Total Factor Productivity in Advanced Countries: A Long-term Perspective

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ABSTRACT

Changes in GDP during the 20th century have been mainly driven by total factor productivity (TFP). This article synthesizes results from our research based on the long period (1890-2015) productivity database we have constructed. In particular, we aim to refine our TFP measure by including the contribution of the improved quality of factor inputs and technology diffusion to TFP growth in four developed areas or countries: the United States, the euro area, the United Kingdom, and Japan. Two types of factor quality are considered: the average level of education and the average age of equipment. Two technological shocks corresponding to two general purpose technologies are investigated: electricity and information and communication technologies (ICT). However, even after these adjustments, long-term patterns of TFP growth do not change, with two major waves appearing over the past century and much of TFP growth remaining unaccounted for by quality-adjusted factors of production and technology diffusion. Our estimates show that the productivity impact of the recent ICT wave remains much smaller than that from the electricity wave, and that the post-1973 and the most recent slowdowns in TFP growth are confirmed.

GDP per capita indicators are often used to analyze standards of living.[2] This measure allows country comparisons that can be made either in terms of levels or growth rates, these

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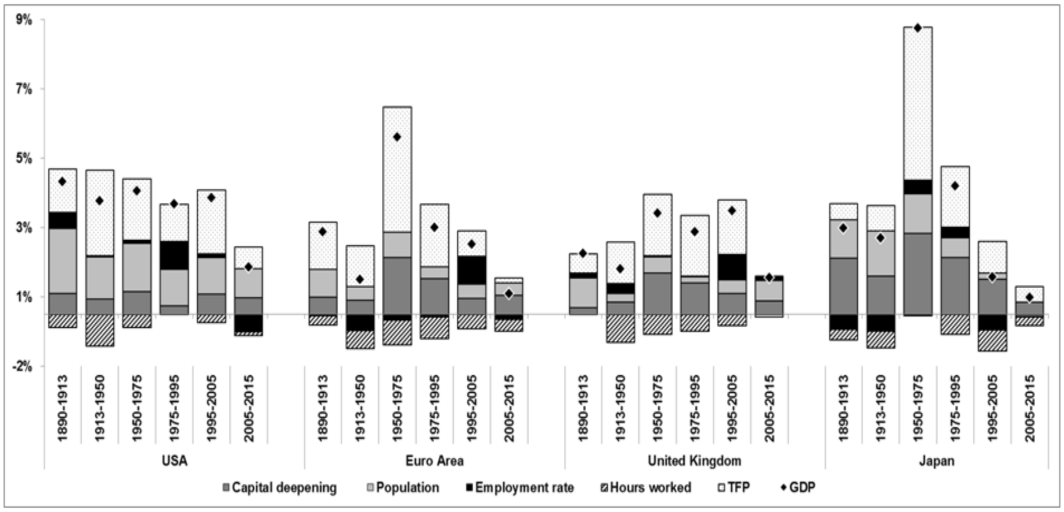
2 This measure is however frequently criticized, notably in the famous Stiglitz, Sen and Fitoussi (2009) report, as it excludes many dimensions that impact the well-being of the population.

Chart 1: Sources of Growth in the United States, the Euro Area, Japan and the United Kingdom - Total Economy, 1890-2015

Average annual contributions (percentage points)



Source: Bergeaud, Cette and Lecat (2015), updated in 2016.

Table 1: Sources of Growth in the United States, the Euro Area, Japan and the United Kingdom - Total Economy, 1890-2015

Average annual contributions (percentage points)

	USA						United Kingdom					
	1890-1913	1913-1950	1950-1975	1975-1995	1995-2005	2005-2015	1890-1913	1913-1950	1950-1975	1975-1995	1995-2005	2005-2015
GDP	3.8	3.3	3.5	3.2	3.4	1.4	1.7	1.3	2.9	2.4	3.0	1.0
Capital deepening	0.6	0.5	0.7	0.2	0.6	0.5	0.2	0.4	1.2	0.9	0.6	0.4
Population	1.9	1.2	1.4	1.1	1.0	0.8	0.9	0.3	0.5	0.2	0.4	0.6
Employment rate	0.5	0.0	0.1	0.8	0.1	-0.5	0.1	0.3	0.0	0.0	0.7	0.1
Hours worked	-0.4	-0.9	-0.4	0.0	-0.2	-0.1	0.0	-0.8	-0.6	-0.5	-0.3	0.0
TFP	1.3	2.5	1.8	1.1	1.8	0.6	0.5	1.2	1.8	1.8	1.6	-0.1

