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Abstract
ICT productive performances have slowed down since the beginning of the 2000s, before the current crisis. This diagnosis could be due, at least partly, to some statistical mis-measurements of ICT improvements. Nevertheless, improvements in ICT performances will probably be positively impacted, in some years, by large technological developments as for example the productive use, in computers, of the 3D chip. The lag of ICT diffusion in non-US developed countries, mainly Europe and Japan, compare to the US, is explained by institutional aspects: a lower education level, on average, of the working-age population and more regulations on labour and product markets. By implementing structural reforms, these countries could benefit from a productivity acceleration linked to a catch-up of the US ICT diffusion level. And they could benefit, without any delay with the US, from the possible ICT productivity growth second wave.

JEL classification: O31, O33, J24, O47, E22
Keywords: ICT, productivity, growth, innovation

Résumé
La performance productive des TIC semble avoir ralentie depuis le début des années 2000, avant la crise actuelle. Ce ralentissement apparent peut cependant être en partie lié à des erreurs de mesure statistique. L'amélioration des performances des TIC devrait bénéficier, dans quelques années, de fortes améliorations comme l'utilisation dans les ordinateurs de puces 3D. Le retard de diffusion des TIC dans les pays européens et au Japon, par rapport aux Etats-Unis, s'explique par des raisons institutionnelles : un niveau d'éducation plus faible en moyenne de la population en âge de travailler et des rigidités sur le marché des biens et le marché du travail. La mise en œuvre de réformes structurelles permettrait à ces pays de bénéficier d'une accélération de la productivité induite successivement par le rattrapage du retard de diffusion des TIC et par les effets de la possible prochaine seconde vague de croissance de la productivité associée au TIC.

Codes JEL : O31, O33, J24, O47, E22
Mots clés : TIC, productivité, croissance, innovations

Non technical summary

Productivity has slowed down in all advanced countries since the beginning of the 2000s, before the current crisis.[1] This fact is now well documented by several recent studies These countries already suffered from a productivity slowdown at the end of the 1960s or during the 1970s, and from another one at the end of the 1980s or during the 1990s, except for the US where we observe from the mid 1990s an acceleration due to a faster improvement of Information and Communication Technologies (ICTs thereafter) productive performances (Jorgenson, 2001, was the first of numerous papers to stress this last point). Productivity growth is now very low, even quite nil in some countries, and, if it lasts, this situation will be alarming for a lot of reasons (for example for the consequent difficulties to consolidate public finances).

The last productivity slowdown seems to be due both to ICTs and to other factors. This paper deals with the role of ICTs in the recent productivity slowdown, and with the possible future impact of ICTs on productivity.

Numerous papers analyze the contribution of ICTs to productivity growth over the last decades. Among other results, these papers emphasize the growing impact of ICTs on productivity growth during the last decades, and the delay in ICT diffusion of Europe and Japan compared to the US.

Fewer papers analyze the recent slowdown of the ICT contribution to productivity growth, and these papers, which concern only the US, disagree on some important aspects. For example, for Gordon (2012, 2013) the recent slowdown of ICT contribution to productivity growth will probably last and for Byrne, Oliner and Sichel (2013), this apparent slowdown is at least partly the result of mis-measurement of the ICT performance improvements in national accounts.

Some of the main outputs of our analysis are the following:

1. US national accounts and some other sources indicate that the ICT productive performances seem effectively to slow down from the beginning of the 2000s. The productivity growth wave associated to the ICTs appears to be smaller and shorter than the previous productivity wave associated to the 2nd industrial revolution, which happens during the XXth Century.

2. We cannot exclude that this diagnosis could be due, at least partly, to some statistical mis-measurements of the ICT improvements.

3. The pessimistic scenario of a slowdown gets some support from the fact that ICT productive capital diffusion seems to have stopped also since the beginning of the 2000s.

4. ICT performance improvements will probably be positively impacted, in some years, by large technological developments as for example the productive use, in computers, of the 3D chip. These large steps could provoke a second ICT productivity wave in the future.

5. The lag of ICT diffusion in the non-US developed countries, mainly Europe and Japan, compared to the US, is explained by institutional aspects: a lower education level, on average, of the working-age population and more regulations on labour and product markets.

[1] The productivity has accelerated in Spain from 2008, the beginning of the current crisis, for very specific reasons (see Bergeaud, Cette and Lecat, 2014).

6. By implementing structural reforms, these countries could benefit from a productivity acceleration linked to a catch-up of the US ICT diffusion level. Apart from this impact through ICTs, structural reforms may also have a large impact on productivity growth, in the US and also in other advanced countries.

The last output of our analysis means that the future of productivity will depend, in all advanced countries, on technological progress (for example the productive use of the 3D chip) and also on institutional changes. These changes have a large potential role to play to reduce some brakes on productivity, to tackle some headwind productivity threats and, concerning the non-US countries, to help to catch up with the US level of ICT productive capital diffusion. This gives room for economic policies to play an essential role for the future of productivity growth.

1. Introduction

Productivity has slowed down in all advanced countries since the beginning of the 2000s, before the current crisis.[2] This fact is now well documented by several recent studies (see for example for the US Gordon, 2012, 2013, or Byrne, Oliner and Sichel, 2013, and for all advanced countries Crafts and O'Rourke, 2013, or Bergeaud, Cette and Lecat, 2014). These countries already suffered from a productivity slowdown at the end of the 1960s or during the 1970s, and from another one at the end of the 1980s or during the 1990s, except for the US where we observe from the mid 1990s an acceleration due to a faster improvement of Information and Communication Technologies (ICTs thereafter) productive performances (Jorgenson, 2001, was the first of numerous papers to stress this last point). Productivity growth is now very low, even quite nil in some countries, and, if it lasts, this situation will be alarming for a lot of reasons (for example for the consequent difficulties to consolidate public finances).

The last productivity slowdown seems to be due both to ICTs and to other factors. Concerning non ICT factors, Gordon (2012, 2013) points to the US 'six headwinds' which are already in action and which could play a larger role in the future. These headwinds are: i) A reversal of the demographic dividend; ii) A plateau in educational attainment; iii) Rising income and wealth inequalities; iv) Globalization; v) Energy and environment risks; vi) Twin household and government deficits. In the other advanced countries, some of these six headwinds already play or will soon start to play a role.

This paper deals with the role of ICTs in the recent productivity slowdown, and with the possible future impact of ICTs on productivity.

Numerous papers analyze the contribution of ICTs to productivity growth over the last decades (see for example for the US, Jorgenson, 2001, Jorgenson, Ho and Stiroh, 2006, 2008, and for country comparisons van Ark, O'Mahony and Timmer, 2008, Cette, Kocoglu and Mairesse, 2009 or Timmer *et al.* 2011). Among other results, these papers emphasize the growing impact of ICTs on productivity growth during the last decades, and the delay in ICT diffusion of Europe and Japan compared to the US.

Fewer papers analyze the recent slowdown of the ICT contribution to productivity growth, and these papers, which concern only the US, disagree on some important aspects. For example, for Gordon (2012, 2013) the recent slowdown of ICT contribution to productivity growth will probably last and for Byrne, Oliner and Sichel (2013), this apparent slowdown is at least partly the result of mis-measurement of the ICT performance improvements in national accounts.

