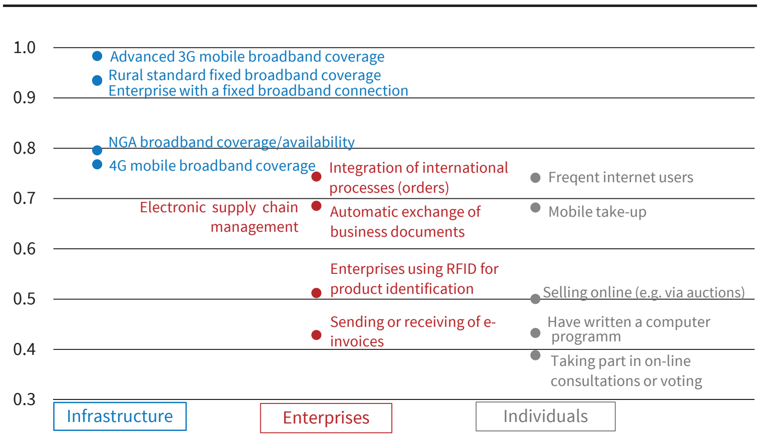
Figure 1 sets the average penetration rates against the last data point available of the respective technology – ranging from 2012 to 2014. The penetration rate of each technology *i* is defined in equation (1). The arithmetic average of all standardised (e.g. per capita) technology use for all *j* countries (with *j* representing the amount of countries sorted by the intensity of technology use), but the frontier country in the peak year is divided by the technology usage in the frontier country and peak year.

$$(1)\quad pen_i = \frac{\left(\sum_{j=1}^{J-1} tech_{i,j}\right) \big/ _{(N-1)}}{tech_{i,front}}$$

The discrepancies between penetration rates are high – even for the homogeneous sample including only EU countries and only digitization technologies. The infrastructural subcategory is clustered around 80 percent and higher. In combination with the high levels of these technologies' distribution, this means that basic pre-conditions for technological progress are equally in place, and the countries in the sample are well-prepared to develop complementary innovations. The lower and more dispersed penetration rates of technologies in the applied categories enterprises and individuals range between 40 and 80 percent. The significantly lower penetration rates in the applied categories are accompanied by lower intensities of the technologies' use: even in the frontier countries, the technology take-up of enterprises, as well as individuals, is very different. For the analysed set of applied technologies, the Nordic countries as well the Netherlands are located at the technology frontier with a significant gap to other countries – leading to comparatively low penetration rates.

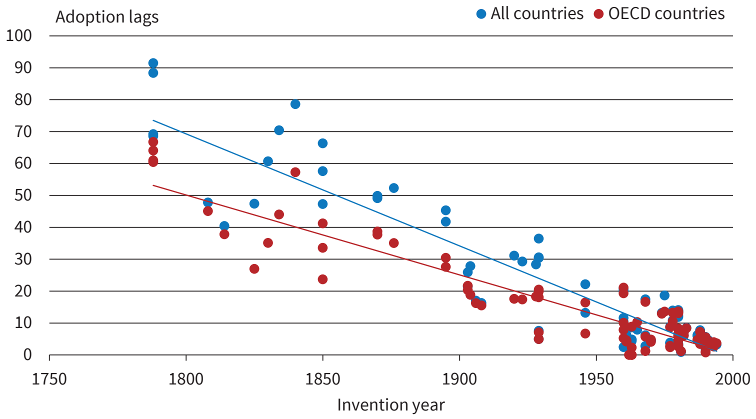
Figure 1

Penetration rates of digital technologies in the EU in different categories



Source: Digital Agenda Scoreboard; Cologne Institute for Economic Research. © ifo Institute

Figure 2
Adoption lags of new technologies



Source: CHAT database; Cologne Institute for Economc Research. © ifo Institute

Unfortunately, the DAS data is limited to EU countries and is still somewhat incomplete as data only became available for many technologies and countries in recent years. To interpret the technologies' penetration rates with respect to the probability of current or future productivity leaps, we will therefore look at the historical perspective of technology diffusion; and especially the role of digitization's technology diffusion. Before determining historical penetration rates, we focus on adoption rates – the amount of time an average country needs to implement a new technology. This is the pre-condition for penetration.