	Euro Area						Japan					
	1890-1913	1913-1950	1950-1975	1975-1995	1995-2005	2005-2015	1890-1913	1913-1950	1950-1975	1975-1995	1995-2005	2005-2015
GDP	2.4	1.0	5.1	2.5	2.0	0.6	2.5	2.2	8.2	3.7	1.1	0.5
Capital deepening	0.5	0.4	1.6	1.0	0.5	0.6	1.6	1.1	2.3	1.6	1.0	0.4
Population	0.8	0.4	0.7	0.3	0.4	0.4	1.1	1.3	1.1	0.6	0.2	-0.1
Employment rate	0.0	-0.5	-0.2	-0.1	0.8	-0.1	-0.4	-0.5	0.4	0.3	-0.4	0.0
Hours worked	-0.3	-0.5	-0.7	-0.6	-0.4	-0.3	-0.3	-0.5	0.0	-0.6	-0.6	-0.3
TFP	1.4	1.2	3.6	1.8	0.7	0.2	0.5	0.7	4.4	1.7	0.9	0.4

Table: Annual growth rate of GDP and its sources in the United States, the Euro Area, Japan and the United Kingdom – Total Economy, 1890-2015.

Box 1: The Long-Term Productivity Database

The database presented in this article (Bergeaud-Cette-Lecat or BCL database) has evolved continuously since its first version in 2013. As soon as the series are improved or new sources enable us to add countries to the database, a new version of the BCL database is constructed. The most recent version of the database can be found at www.longtermproductivity.com. The database currently covers 17 countries: United States, Japan, Germany, France, United Kingdom, Italy, Spain, Canada, Australia, the Netherlands, Belgium, Switzerland, Sweden, Denmark, Norway, Portugal and Finland. It is composed of series for GDP per capita, labour productivity, total factor productivity, average age of equipment, and capital intensity. The underlying series used to construct these measures (GDP, population etc.) are not currently available for download, but can be obtained by request. Data sources are described in a file in the database. The website provides an application that enables users to plot the latest series and to compare several countries. All of the data available on the website can be freely used provided that they are properly acknowledged. The Appendix to the article offers a longer description.

two dimensions being linked by convergence processes. The large literature devoted to this topic shows that numerous factors can influence GDP per capita growth and convergence (Baumol, 1986 ; Barro, 1991 being ones of the seminal papers). Numerous factors can influence GDP per capita growth and convergence. The most important appear to be institutions, education, and of course innovation and technological progress, which are in turn linked to education and institutions.[3] In Bergeaud, Cette and Lecat (2015), we have shown that there is an overall convergence process among advanced countries, mainly after WWII, relying mostly on capital intensity and then on TFP, while developments in hours worked and employment rates are more contrasted. But this convergence process is not continuous and slowed down or was even reversed since 1990, as the convergence of the euro zone, the UK, and Japan stopped well before attaining the U.S. level of GDP per capita.

In this article, we review some of the findings from our earlier research based on an original database for 17 developed countries from 1890 to 2015. The construction of this dataset is described in the Appendix, and at length in Bergeaud, Cette and Lecat (2016a, 2016b). All of this can be found in a dedicated website (see Box 1 for more information).[4] In a nutshell, we built capital data from investment series divided into five different assets (structures, communication equipment, computers, software, and other non-ICT equipment) on the assumption of constant depreciation rates for each of the five asset classes (See Appendix). This allows one to account for the shift from structures to equipment that occurred around the 1920s, the emergence of ICT capital, and overall to better measure the stock of capital. For investment, (GDP, labour, and population), we rely on the updating of the estimates of economic historians such as Angus Maddison and others by Bolt and Van Zanden (2014), as described in Bergeaud, Cette and Lecat (2016a).

3 On the role of education and institutions, see for example Barro (1991), Barro and Sala-I-Martin (1997), and, for more recent assessments, Aghion *et al*. (2008); Madsen (2010a and 2010b); Craft and O'Rourke (2013); and Acemoglu *et al*. (2014). On the impact of institutional and educational factors on innovation and technological progress, see, among others, Aghion and Howitt (1998, 2006 and 2009).