Some of the main outputs of our analysis are the following: i) US national accounts and some other sources indicate that the ICT productive performances seem effectively to slow down from the beginning of the 2000s. The productivity growth wave associated to the ICTs appears to be smaller and shorter than the previous productivity wave associated to the 2nd industrial revolution, which happens during the XXth Century; ii) We cannot exclude that this diagnosis could be due, at least partly, to some statistical mis-measurements of the ICT improvements; iii) The pessimistic scenario of a slowdown gets some support from the fact that ICT productive capital diffusion seems to have stopped also since the beginning of the 2000s; iv) ICT performance improvements will probably be positively impacted, in some years, by large technological developments as for example the productive use, in computers, of the 3D chip. These large steps could provoke a second ICT productivity wave in the future; v) The lag of ICT diffusion in the non-US developed countries, mainly Europe and Japan, compared to the US, is explained by institutional aspects: a lower education level, on average, of the working-age population and more regulations on labour and product markets; vi) By implementing structural reforms, these countries could benefit from a productivity acceleration

[2] The productivity has accelerated in Spain from 2008, the beginning of the current crisis, for very specific reasons (see Bergeaud, Cette and Lecat, 2014).

linked to a catch-up of the US ICT diffusion level. And they could benefit without any delay with the US from the possible ICT productivity growth second wave.

Section 2 presents some stylized facts concerning labour productivity growth over the long term. Section 3 details the channels through which ICTs impact productivity and growth, and section 4 gives some empirical evaluation of these channels on the past. Section 5 looks ahead to the possible future impact of ICTs on productivity and growth. Section 6 concludes.

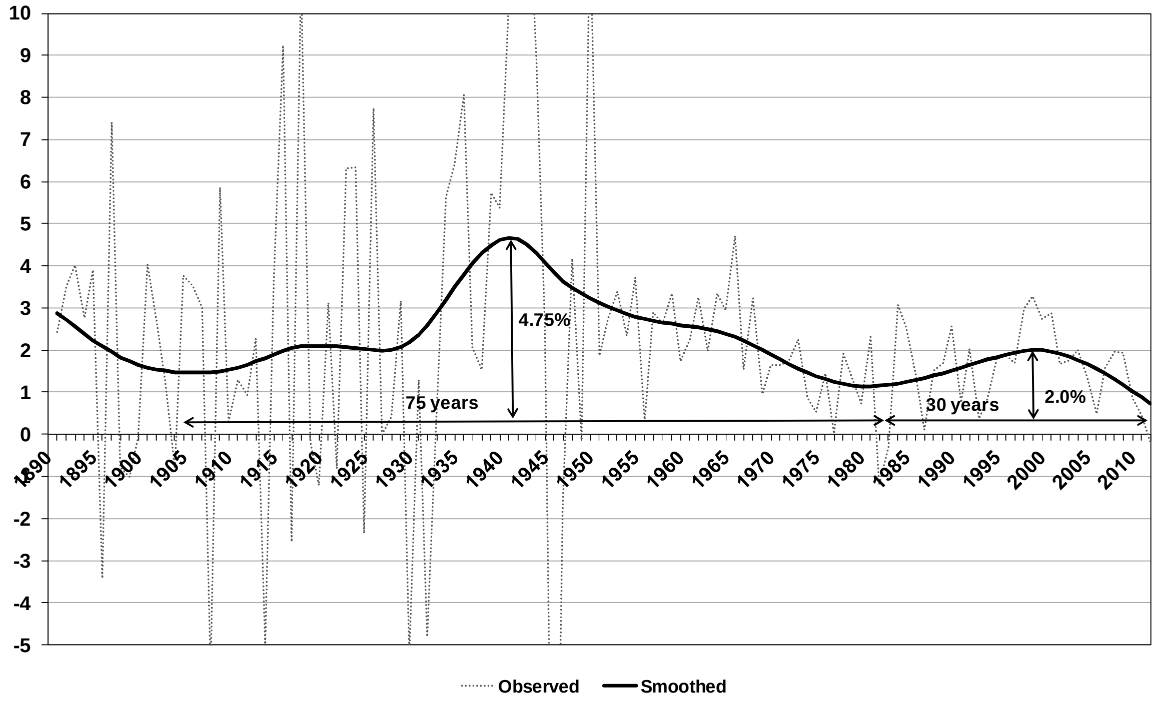
2. Labour productivity growth over the long term: Some stylized facts

The long period database built by Bergeaud, Cette and Lecat (BCL thereafter) (2014) allows us to characterize productivity growth and levels at the macroeconomic level in the main industrialized countries and areas over a long period, more precisely from 1890 to 2012. Different productivity indicators can be considered, for example labour productivity (*LP*) or total factor productivity (*TFP*). To make it more simple, we have chosen a *LP* indicator, but the main stylized facts we are going to comment would be the same with a *TFP* indicator. The *LP* indicator here considered is an hourly one, calculated by dividing the *GDP* by the total number of hours worked, itself corresponding to the product of the total employment by the average working time. To get more details on stylized facts commented hereafter, see BCL (2014).

Graph 1 represents the average annual growth rate of *LP* in percentage from 1891 to 2012 in the US. Over this long period, the stylized facts are well characterized by smoothing the direct *LP* indicator with a Hodrick-Prescott filtration (*HP*). The data appear to be very volatile and the choice of the lambda coefficient of this *HP* is important. We focus on long cycles of 30-year length, which implies a value of 500 for lambda, according to the *HP* filter transfer function.

Graph 1

Average annual growth rate of labour productivity per hour in the USA
Observed and smoothed indicator
Whole economy – 1891-2012 – In %



Smoothed indicator through Hodrick-Prescott filtering (λ = 500).
Data source: Bergeaud, Cette and Lecat (2014).

At the end of the XIXth Century and the beginning of the XXth one, we observe a productivity slowdown. It corresponds to the end of the 1st industrial revolution, itself mainly characterized by the increase of the use of steam energy in numerous industries (manufacturing, transportation…).

This slowdown is followed by a long productivity growth wave of approximately ¾ of a century, corresponding to the 2nd industrial revolution, and which was named “the one big wave” by Gordon (1999). The ascending part of this wave is affected by a transitory slowdown during the Great Depression, before WW2. Gordon (2012, 2013) characterizes the 2nd industrial revolution by four major aspects: the increase in the use of electricity for lighting and for powering motors, the increase of the use of the internal combustion engine in manufacturing and transportation, the development of chemicals, with petrochemicals and pharmaceuticals, and the development of communication and information innovation with telephone, radio, movies… As Ferguson and Washer (2004) have shown, the 2nd revolution was also a revolution in production organization and financial markets (see BCL, 2014, for more details). The top of this long productivity growth wave is located during WW2 and corresponds to a smooth productivity growth of approximately 4¾%.