The adoption and penetration rates presented in Figures 2 and 3 are calculated from the CHAT database, which contains more than 100 technologies in over 150 countries, starting in 1800 and ending in 2003 (Comin and Hobijn 2004; Comin and Hobijn 2009). We proxy the invention year of a technology by using the first data entry on the respective technology for any country. Hence, our invention year is likely to be biased to the right, as numbers might not immediately be reported after the introduction of a technology. Figure 2 plots the proxied invention year against the mean adoption rate of all countries and only OECD countries. The first entry for automobiles, for example, is the year 1895. On average, it took 42 years for the first car to be used in most countries (30 years in those countries known today as OECD countries).

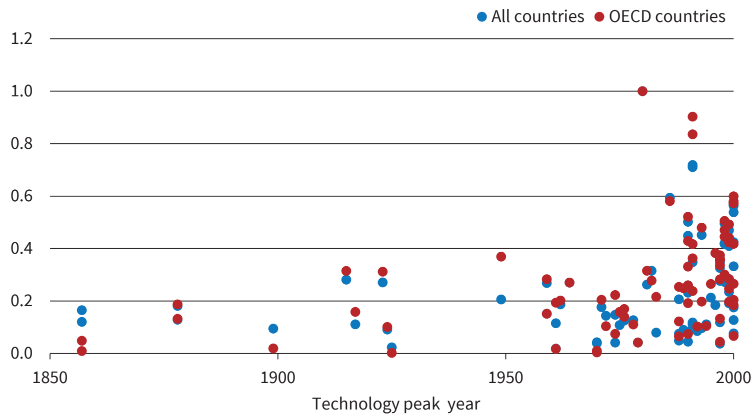
In general, adoption rates of new technologies have decreased significantly over the last 200 years. The newest technologies listed in the database only needed a few years to diffuse in all countries in the sample, whereas an adoption lag of several decades used to be the rule rather than the exception just 50 years ago. Furthermore, adoption lags have decreased independently of whether the OECD membership or the entire sample is considered. In the past, however, an OECD economy has always introduced technologies faster than the average country.

Unfortunately, the sample only includes data up to the year 2003, so brand new digitization technologies cannot be analysed. However, the newest relevant ICT technologies available at the time – the use of personal computers, mobile phones and the Internet – do fit nicely in the adoption rate's acceleration. What is more, anecdotal evidence suggests that the speed-up of technology adoption has tremendously increased in the last few years: new technologies have been adopted not after years, but after weeks or even days. Google+, for example, was used by 10 million people after only 16 days (Ernst & Young 2011).

Due to the facilitated access to real-time networks and the proceeding value chain internationalization, an interpolation of this trend for new technologies, for instance with respect to 'Industrie 4.0', seems extremely probable. In a nutshell, the trend, extracted from Figure 2, confirms that the pre-conditions for the digital revolution are in place. To analyse European technology diffusion further, we now turn to historical penetration rates.

Figure 3 plots the technologies' average penetration rates, defined in equation (1) as the ratio of the average use in the technology peak year in all countries, but the frontier country and the technology use in the respective frontier country. Again, we define the technology's penetration rate as zero if it is used in only one country, and one if it is equally used in all countries. The usage of automobiles, for instance, reached its highest rate in 2001 when 0.8 cars per capita were registered in the United States. The average value of registered cars over all countries was only 0.16 cars per capita, leading to a penetration rate of 21 percent (56 percent for today's OECD countries). This means that the number of

Figure 3
Penetration rates of leading technologies



Source: CHAT database; Cologne Institute for Economic Research. © ifo Institute cars per capita is 21 percent in an average country (56 percent in OECD countries) compared to the amount of automobiles per capita in the United States.