4 www.longtermproductivity.com

Chart 1 and corresponding figures in Table 1 show average GDP growth rates for different sub-periods of the whole 1890-2015 period for the three developed countries (United States, Japan and the United Kingdom) and the euro zone.[5] Chart 1 also provides an accounting decomposition of GDP growth based on a simple Cobb-Douglas production function.[6] In this decomposition, the three main components of GDP growth are population growth, the growth in the number of hours worked per inhabitant and hourly labour productivity growth. The contribution of the number of hours worked per capita to growth is itself decomposed into two sub-components: the employment rate, here the ratio of employment to the total population, and the number of hours worked per worker. The sum of the population and average working time per worker components corresponds to the overall contribution of the total number of hours worked to growth. And the contribution of hourly labour productivity growth is itself also decomposed into two sub-components: total factor productivity (TFP) and capital deepening.

Formally, $GDP = TFP K^{\alpha}(LH)^{(1-\alpha)}$ with K being the stock of physical capital, L the number of workers, and H the average annual hours worked per worker, so that (LH) represents the total number of hours worked. Denoting the total population as Pop, we have:

$$GDP = TFP \times \left(\frac{K}{LH}\right)^{\alpha} \times \left(\frac{L}{Pop}\right) \times H \times Pop \quad (1)$$

Where capital deepening is represented by $(K/(LH))^{\alpha}$, and the hourly labour productivity is $TFP \times (K/(LH))^{\alpha}$. As well, employment rate is determined by $L/(POP)$, and the number of hours worked per employee is H. Log differentiating this last expression gives the decomposition that is represented in Chart 1.

Chart 1 shows that hourly labour productivity growth is the main contributor to GDP growth in the four economic areas considered. The overall contribution of hours worked (which corresponds to the sum of the contributions made by change in the population, the employment rate and average working time) is generally small, if not nil. Within hourly labour productivity growth, the contribution of the TFP sub-component is the largest, with that of capital deepening being smaller. The TFP contribution varies considerably from sub-period to sub-period, with these variations generally being the main driver of changes in GDP growth. However, in our accounting we define TFP as a residual encompassing any variation of output that cannot be explained by the aggregation of physical capital and labour. As such, Chart 1 gives no real explanation for these large changes in GDP growth other than the small fluctuations explained by the hours worked component. This is why, as Abramovitz (1956) wrote, TFP is traditionally considered 'a measure of our ignorance.'

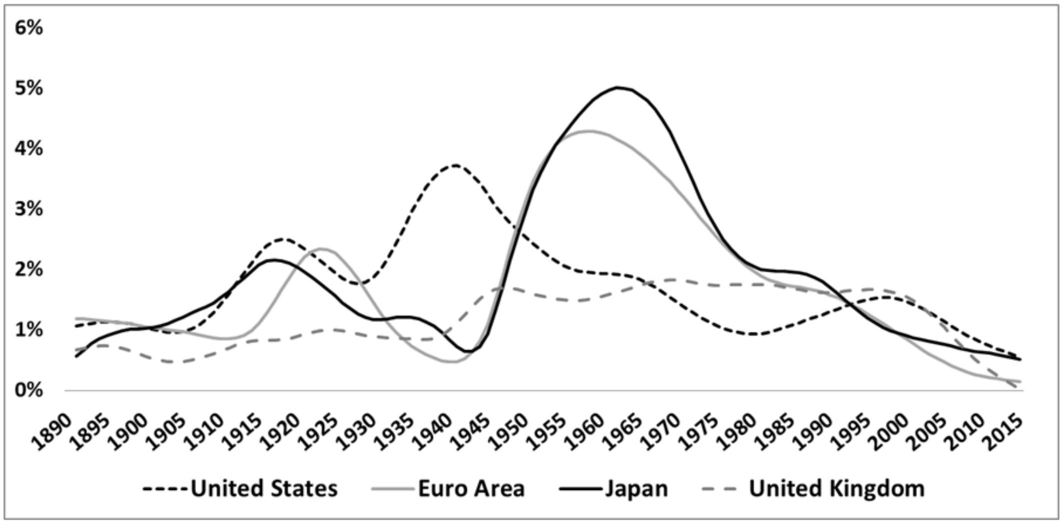
GDP growth appears very low during the 2005-2015 sub-period in the four economic areas studied. And the main reason for this low growth is a small contribution from TFP, especially when compared with previous sub-periods. Once again, our accounting framework cannot give any more insight on this slowdown

5 The euro area is defined as the aggregation of the zone's eight of the largest countries: Germany, France, Italy, Spain, the Netherlands, Belgium, Portugal and Finland. These countries represent more than 93 per cent of the euro area's 2010 GDP. See Bergeaud, Cette and Lecat (2016a) for more details.

6 In this decomposition, we assume constant returns to scale and an elasticity of output to capital that is constant and equal to 0.3 in the four economic areas for the whole period. For more details, see Bergeaud, Cette and Lecat (2015).