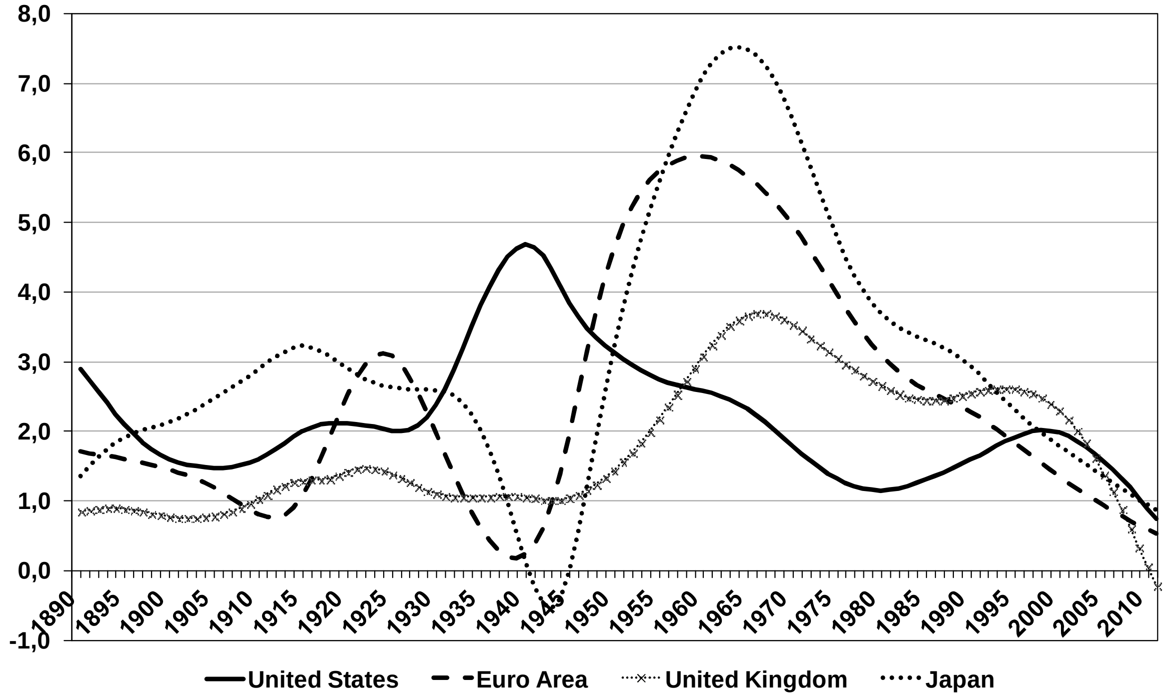
This long productivity growth wave is followed by a shorter one of approximately three decades corresponding to the 3rd industrial revolution. The 3rd industrial revolution is related to the production and the increase in use of information and communication technologies (ICTs). This productivity improvement from ICTs has been stressed by numerous papers and for example by Jorgenson (2001) or Jorgenson, Ho and Stiroh (2006, 2008). The top of this productivity growth wave is located at the end of the XXth Century and corresponds to a smooth productivity growth of approximately 2%. The productivity slowdown part of this wave starts at the beginning of the 2000s, before the Great Recession. So, this second productivity wave appears to be shorter and smaller than the previous one.

The stylized facts which we have commented seem to give a complete credit to the story proposed by Gordon (2012, 2013). The productivity improvements from the ICT technological shock would be less important than the one from the technological shock associated to the 2nd industrial revolution. Even more, the 3rd industrial revolution would be declining if not over, and the US future could be suffering from a low productivity growth, which would be an alarming situation. What do we observe in the other main advanced economic areas?

Graph 2 represents the smoothed labour productivity growth of the US, the Euro Area, the United Kingdom and Japan over the period 1891 to 2012. It appears that the productivity growth wave corresponding to the second industrial revolution is interrupted in the Euro Area, the United Kingdom and Japan from the 1930 and during WW2, but becomes higher than in the US after. In these three areas, the little wave, apparent in the US and corresponding to the third industrial revolution (the ICTs one), is absorbed in the previous one corresponding to the second industrial revolution or is too small to get visible. As in the US, the productivity slows down and the smoothed productivity growth becomes event lower than in the US from the end of the 1990s or the beginning of the 2000s.

Graph 2

Average annual growth rate of labour productivity per hour in the USA, the Euro Area, The United Kingdom and Japan
Smoothed indicator
Whole economy – 1891-2012 – In %



Smoothed indicator through Hodrick-Prescott filtering (λ = 500).
Data source: Bergeaud, Cette and Lecat (2014).
The Euro Area is here the aggregation of Germany, France, Italy, Spain, The Netherlands, and Finland. These six countries represent together, in 2012, 85¼% of the total GDP of the Euro Area.

Graph 3 represents the hourly labor productivity level of the Euro Area, The United Kingdom and Japan, relative to the US level, over the period 1890-2012. It appears first that the UK was the country which benefited from the highest productivity level until WW1, followed by the US, the Euro Area and Japan. The US became the most productive country from the end of WW1. This means that country productivity hierarchy is not invariant and can change over time. As shown in an abundant literature (see Aghion and Howitt, 2009, for a complete overview, Crafts and O'Rourke, 2013, or BCL, 2014, for recent literature reviews), it depends of the capability of countries to benefit from technology shocks, this capability depending itself from numerous institutional dimensions, and in particular education level of the working age population, labour, product and financial market regulation, property right protection… Changes in relative productivity depend directly on the country productivity growth change differences commented above. So, the productivity gap between the US and the three other areas increased dramatically during WW2[3], and decreased after during the golden age of the following four decades, this catching-up being slower for The United Kingdom than for the two other areas. At the end of the 1990, this catching-up was even achieved for the Euro Area[4]. From the second half of the 1990, the relative productivity of the three areas stopped to improve and even decreased in the Euro Area.

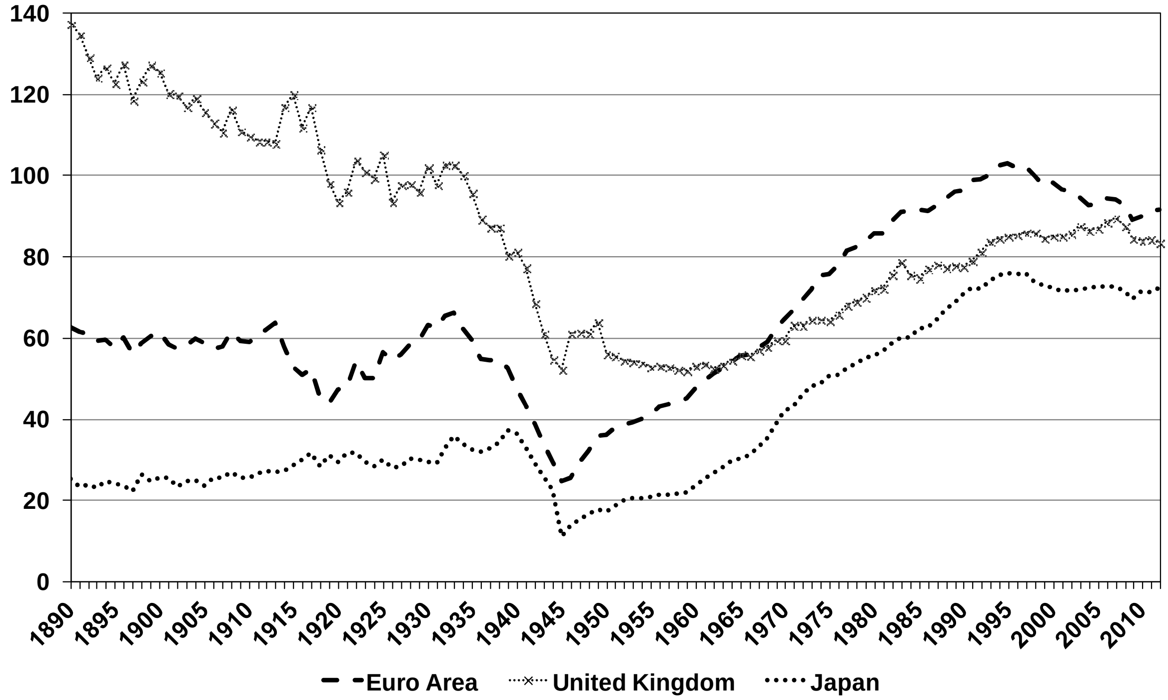
[3] BCL (2014) show that productivity change differs by a lot between countries having wars on their own soil and the others. It decreases dramatically in the first and increases in the others.