Whereas OECD country penetration rates are slightly higher than the penetration rates for the entire sample, the striking feature of Figure 3 is the increasing dispersion of the rates over time. From the 1990s onwards in particular, countries begin to use some technologies with equal intensity. Other technologies are used with very different intensities, resulting in penetration rates of less than 30 percent. With respect to the ICT technologies in the sample, personal computer, mobile phones and the internet, we find especially high penetration rates within the OECD country sample. The OECD penetration rate for internet use – with Sweden being the country from the sample with the highest take-up, amounts to 58 percent in the peak year 2002, while the penetration rate of the entire sample is only 21 percent. This shows a similar picture as in Figure 1.

Again the Nordic European countries and the United States are at the technology frontier for ICT technologies. In fact, these countries also had high TFP growth before the financial crisis – the period after the last data point of the CHAT sample. Again, this could be interpreted as meaning that paving the way for productivity-driving innovations by strengthening pre-conditional digitization technologies might be a very effective productivity policy.

Hence, the low penetration rate for non-OECD countries in ICT technologies might be a huge problem in the future. It is also possible, however, that penetration rates in Figure 3 are constantly biased downwards as more countries enter the sample over time. If that were to prove the case, we would underestimate technological convergence and overestimate the technological leader's advantage over the followers. In fact, the sample gradually increases from 49 countries (21 OECD countries) in 1900 to 147 countries (30 OECD countries) in 2000. In order to eliminate the possibility of a misinterpretation, we construct a penetration time-series index for OECD countries, non-OECD countries and the entire sample by the formula in equation (2). To build the mean penetration time series, we calculate the ratio between each technology i's use and this technology's use of the frontier country in the respective year. Then, for each country and year from 1900 on, we take the arithmetic mean of all technology ratios: dividing the mean of all technologies by I, the number of technologies used. Finally, we build the regional aggregates by taking the arithmetic mean of the corresponding country groups.

(2) $$pen_t = \frac{\sum_i \left[\frac{\left(\sum_{j=1}^{J-1} tech_{i,j,t}\right) / (N-1)}{tech_{i,front,t}} \right]}{I}$$

Figure 4 visualizes that, in fact, penetration rates increased constantly for the entire sample between the 1950s and the 1980s, but subsequently stagnated for non-OECD countries. During the same period, the average penetration rate of OECD countries increased from around 30 percent to 55 percent. This means that the group of OECD countries became highly homogeneous, whereas non-OECD countries were left behind with respect to technology diffusion. This result is especially interesting when compared to the results of Figure 3. Looking at the penetration rates with respect to the technology's peak use, we find a strong dispersion during the final years of the sample period.

The time-series index indicates a homogenisation of technology use between OECD countries – represented by the different penetration rates' increasing arithmetic mean towards the end of the sample period in Figure 3. Digitization technologies increase for OECD countries (e.g. 0.58 penetration for the use of internet) and decrease mean penetration rates for the entire sample (e.g. 0.21 penetration for the use of internet). This observation supports the interpretation that digitization offers strong potential – for intra industry trade for example – especially for developed economies. Developing countries, by contrast, still have to catch up with respect to the pre-conditions before being able to exploit productivity-enhancing innovations.

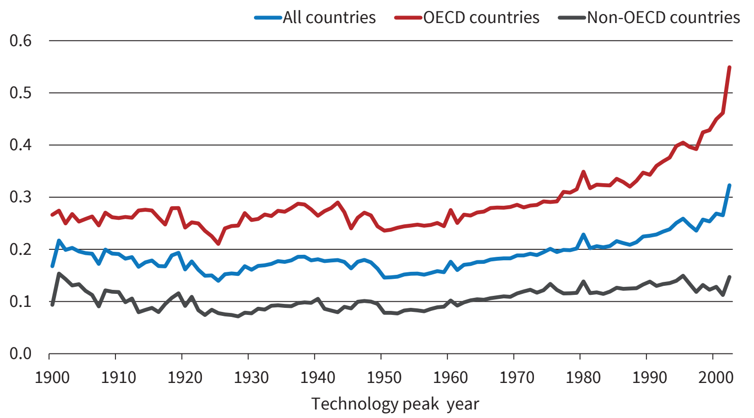
IS DIGITIZATION PRODUCTIVITY DRIVING PRODUCTIVITY ALREADY?