Chart 2: Trend TFP Growth in the United States, the Euro Area, United Kingdom and Japan, Total Economy, 1890-2015 (average annual growth rate)

Smoothed indicator (HP filter, λ = 500) - Whole economy



Source: Bergeaud, Cette and Lecat (2016a), updated in 2016.

since it is driven almost entirely by a slowdown in TFP growth.

These observations raise important questions: are we facing a risk of 'secular stagnation'? This expression was coined by Hansen (1939) and was used again to describe the current situation notably by Summers (2014, 2015) and Eichengreen (2015). This low TFP growth is now well documented and affects most of the advanced economies.[7] In our four areas, the slowdown of TFP can be observed from the end of the 1960s, and intensifies during the 1970s, the 1980s and the 1990s. One notable exception is the UK, which experienced very steady TFP growth from the 1950s to the late 1990s (Broadberry and O'Mahony, 2004) and had more rapid TFP growth during the period 1975-2005 than 1950-1975. As for the United States, we clearly observe from the mid-1990s an acceleration due to faster improvements in the productive performances of information and communication technologies (ICT hereafter). Jorgenson (2001) was the first of numerous economists to stress this point. For some authors such as Gordon (2012, 2013, 2014, 2015), this situation could be the future for long-term productivity.

TFP plays the most important role in explaining GDP dynamism. As shown in Bergeaud, Cette and Lecat (2015), convergence across advanced countries, which took place mostly in the post WWII period, proceeded mostly from TFP convergence, followed by capital deepening. Rapid TFP growth in the euro area and Japan in 1950-1975 represented catching up to the TFP level generated by the rapid TFP growth experienced by the United States over the 1913-50 period.

We now seek to refine our measure of TFP by including factor quality adjustment and technology diffusion indicators over the 1890-2015 period. In other words, we investigate the importance of some potential factors that can

7 See for example for the United States, Gordon (2012, 2013, 2014, 2015), or Byrne, Oliner and Sichel (2013), and for other advanced countries, Crafts and O'Rourke (2013), or Bergeaud, Cette and Lecat (2016a).

improve our measure of TFP growth in order to better understand changes in growth and to give insight into why TFP growth has been low over the 2005-2015 sub-period. We consider two factor quality dimensions: the average level of education and the average age of equipment. Two technological shocks corresponding to two general purpose technologies are then examined: electricity and ICT. This analysis is performed for our four major economic areas using annual data.

Our main contribution is to show that including the quality of factors of production, especially education and technological shocks, significantly reduce the share of 20th century GDP growth that is unexplained. Nevertheless, still this share remains important, which suggests that there is scope for further analysis to better measure TFP growth.

The article is organized as follows. Section 2 provides a detailed descriptive analysis of TFP growth waves. Section 3 refines our measure of TFP and presents a TFP decomposition, taking into account some factor quality and technological shock aspects. Section 4 comments on two contrasting growth scenarios. Section 5 concludes.

TFP Growth Waves over the Long Period, 1890-2015

In order to establish long-run stylized facts in terms of TFP growth, we follow the analysis of Bergeaud, Cette and Lecat (2016a) and smooth the annual TFP growth rate over the whole period using the Hodrick-Prescott filter (HP). Given the very high volatility of the TFP indicator, the choice of the filter bandwidth, which sets the length of the cycle we capture, is important. We decided to focus on 30-year cycles, which implies a value of 500 for lambda, according to the HP filter transfer function. This values can be rationalized by considering the typical duration between two global statistical breaks in the TFP time series as measured in Bergeaud, Cette and Lecat (2016a) (for example between WWII and the oil crisis). Chart 2 shows smoothed TFP growth, from 1890 to 2015, for the United States, the euro area, the United Kingdom and Japan.

We distinguish five sub-periods from 1890 to 2015.[8]

- From 1890 to WWI, TFP grew moderately. Developed countries were at the end of the very long first Industrial Revolution linked to the spread of the steam engine and the development of the railways. The UK enjoyed the highest level of TFP.
- After the WWI slump, the United States experienced an impressive 'big wave' of TFP growth, interrupted for some years during the Great Depression and identified by Gordon (1999) as the 'one big wave'. Other countries struggled with the legacy of the Great Depression and WWII. This TFP growth wave corresponds to the second Industrial Revolution (Gordon, 2012, 2013, 2014, 2015) linked to the spread of large-scale use of electricity and the internal combustion engine, to the development of chemistry, namely oil-based chemistry and pharmaceuticals, and to the development of communication and information innovations (telephone, radio, cinema), etc. During this sub-period, the US took the lead in terms of TFP, which it has retained up to the present day.[9]
- After WWII, european countries and Japan benefited from the big wave experienced

8 These sub-periods can be endogenously identified through time series analysis. For more details, in particular regarding TFP levels, see Bergeaud, Cette and Lecat, 2016a.