[4] It could be wrong to conclude from this that the Euro Area was, at that moment, as efficient as the US in terms of productivity. In this area, the working time and/or the employment rate were lower than in the US. Several empirical studies find diminishing returns to hours worked and to the employment rate

Graph 3

Level of productivity per hour relative to the current US level, in the Euro Area, The United Kingdom and Japan

Whole economy – 1890-2012 - § 2005 ppp – In % of the US level



Data source: Bergeaud, Cette and Lecat (2014).

The Euro Area is here the aggregation of Germany, France, Italy, Spain, The Netherlands, and Finland. These six countries represent together, in 2012, 85¼% or the total GDP of the Euro Area.

The facts commented above raise the fundamental question of a possible end, in all advanced countries, of the productivity impact of the third industrial revolution linked to the ICT technological shock. Such a perspective would have heavy consequences for the growth perspectives in these countries. Gordon (2012, 2013) proposes such a pessimistic approach, but other analyses seem more skeptical. The following sections of this paper present the terms of this debate and propose a less pessimistic point of view, even in the short term for the non-US areas.

3. ICT, productivity and growth: the channels

A technological shock as the ICT one may impact productivity in the medium to long run[5] through different channels (see Jorgenson, 2001 or Cette, Mairesse and Kocoglu, 2005, for a detailed presentation). First, it can accelerate the capital deepening process in the ICT user industries if it decreases the investment to output relative price. Secondly, it can improve the TFP by three different ways: i) in the ICT producer industries, from the decrease of the output price, meaning that a same output value corresponds to more output volume; ii) in the ICT user industries in case of miss-measurement of the ICT production factor volume or of the output volume, or also in case of mis-

(see Bourlès and Cette, 2005, 2007, for a survey and estimates) which means that at least part of the productivity performance of the Euro Area was obtained from relatively low levels of hours worked or employment rate compared to the US ones.

5 It may also impact productivity in the short run through a transitory decrease of the non-accelerating inflation rate of unemployment (the NAIRU). This channel was the topic of a large amount of literature from 1995 to 2005. See Cette, Mairesse and Kocoglu (2005) for a survey.

specification of the production function. This impact would correspond to what Abromovitz (1956) was naming concerning TFP: « *a measure of our ignorance* »; iii) in both industries from externalities, network ones in particular, this impact being by definition « *Manna from heaven* », to use the expression from Hulten (2000).

Cette, Mairesse and Kokoglu (2005) propose a simple model to represent these capital deepening and TFP channels. They first assume a Cobb-Douglas production function with constant returns to scale, in growth rate:

(1) $$\overset{o}{Q} = \overset{o}{TFP} + \alpha.\overset{o}{K} + (1-\alpha).\overset{o}{N}$$

where $\overset{o}{Q}, \overset{o}{TFP}, \overset{o}{K}$ and $\overset{o}{N}$ correspond to the growth rates of, respectively, output volume, TFP, capital volume and labour. The parameter α corresponds to the elasticity of output volume to capital volume.

Secondly, they assume that, in the long run, the ratio of the output value divided by the capital value must keep stable. This long term constraint corresponds, in growth rate, to the following relation:

(2) $$\overset{o}{P}_Q + \overset{o}{Q}* = \overset{o}{P}_K + \overset{o}{K}*$$

where $\overset{o}{P}_Q$ and $\overset{o}{P}_K$ correspond to the growth rates of, respectively, output price and capital price. A * indicates the long term variable levels.

From these two relations, we get the following ones corresponding to the long term output volume growth (relation (3)) and the long term productivity growth (relation (4)):

(3) $$\overset{o}{Q}* = \frac{\overset{o}{TFP}}{1-\alpha} + \frac{\alpha}{1-\alpha}.(\overset{o}{P}_Q - \overset{o}{P}_K) + \overset{o}{N}*$$ and (4) $$\overset{o}{Q}* - \overset{o}{N}* = \frac{\overset{o}{TFP}}{1-\alpha} + \frac{\alpha}{1-\alpha}.(\overset{o}{P}_Q - \overset{o}{P}_K)$$

From these relations (3) and (4), it appears that: i) a decline of the capital price relative to the output price increases the output growth and labour productivity growth through a capital-deepening mechanism; ii) a TFP growth improvement increases directly the output growth and the labour productivity growth. A technological shock such as the ICT one can accelerate both potential growth and long term productivity growth through these two channels. Other approaches get the same relation to explain the impact of the ICTs on long term output growth or productivity growth. It is for example the case of Oulton (2012) from a two sector theoretical model, one producing ICTs and the other one using them as production factors.

In the following, we assimilate the growth rate of the capital price to the growth rate of the investment price, which seems an acceptable assumption.[6] If the productive performance of the investment is taken into account through the split of the investment value into investment price and

[6] Following Jorgenson (1963), we approximate the user cost of capital *c* by the relation: $c = P_I.(i - \overset{o}{P}_I + \delta)$ where P_I is the investment price, $\overset{o}{P}_I$ its growth rate, i the nominal interest rate and consequently $i - \overset{o}{P}_I$ a real interest rate, and δ the scrapping rate of the capital. On a regular path growth, i, $\overset{o}{P}_I$ and δ are considered as constant. So, we obtain from the previous relation, that the growth rate of the user cost of capital can be approximated by the growth rate of the investment price: $\overset{o}{c} = \overset{o}{P}_I$.

investment volume, then the quality improvement of the investment should correspond, for a similar investment value, to a higher investment volume and a lower investment price. Quality improvements of investment are at least partly evaluated in national accounts through hedonic or matching methods. This is mainly done for ICTs, these investments benefitting more than others from performance improvements. From this, the investment price has declined significantly relative to the output price over the last decades.

Table 1 reports the average annual growth rate (in %) of investment price relative to GDP price, in the USA, over the period 1959 to 2012. It appears that the investment price relative to the GDP price has declined, on average, by 2.27% per year. This decline is mainly due to ICT. From relation (3), if we assume for the capital elasticity a usual value of 1/3 ($\alpha = 1/3$), it means that the technological shock corresponding mainly to ICTs has been the source, through its capital deepening impact, of an improvement of the USA GDP growth by ¾ of a percentage point on average per year over the period 1959 to 2012, which is impressive. And the global ICT impact on growth adds to this capital deepening channel effect the part of the impact acting through the TFP channel, also from the ICT relative price decline.

Table 1

Average annual growth rate of investment price relative to GDP price
In the USA – 1959-2012 - In %

	1959-2012	1959-1974	1975-1995	1995-2004	2004-2012
Investment	-2.27	-1.85	-1.88	-4.11	-2.02
ICT	-7.16	-6.02	-8.26	-8.95	-4.46
Computers	-18.56	-22.71	-18.45	-19.89	-9.93
Software	-4.23	-4.45	-5.35	-2.72	-2.22
Communication equipment	-3.33	-0.86	-2.70	-6.52	-5.29

Calculation of the author from BEA original data.