To a certain extent, the Digital Agenda Scoreboard database allows us to further test digitization's impact on productivity in recent years; despite the fact that the data is somewhat incomplete and unfortunately, no comparable numbers could be found about the United States. For our further analysis, we use the same 15 digital technologies categorized as in Figure 1: infrastructural pre-conditions, enterprises' as well as individuals' digital empowerment in line with Evangelista *et al.* (2014).

To test the productivity enhancement of digital technologies, we would like to check how different lags in the technology use indicator drive productivity progress today. To proxy recent productivity development,

Figure 4

Average penetration rates given fixed country composition



Source: CHAT database; Cologne Institute for Economc Research. © ifo Institute we take the arithmetic mean of the TFP contributions to GDP growth in 2013 and 2014. Constructing the lagged technology use indicator is more difficult. Unfortunately, the database does not contain entries for all technologies that allow for the different lag's consistent calculation of changes in technology use (absolute measure of technology intensification) and in technology penetration rates (relative measure of technology intensification). In order to construct an indicator with sufficient lead, we take the annual percentage change of technology use and penetration between 2008 or 2009. For those technologies where these data points are missing, we take the average annual percentage change in use and penetration (calculated as defined in formula (2) between the first two data points available.[1]

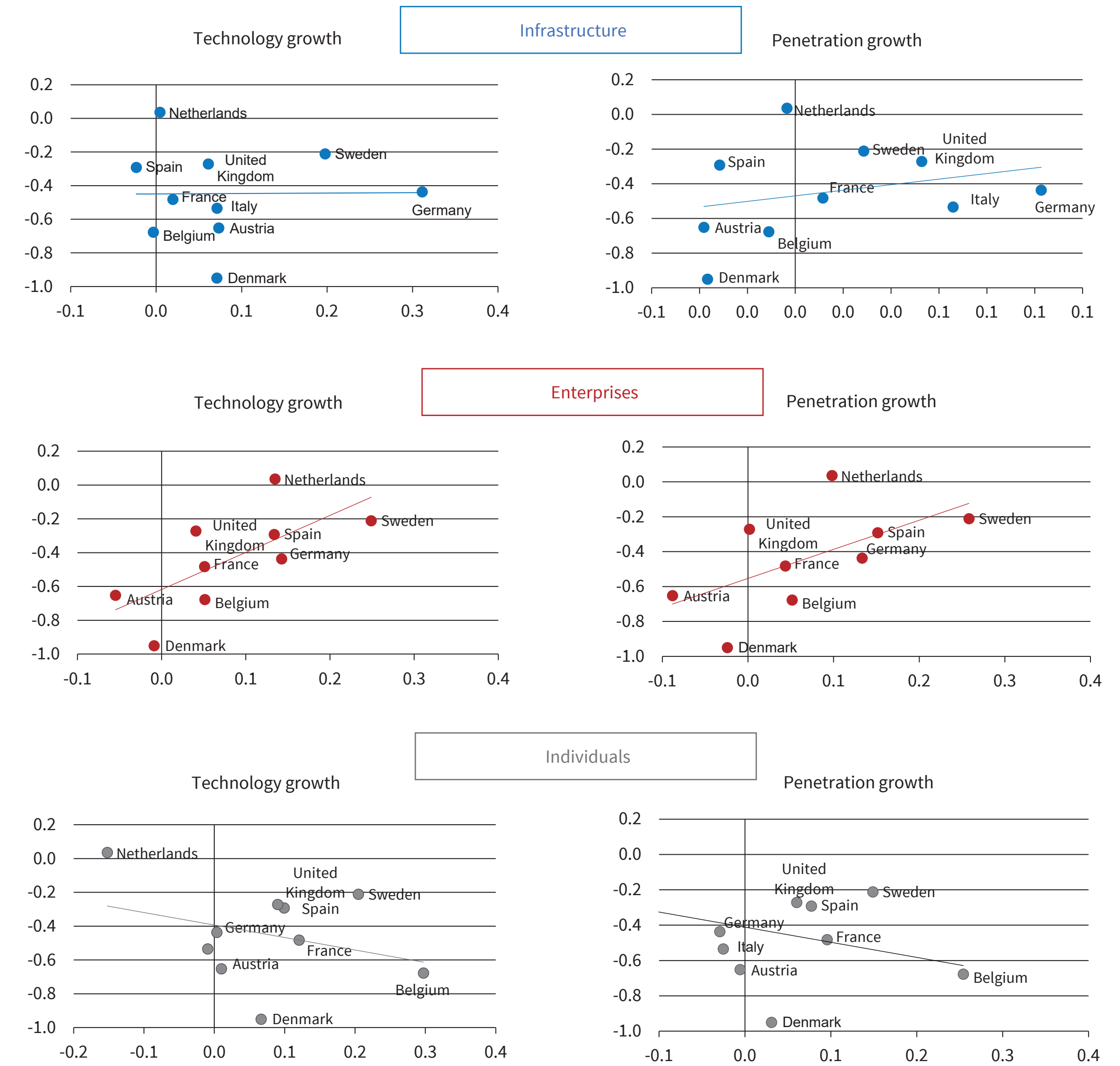