9 Some countries have a higher TFP level over the period for specific reasons, for example Norway due to its particular sectoral composition.

earlier in the United States. During this catch-up process, TFP growth was decelerating in the United States. This TFP slowdown appeared later, from the 1970s onwards, in the other three areas.

- After 1995, the post-war convergence process came to an end as US TFP growth overtook that of other countries, although it did not return to the pace observed in the 1930s, 1940s and 1950s. Of more limited duration and less revolutionary than the first wave, a second TFP wave appeared in the United States and, in a less explicit way, in some of the other advanced countries. As documented in numerous studies (e.g. Jorgenson, 2001, van Ark *et al.*, 2008, Timmer *et al.*, 2011, Bergeaud, Cette and Lecat, 2016a), this TFP wave corresponded to the third Industrial Revolution linked to ICT.
- From the mid-2000s, before the beginning of the Great Recession, TFP growth decreased in all countries. The current pace of TFP growth appears very low compared to what was observed previously, except during the world wars. Some analyses regard this slow growth as structural (Gordon 2012, 2013, 2014, 2015); others as a pause before a new acceleration (Pratt, 2015; Mokyr *et al.*, 2015; Brynjolfsson and McAfee, 2014); and still others as at least partly mismeasurement (Byrne et al., 2013).[10] Other explanations of this slowdown are also plausible (for a survey, see Cette, 2014, 2015 and OECD, 2015).

Refining our TFP Measure

We try to better measure TFP growth by accounting for factor quality and technological shocks.[11] Two types of factor quality dimensions are considered: the average level of education and the average age of equipment capital stock. Two technological shocks are considered, corresponding to the two General Purpose Technologies examined: electricity and ICT.

Impact of Education

Regarding education, which is an indicator of labour force quality, we use new series on educational attainment for the population 15 and over developed by van Leeuwen and van Leeuwen-Li (2014) available yearly from 1870 to 2010.[12] The average duration of schooling increases continuously over the period in the four economic areas. At the end of the 19th century, Japan was the area with the lowest level of educational attainment with on average less than 2 years of education among its population. The other three areas recorded about 4 years of education. At the end of our dataset, the euro area has the lowest level of education, with an average duration of 11.5 years, less than the other three areas which had 12.5 to 13 years. 13 years seem to be a maximum for the average duration of schooling, which means that TFP gains from the increase of this duration belong to the past for the United States, the United Kingdom and Japan, and that few gains remain to be obtained from this for the euro area.[13]

10 Syverson (2016) and Byrne, Fernald and Reinsdorf (2016) argue that measurement error in the growth of the ICT sector cannot explain the current observed productivity slowdown. Aghion *et al.* (2017) estimate that at most one sixth of the decrease in the productivity growth rate from the 1996-2005 period to the 2005-2013 period could be attributed to mismeasurement.

11 Estimates are all made using instrumental variables approaches on a panel of 17 countries over the period 1890-2010, and 1913-2010 in the case of electricity. See Bergeaud, Cette and Lecat (2016b) for details concerning estimation procedures.

12 The calculation starts with primary school and does not include kindergarten or any other type of education received before 6.

13 Productivity gains from education could now be sought by improving the quality of education and promoting continuous education, with a potential significant impact of ICT in this area. Further improvements in the quality of labour could also stem from on-the-job training and learning.

The rather low level of education achieved in the euro area hides large disparities among countries. Some countries like the Netherlands, Germany and France have levels of educational attainment comparable to that of the United States. On the other hand, other countries such as Spain, Portugal and Italy lag behind. For example, the average duration of schooling in Portugal in 2010 was below 8 years.