4. ICT productivity and growth: the facts

Byrne, Oliner and Sichel (2012) propose a growth accounting analysis of the US non-farm business sector productivity growth from 1974 to 2012. Their main results are summarized in Table 2. It appears that the US productivity growth increases for ten years (by 1.5 percentage points), from the mid 1990s to the mid 2000s. This improvement is mainly explained by three factors: i) an acceleration of ICT capital deepening (0.4 percentage point); ii) an acceleration of the TFP in ICT industries (0.4 percentage point); iii) an acceleration of the TFP in the other industries (0.7 percentage point). As already stressed by Jorgenson (2001), the productivity growth at this time is mainly due to ICTs. And the TFP acceleration in the other industries could even be, at least partly, also attributed to ICTs, the price decrease of some ICT components, as software for example, being under-evalued in the national accounts.[7] From the mid 2000s to 2012, US productivity growth decreases (by 1.5 percentage points). This decrease is mainly explained by the same three factors as for the previous acceleration: i) a deceleration of the ICT capital deepening (0.4 percentage point); ii) a deceleration of the TFP in ICT industries (0.4 percentage point); iii) a deceleration of the TFP in the other industries (0.7 percentage point). These results suggest than the mid 1990 to the mid 2000 sub-period is a very particular interval of fast ICT performance improvement.[8]

[7] For example, because it would be too difficult (or even impossible) to realize, hedonic or matching methods are not used to split price and volume for the own-account software spending, which represents in the US about 50% of the total software spending.

[8] ICT price decreases play a large role to explain productivity growth from the end of the XXth Century but are not specific to this period. For example, Ferguson and Wascher (2004, p. 8) relate that during the second half of the XIXth Century, "*… telegraph aided the expansion of railroads by improving the coordination of rail traffic. But the ability to send messages rapidly over long distances also proved valuable in many other industries. Initially, sending a telegram was relatively expensive, with rates between New York and San*

Table 2
Contributions to growth of labour productivity in the US non-farm business sector

	1974-1995	**1995-2004**	**2004-2012**
Growth labour productivity (in %) [1] = [2] + [5] + [6]	**1.56**	**3.06**	**1.56**
Contributions (in percentage points)			
Capital deepening [2] = [3] + [4]	0.74	1.22	0.74
ICT capital [3]	0.41	0.78	0.36
Other capital [4]	0.33	0.44	0.38
Labour composition [5]	0.26	0.22	0.34
Total factor productivity [6] = [7] + [10]	0.56	1.62	0.48
ICT producing sectors [7] = [8] + [9]	0.36	0.72	0.28
Semi conductors [8]	0.09	0.37	0.14
Other ICT sectors [9]	0.27	0.35	0.14
Other sectors [10]	0.20	0.90	0.20

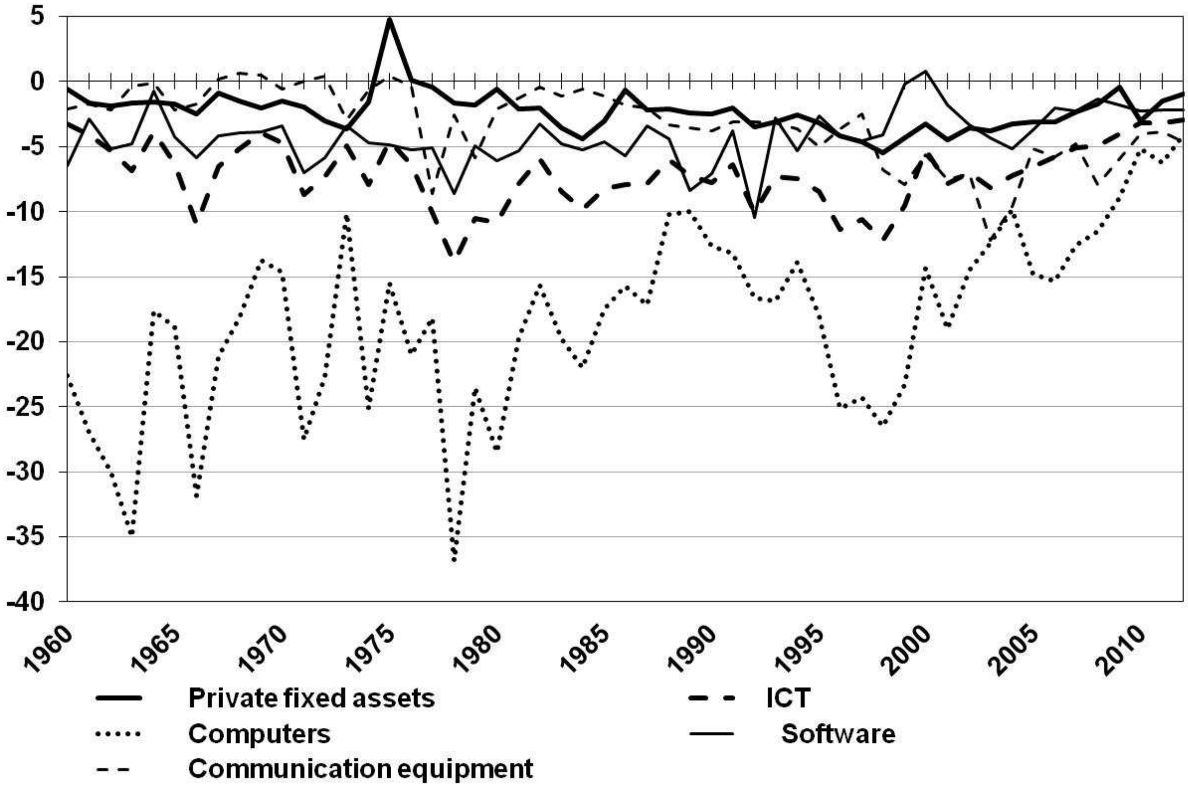
Source: Byrne, Oliner and Sichel (2013).

The annual growth rate of investment price relative to GDP price over the three sub-periods distinguished by Byrne, Oliner and Sichel (2013) corresponds to the ICT contribution to productivity growth (see Graph 4). On average, this annual growth rate is -1.88% from 1974 to 1995, decreasing to -4.11% from 1995 to 2004 and increasing to -2.02% from 2004 to 2012. These changes seem mainly due to the changes of the ICT relative price growth.

Within the last sub-period 2004-2012, it appears that the investment relative price and the ICT relative price decreases continue to slowdown. The investment relative price (the ICT relative price) decreases by -2.56% on average per year (-5.58%) from 2004 to 2008 and by -1.48% (-3.34%) from 2009 to 2012. It means that the productivity slowdown from the slowdown of ICT performance is quite continuous from the mid 2000s. As Gordon (2012, 2013) underlines, the productivity gains could now be structurally very low.

Francisco averaging $7.45 for ten words or less in the late 1860s. By the late 1880s, rates for the same message had fallen to as little as $1.00." This telegram price change corresponds on average to an annual decrease of about -9.½% over two decades!

Graph 4
Annual growth rate of investment price relative to GDP price
In the USA – 1960-2012 – In %



Data source: BEA.