1 For the NGA broadband coverage, rural broadband coverage as well as 4G and advanced 3G coverage this is between 2011 and 2012; for mobile phone take-up between 2009 and 2010; for individual programming skills between 2009 and 2011; for individuals taking part in online consultations between 2011 and 2013; for enterprises using RFID for product identification between 2011 and 2014.

After taking the arithmetic mean of the five technologies' use and penetration rates in the three respective groups, we calculate the groups' yearly average percentage change in technology use and penetration in the first two data points available after 2008 against the average change in TFP in 2013 and 2014. We limit our analysis to the ten biggest EU-economies ranked by GDP – whereas enterprise technology data is missing for Italy.

Figure 5 demonstrates the results from this procedure in six graphs. It should be noted that in 2013 and 2014 Total Factor Productivity decreased in all countries apart from the Netherlands. Hence, all but the Dutch dots are located below the horizontal axis. Interestingly, the percentage change in the penetration rate's sign differs over the three groups: for the infrastructural and individual group some penetration rates increased and others decreased – in many cases indicating that technology frontier countries have lost their relative advantage by an absolute decrease in technology use. By contrast, the group of applied digitization technology use of enterprises experienced basically only positive percentage changes in the penetration

Figure 5

TFP growth 2013–2014 given percentage change in past technology use and penetration



Source: Digital Agenda Scoreboard; Cologne Institute for Economic Research.

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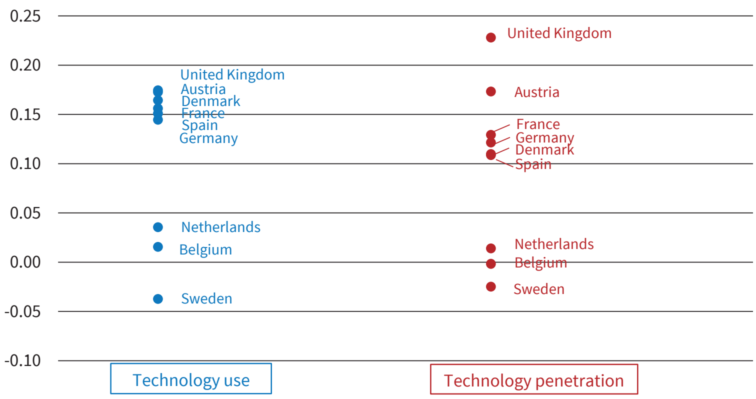
Figure 6
Country ranking by the enterprise's use and penetration of digital technologies