Many studies, using micro or macro approaches, have focused on estimating the returns on education, corresponding to the wage or productivity gains associated with an average increase of one year in educational attainment. There is a broad empirical consensus in most micro studies on a private return on education of between 4 per cent and 8 per cent in developed countries. The standard equation for the macroeconomic return to education takes the following form (Barro and Lee, 2010):

$$gdp - l - h = (\alpha(k - l - h)) + (1 - \alpha)\theta s + \varepsilon \tag{2}$$

Where a lower case x stands for the logarithm of variable X from equation (1), s is our measure of education attainment, ε is a residual that we will consider to be an improved measure of TFP and $gdp–l–h$ is the log of labour productivity. Finally, θ is a coefficient measuring the impact of education on productivity. Our estimates of this equation indicate a return of education to GDP of 4.9 per cent, which means that an increase of one year in educational attainment would increase labour productivity (or TFP as typically measured) by 4.9 per cent. From this result, and from the fact that education attainment increased by 7 to 11 years in our four areas, we can attribute 16-23 per cent of the cumulative rise in TFP over the 1890-2010 period to rising education; that is, 34.3 percentage points (4.9 per cent x 7 years) to 53.9 percentage points (4.9 per cent x 11 years) over the long period starting in 1890. Of course, this result rests upon the assumption that the elasticity of productivity with respect to education is constant across time and countries. We make this assumption in order to produce estimates comparable with the literature (e.g. Barro and Lee, 2010). It is also consistent with our assumption of constancy for other parameters (e.g. the depreciation rate and the elasticity of substitution between capital and labour).[14]

We have calculated the average age of the capital stock for equipment. This is an indicator of the quality of this factor and should therefore be incorporated into the production function. We estimate the contribution of this factor from a Solow residual regression, as we cannot calibrate directly the quality correction we should apply to the capital stock. This simply corresponds to the intuitive idea of a vintage effect: older capital is expected to be less productive than newer capital, as suggested by Solow (1959, 1962) and developed subsequently by numerous authors (Gittleman *et al.*, 2003; Wolff, 1991, 1996; Greenwood *et al.*, 1997; Mairesse, 1977, 1978; Mairesse and Pescheux, 1980; Cette and Szpiro, 1989). In theory, capital stock series should be constructed using quality-adjusted investment series (through appropriate investment deflators). Changes in average age would then not impact TFP. But national accounts can only partially take into account embodied technical progress, which is not fully included in declines in investment prices and increase in real investment. Consequently, the accounting split between capital deepening and TFP within labour productivity growth is biased in favour of

14 There is evidence that suggests a decline in the marginal return from educational attainment due to the fact that tertiary education yields lower gains in terms of productivity than primary and secondary schooling (Psacharopoulos and Patrinos, 2004).

the latter. Using an indicator of the age of equipment is therefore a way to correct this bias and to consider the impact of embodied technical progress.

It appears that variations in the average age of equipment differ across economic areas: the range of these variations is 5 years for Japan (from a minimum of 4 years to a maximum of 9 years), 4 years for the euro area (from 5.3 years to 9.3 years), and 3 years in the United States (from 5.7 years to 8.7 years) and the United Kingdom (from 6 years to 9 years). The average age increased significantly during the Great Depression in the United States, resulting from low investment; it greatly decreased during WWII due to the war effort, and more modestly during the ICT wave, as investment was needed to incorporate the new technology. In the euro area and the UK, it increased strongly during WWII, as the conflict depressed investment, and decreased in the post-war reconstruction period. It has been on an increasing trend since 1990 in Japan due to the banking crisis, and since the financial crisis in other areas, as credit constraints and low demand prospects weigh on investment. Smaller conter-cyclical fluctuations can be observed.

As with education, many studies, using micro or macro approaches, have estimated the impact of changes in the average age of capital on TFP. The results show that an increase of one year in the average age usually had a negative impact on TFP of -1 per cent to -6.5 per cent, with results concentrated around -4 per cent. Using an equation we include a regressor to capture the effect of the age of capital stock, similar to the one for education. We estimate an impact of -3 per cent, which means that average age variations during the period, from the minimum to the maximum values of capital age, would have changed TFP levels by 15 per cent (3 per cent x 5 years) in Japan, 12 per cent (3 per cent x 4 years) in the euro area, and 9 per cent (3 per cent x 3 years) in the United States and the United Kingdom. On average over the whole period, age plays no role in explaining changes in GDP and only has cyclical effects.