The ICT performance improvements are mainly linked to semiconductor chips, which are intermediate components used in hardware and communication equipment. And among semiconductors, microprocessors are the most used ones. The performance of a microprocessor is usually appreciated through the number of transistors located on it. As the size of transistors decreases, this number can increase. Gordon Moore, a cofounder of Intel, predicted in 1975 that the number of transistors located on a microprocessor would double every 2 years. This prediction is named 'Moore's Law'.[9]

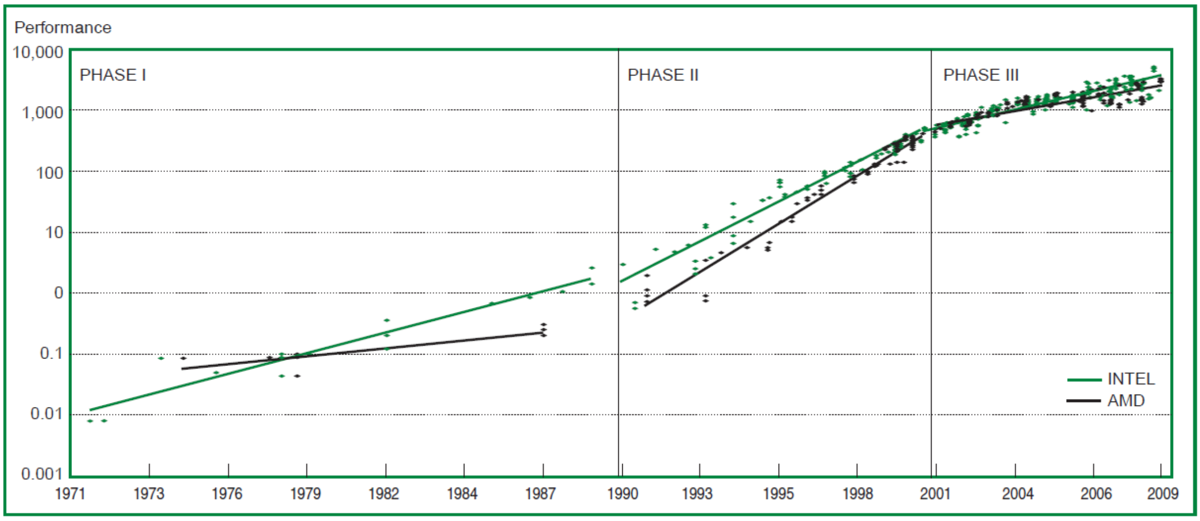
Chart 5, from Pillai (2011), shows the performance improvement of microprocessors produced by Intel and AMD over the period 1971 to 2009. It appears that this improvement is quite regular until the beginning of the 1990s, when an acceleration happens. This acceleration ends at the beginning of the 2000s, and since, the improvement is back to its pre-acceleration path. This corresponds well to the Byrne, Oliner and Sichel (2013) productivity growth story concerning the US non-farm business sector (see Table 2). The improvement acceleration interval, from 1990 to 2000, is first pointed out by Jorgenson (2001) who stresses that it corresponds to less than the two year period for Moore's Law. The analysis of Pillai (2011) ends in 2009 and cannot perceive a possible new slowdown of Moore's Law, at the end of the 2000s, which would be consistent with what national account data tell us concerning ICT price growth over the very recent years.

9 Gordon Moore expresses the principle of the continuous increase of the transistor number located on a chip already in 1965 (see Moore, 1965). In 1975, he evaluates this increase to be a factor 2 (more precisely 1.96) every two years (see Moore, 1975).

Graph 5

Growth of microprocessors performance

Microprocessors produced by INTEL and AMD – 1971-2009



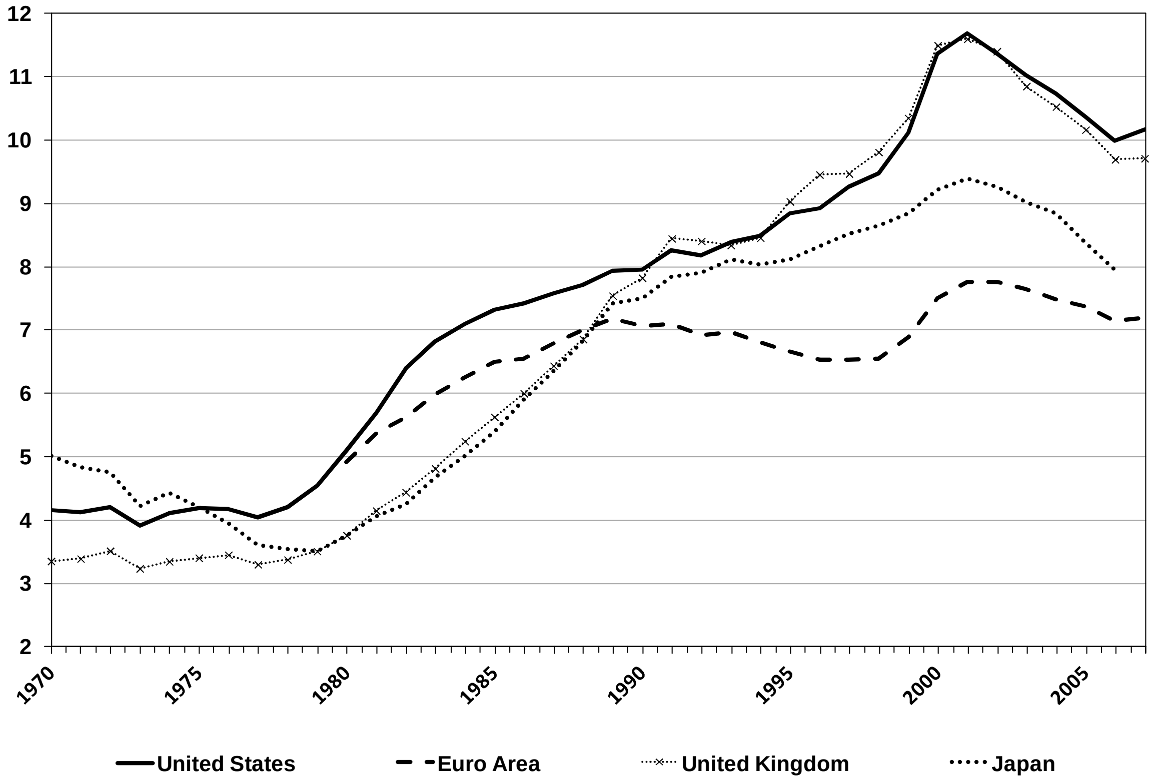
Source: Pillai (2011);

The slowdown of the ICT quality improvement may explain the break in ICT investment diffusion from the early 2000s. Graph 6, from Cette and Lopez (2012), represents the evolution of ICT capital coefficient at current prices (ratio of ICT capital stock to GDP in current prices), from 1970 to 2009, in the US, the Euro Area, The United Kingdom and Japan. It appears that the ICT productive capital diffusion increases from the 1970s to the end of the 1990s in these four areas, except in Japan where this increase stops at the end of the 1980s. At the beginning of the 2000s, the ICT productive capital diffusion stops increasing in the US, the Euro Area and the UK. It corresponds exactly to the starting point of the slowdown in ICT performances (see above).

So, these different data, coming from different sources, seem to give a consistent picture: the ICT performances slow down from the beginning of the 2000s, and the ICT price decrease, which measures these performance improvements, also slows down at the same moment. Consequently, at least in the US, the Euro Area and the United Kingdom, the investment in ICTs slows down and the ICT productive capital diffusion, measured by the ICT capital coefficient at current price, also stops at the beginning of the 2000s.