Source: Digital Agenda Scoreboard; Cologne Institute foe economic Research. © ifo Institute

rate, which also indicates a relative catch-up effect, with all countries except from Austria and Denmark intensifying their use of the respective technologies. The similarity between the graphs on the individual digitization technology use and penetration can be explained by the fact that the relative change in comparison with the technology frontier strongly overlap with the actual change in the technology use.

Strikingly, a strong correlation between the change in use and penetration several years ago with TFP growth in 2013 and 2014 can only be found for the enterprises' digital empowerment. Statistically, the correlation between enterprises' penetration of digitization technology, and later TFP, growth are significant at the 10 percent significance level. The enterprises' growth in digitization technology use yields even more significant results: The correlation between technology use and TFP growth is significant at the 5 percent level. For the infrastructural and individual group, the visual and econometrical analysis shows no such relationship. Again, this result strengthens our findings from above: infrastructure might be only a necessary condition for productivity growth – by itself, it does not trigger productivity. It might also be possible that changes in a country's infrastructure have productivity effects that kick in after a longer time lag. Unfortunately, the data does not allow comprehensive testing of this hypothesis.

As soon as enterprises start applying productivity enhancing technologies, an impact on TFP can be found; even at the macro-level. The limited data amount and quality, however, does not allow for a sensible estimation of this effect's size. Unfortunately, it is impossible to impute data in order to micro-econometrically test different lag levels due to structurally missing data in the past. The data available for several years is insufficient to reasonably apply imputing techniques on the technology level.

CONCLUSION

Measuring the level of technological progress is difficult. The most commonly applied measure is TFP. In general, this might be a reasonable approximation for technological progress, but in extraordinary times such as during the financial crisis, TFP apparently fails as a productivity measure.

Ongoing digitization constitutes another 'extraordinary time period' with regard to TFP's accuracy. On the one hand, we are possibly failing to measure enhanced productivity it with our strict national accounts statistics and need to change our measurement of both GDP and TFP. On the other hand, it is possible that current low TFP growth is driven by the fact that digitization is still lacking productivity-enhancing complementary innovations. Thus, we would expect productivity to increase in the future.

In order to scale down the TFP black box, we decide to zoom in on technology diffusion, and especially digitization's technology diffusion. We find that technology adoption rates today are far higher than historical technology adoption. Digitization technologies in particular are a driver of this process. With respect to technology penetration we find a strong increase in the dispersion of penetration rates between OECD and non-OECD countries over time. It is possible that non-OECD countries have improved their technology use over time; in relative terms, however, they have not. This particularly holds for digitization technologies such as internet use.

Focusing on digitization technologies in Europe, we find high penetration rates for the digitization infrastructure. Follow-up technologies, applied by enterprises and individuals are not totally diffused yet. Strikingly, a strong change in the diffusion of enterprises' digital empowerment seems to be productivity enhancing in the future. Although a sensible estimation of the digitization effect's size is beyond the scope of this paper, ranking countries by their intensity of digitization technology use does provide some insights: digitization is currently applied most dynamically in UK companies. No such effect can be found with respect to digitization's infrastructure, or to individual digital empowerment. Front-running enterprises need to step in and apply digitization technologies in order to trigger technological progress measurable on a large macro scale.

Thus, if digital innovations are in the pipeline, productivity policy should ensure that the pre-conditions for complementary innovations are in place. Enterprises will take their chances if infrastructural and regulatory obstacles are removed. Digitization is most probably the driving force behind future productivity progress.

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