Impact of Electricity

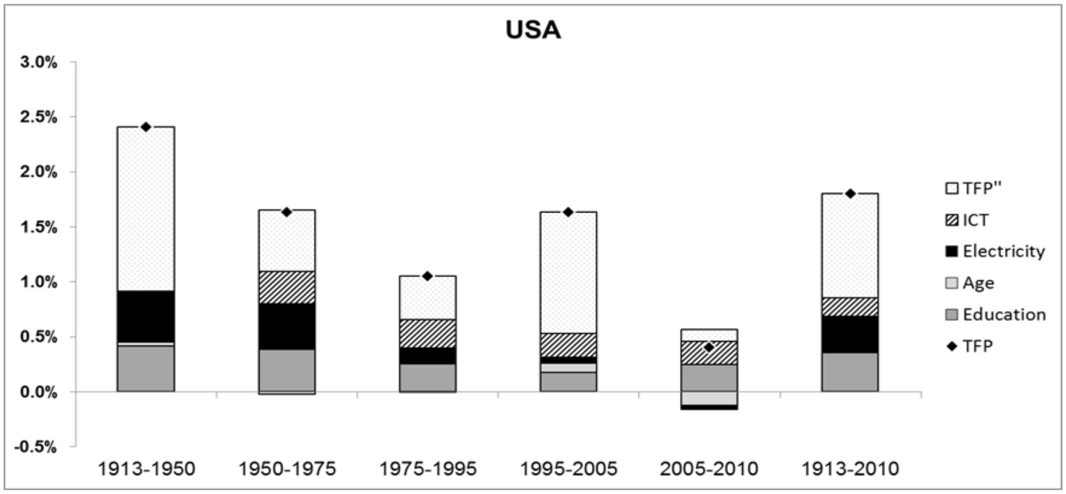
To measure the diffusion of technology over the whole period, we have drawn on the CHAT database constructed by Comin and Hobijn (2009). This database provides annual estimates of the diffusion of more than 100 technologies for a large set of countries. We have selected one technology which is often considered to be representative of the development of technologies during the 20th century, i.e. the production of electricity in kilowatt hours (Comin *et al.*, 2006a and 2006b). Data have been completed with series using the World Development Indicators from the World Bank up to 2013 and have been standardized by total population.

This indicator, which we consider as a proxy for the diffusion of electrical machinery and devices, has increased over time in the four economic areas, but this rate of increase has slowed since the 1970s. In line with the literature that focuses on the impact of electricity on US productivity growth (Bakker *et al.*, 2015), the take-off of electricity in the United States started at the beginning of the 20th century and accelerated during the 1920s. The UK lags just behind with a take-off that started in the 1930s, while the euro zone and Japan started to massively adopt electricity after WWII. The take-off date depends both on the fall in electricity prices and on a reorganization of the production process to fully benefit from electricity (David, 1990).

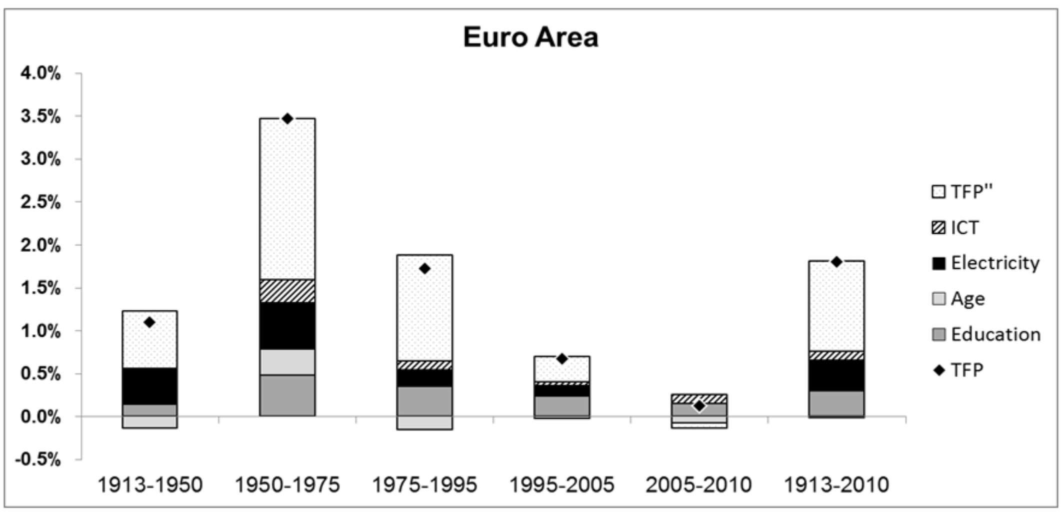
Here again, we make the assumption that the elasticity of TFP to electricity production per inhabitant is constant over time. The constant elasticity assumption, as it has also been used for the impact on productivity of education and capital age, appears preferable to an ad hoc rule.