Graph 6

ICT capital coefficient (x100), at current prices
(Ratio of ICT capital stock to GDP in current prices)
Scope: The whole economy – 1970-2009



Source: Cette and Lopez (2012).
The Euro Area is here the aggregation of Germany, France, Italy, Spain, The Netherlands, Austria and Finland. These seven countries represent together, in 2012, 88½% or the total GDP of the Euro Area.

Aizcorbe, Oliner and Sichel (2008) and Byrne, Oliner and Sichel (2013) stress that the decline of the ICT price decrease, since the early 2000s, could be, at least partly and for microprocessors, a consequence of statistical mis-measurement. On semiconductor detailed data from Intel, they use an hedonic approach to evaluate semiconductor price changes. Their results are a faster price decrease, since the beginning of the 2000s, than the price indicator calculated by the BLS by a matched approach, and used in national accounts. The explanation given for this difference is that, by the discount price behavior of Intel, chips are sold at a price below the catalogue price used to implement matched approach evaluation.[10] Byrne, Oliner and Sichel specify that the price index calculated from an hedonic approach is now in use, since March 2013, in the Federal Reserve calculation of industrial production indexes. They also suggest that a slowdown of chip performance could be also explained by the fact that a part of research spending in the chip industry is devoted to reducing the heat generated by the chips.[11]

[10] "*… existing chips are being sold at a discount relative to the constant list price that widens when new models are introduced. Thus, to the extent that significant chip sales are taking place at transaction prices that fall ever further below the list prices, a standard procedure that relied on those list prices or other similar prices reported by manufacturers would be biased. Our hedonic index, which only uses prices at the time of each new chip's introduction, provides a very rough way of avoiding this potential biais.*" Byrne, Oliner and Sichel (2013, p. 32).

[11] "*While the pace of miniaturization has been sustained, semiconductor producers have changed the approach used to translate these engineering gains into faster performance. Historically, each new*

It cannot be excluded that the slowdown of the chip price decrease observed from the early 2000s in the US national account statistics, and which would mean a deceleration of the chip and ICT performances, is in reality at least partly a chip price mis-measurement. In the following of this paper, we assume not to exclude that this slowdown receives the two explanations, in unknown proportions, and that it can also be the consequence of an effective slowdown of chip performances.

By the way, the ICT contribution to productivity growth must have slowed down from the early 2000s also because of the end of the ICT increasing diffusion in all advanced economic areas, if we evaluate this diffusion through an ICT capital coefficient indicator calculated in current prices (see Graph 6). This diagnosis can be only slightly affected by the uncertainties in ICT price evaluation. Note that this stabilization of the ICT capital coefficient in current prices corresponds also to a stabilization of an indicator calculated in constant prices if ICT relative price to GDP price have themselves stopped decreasing, but to a slowdown if they continue to decrease even at a lower rate.

5. ICT, productivity and growth: Which future?

The contribution of ICTs in future productivity growth, let's say over the two next decades, is very uncertain. This uncertainty is of course linked to the uncertain diagnosis commented above concerning the improvement in ICT productive performances over the last decade. For this reason, optimistic or pessimistic scenarios are both realistic. Gordon (2012, 2013) for example is very pessimistic and for him this contribution will be very low. Byrne, Oliner and Sichel (2013) propose two steady-state scenarios. In the first lower-bound one, ICT performance improvements, measured by their relative price growth, could keep quite the same path as the one observed on average during the 2004-2012 sub-period. It means a slowdown of the ICT performance improvement compared to the 1995-2004 sub-period but even also, slightly, compared to the 1974-1995 sub-period. But it also means an acceleration in comparison to what we observe on the more recent years. In the second upper-bound scenario, ICT performance improvements could adopt a path intermediate to the one observed on the 1974-1995 long sub-period and to the one observed on the 1995-2004 favorable sub-period. The contribution of ICTs in future productivity growth (both from ICT capital deepening and from TFP in ICT producing sectors) differs by ¼ to ½ a percentage point between these two scenarios. This gap is not so wide, but we could imagine more pessimistic scenarios than the lower-bound one (that's what Gordon proposes) but also more optimistic scenarios than the upper-bound one.

To illustrate this last point, we can add two remarks. The first one, pessimistic, is that, to respect the two year option of Moore's Law over the last decades, the R&D spending in semiconductor manufacturing has grown at an impressive average rate (see Table 3). This evolution corresponds to an increase of R&D spending in the semiconductor industry by a factor 2,500 from 1970 to 2008. Such a progression could not remain sustainable, which means a slowdown in the future. This slowdown would have as a consequence a slowdown of Moore's Law and consequently of the ICT performance improvements. The second remark, optimistic, is that the semiconductor producers consider that some big improvement steps will happen in the future (see ITRS, 2013). The next one

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generation of technology in semiconductors has allowed for an increase in the number of basic calculations performed per second for a given chip design. However, as speed continued to increase, dissipating the generated heat became problematic. In response, Intel shifted in 2006 toward raising "clockspeed" more slowly and boosted performance instead by placing multiple copies of the core architecture on each chip — a change enabled by smaller feature size — and by improving the design of those cores…" Byrne, Oliner and Sichel (2013, p. 31).

could be the 3D chip, which will allow for many years fast ICT performance improvements.[12] It could happen in some years. Other improvement steps, further in time and still more uncertain, could be quantum computing and bio chips. From even only the first one step, the future contribution of ICT to productivity growth could be more favorable than the upper-bound scenario of the Byrne, Oliner and Sichel (2013), and the US could benefit from a second ICT productivity growth wave.

Table 3

Average annual R&D growth rates in the semiconductor machinery manufacturing

In %

	1971-1989	**1990-2008**
US companies	25.9	19.6
US and foreign companies	25.9	22.1

Source: Pillai (2011).

Concerning the non-US countries, the question is different. Except for the UK for particular reasons, these countries are lagging compared to the US in terms of ICT diffusion (see Graph 6). A number of studies provide alternative explanations for this ICT diffusion lag, using descriptive or econometric approaches (see Cette and Lopez, 2012, for a survey). Two explanatory factors are often put forward: the level of education of the working-age population and market rigidities. An efficient use of ICT generally requires company reorganization and institutional flexibility, which can be restricted by excessively stringent regulations. Moreover, product market regulations can reduce competitive pressure and thus lower the incentives to use the most efficient production techniques. In addition, the use of ICT generally requires labour with a higher degree of skills than other production technologies.

Aghion *et al.* (2008) or Cette and Lopez (2012) evaluate the impact of education levels of the working age population and of market rigidities on ICT diffusion levels.[13] This impact is evaluated through an econometric estimation of a factor demand model on country level panel data. The estimates strongly confirm the idea that the persistent ICT diffusion differences between the main advanced countries can largely be explained by differences in the education level of the working-age population and in market rigidities. From their estimates, which include also an influence of ICT user cost on ICT diffusion[14], Cette and Lopez (2012) calculate the contribution of these different factors to explain the ICT diffusion lag of the European countries and Japan compared to the US. It appears (see Graph 7) that market rigidities play a large role in the two areas, education in the Euro Area and ICT user cost also playing a large role in the UK and Japan respectively. In the UK, the ICT diffusion lag is small and comes mainly from education, market rigidities having even, because of a lower level than in the US, a positive impact on relative ICT diffusion.

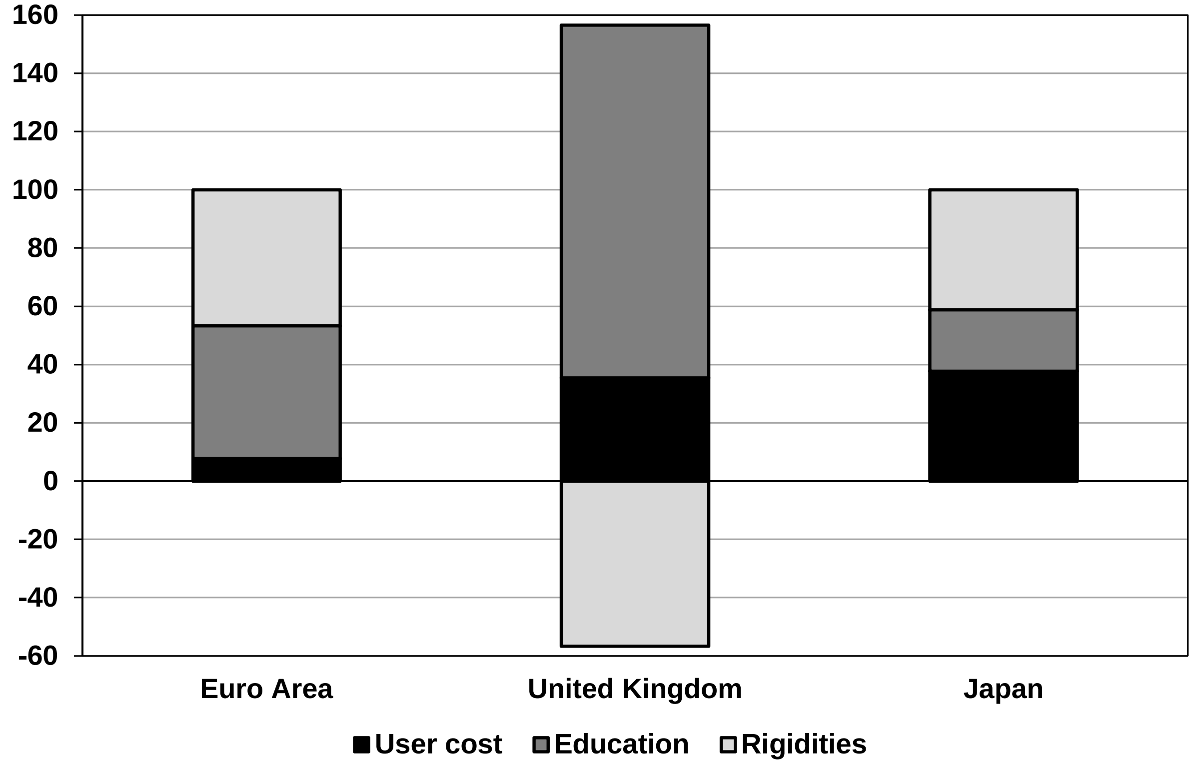
[12] *"By fully utilizing the vertical dimension, it will be possible to stack layers of transistors on top of each other and this 3D approach will continue to increase the number of components per mm² even when horizontal physical dimensions will no longer be amenable to any further reduction."* ITRS (2013, p 2)

[13] In a recent econometric analysis on a country*industry database, Cette, Lopez and Mairesse (2013) emphasize the large role of product market regulation on ICT diffusion.

[14] ICT user cost can differ among countries from differences in nominal and real interest rates.

Graph 7

Sources of ICT capital coefficient gap with the US in 2008
Whole economy - In % of the gap



Source: Cette and Lopez (2012).
The Euro Area is here the aggregation of Germany, France, Italy, Spain, The Netherlands, Austria and Finland. These seven countries represent together, in 2012, 88½% or the total GDP of the Euro Area.

These results confirm that structural reforms could reduce the ICT diffusion gap of the Euro Area and Japan compared to the US. Therefore, even in a pessimistic scenario of a long period of few improvements in ICT performances, European countries and Japan could benefit from an important ICT contribution on productivity growth by implementing structural reforms which would allow them to catch up the US level of ICT diffusion. And these structural reforms could help them to benefit from the possible second wave of ICT performance improvement, without substantial delay with the US. It means that in the optimistic scenario of a resurgence of the ICT performance improvement, European countries and Japan could successively benefit, concerning productivity growth, from the catch-up process of the US level of ICT diffusion and from the new ICT performance improvement wave.

6. Concluding remarks

As reminded in the introduction, productivity has slowed down in all advanced countries from the beginning of the 2000s, before the current crisis. All advanced countries already suffered from a productivity slowdown at the end of the 1960s or during the 1970s, and another one at the end of the 1980s or during the 1990s, except the US where we observe from the mid 1990s an acceleration due to a faster improvement of ICT productive performances. The present analysis focuses on the current period and the main outputs of the previous developments are the following: i) US national accounts and some other sources indicate that the ICT productive performances could be slowing down also from the beginning of the 2000s. On recent years, these improvements could even be almost nil. The productivity growth wave associated to the ICTs would then be smaller and shorter than the previous productivity wave associated to the 2nd industrial revolution, which happens during the XXth Century; ii) Nevertheless, we cannot exclude that this diagnosis could be due, at least partly, to some statistical mis-measurements of the ICT improvements. This doubt should vanish in some years, and in the case of a confirmation of these mis-measurements, it will appear that the US productivity is, since the early 2000s, more dynamic than the picture currently given by national accounts; iii) The pessimistic scenario of a slowdown gets some support from the fact that ICT productive capital diffusion seems to have stopped also since the beginning of the 2000s; iv) In the case of a confirmation of the pessimistic scenario, the US productivity growth could stay weak in the future, the non-ICT sources of productivity gains experiencing themselves some large headwinds characterized by Gordon (2012, 2013). Some of these headwinds concern not only the US but also other advanced countries; v) ICT performance improvements will probably be positively impacted, in some years, by large technological developments as for example the productive use, in computers, of the 3D chip. The timing of these improvements is still unknown but from it, the US productivity growth could benefit from a second ICT wave which could be as important as the first one; vi) The ICT diffusion in the non-US developed countries, mainly Europe and Japan, is lagging compared to the US. This lag is explained by institutional aspects: a lower education level, on average, of the working-age population and more regulations on labour and product markets; vii) By implementing structural reforms, these countries could benefit from a productivity acceleration linked to a catching-up of the US ICT diffusion level. And they could benefit without any delay with the US from the possible ICT productivity growth second wave.

Apart from the impact on ICTs, structural reforms may also have a large impact on productivity growth, in the US and also in other advanced countries (for recent analyses see for example Baily, Manyika and Gupta, 2013[15], for the US and Cette, Lopez and Mairesse, 2013, for the most advanced countries). It means that the future of productivity will depend, in all advanced countries, on technological progress (for example the productive use of the 3D chip) and also on institutional changes. These changes have a large potential role to play to reduce some brakes on productivity, to tackle some headwind productivity threats and, concerning the non-US countries, to help to catch up with the US level of ICT productive capital diffusion. This gives room for economic policies to play an essential role for the future of productivity growth.

[15] « *Technological opportunities remain strong in advanced manufacturing and the energy revolution will spur new investment, not only in energy extraction, but also in the transportation sector and in energy-intensive manufacturing. Education, health care, infrastructure (construction) and government are large sectors of the economy that have lagged behind in productivity growth historically. This is not because of a lack of opportunities for innovation and change but because of a lack of incentives for change and institutional rigidity.*” Baily, Manyika and Gupta (2013, p. 3).

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