Chart 3: Factors Affecting TFP Growth, Total Economy, 1913-2010 (contribution in percentage points)

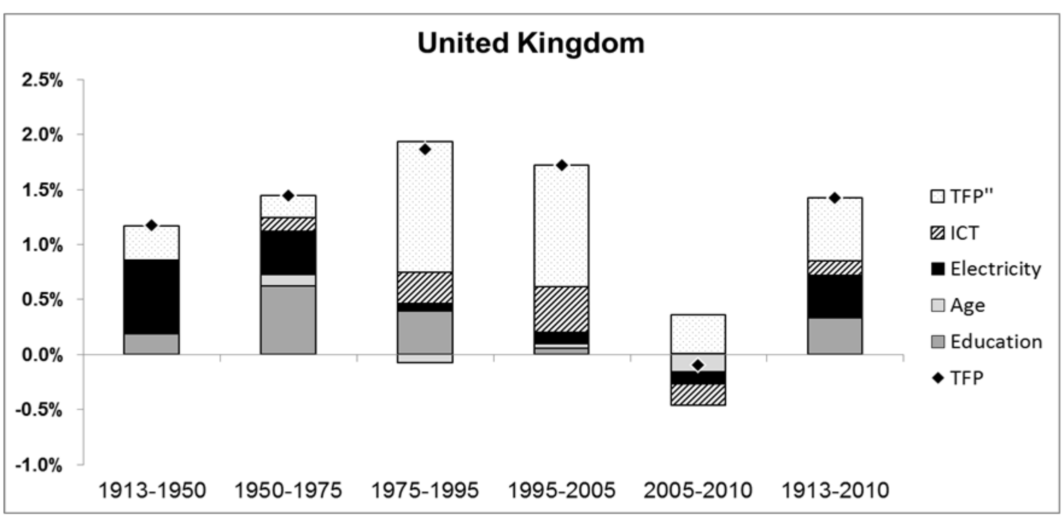
Panel A:



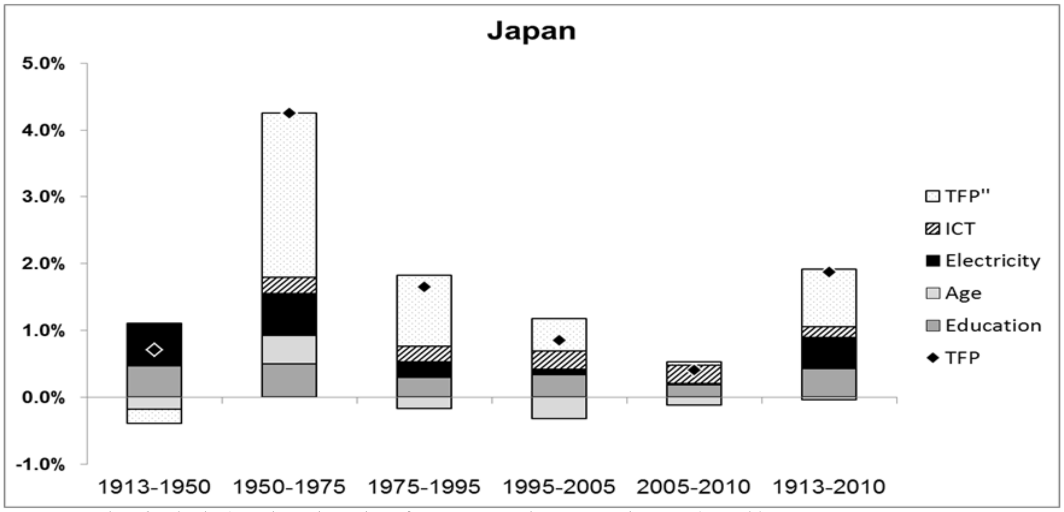
Panel B:



Panel C:



Panel D:



Source: Authors' calculations based on data from Bergeaud, Cette and Lecat (2016b).

Our results indicate that a 1 per cent increase in electricity production per capita explains a 0.079 per cent increase in TFP. With this elasticity, it appears that, from 1913 to 2010, the increase of electricity production and use would have increased the TFP level by 31 percentage points in the United States, 35 points in the euro area, 37 points in the United Kingdom, and 46 points in Japan.

Impact of ICT

Concerning the second measure of technology, we have taken the ratio of the stock of ICT capital to GDP in nominal terms. To compute this ratio, we have drawn on the work of Cette *et al.* (2015) based on investment data provided by the OECD. ICT is split into three components: hardware, software, and communication equipment. The ICT capital stock is computed using a permanent inventory method. Note that for ICT, we have used a stock measure while for electricity we have used a measure of production. However, electricity production should reflect productive capacity, as electricity cannot be stored, electricity imports and exports are low relative to production, and utilization of productive capacities should not create a systematic bias. It appears that the ICT capital stock took off in the 1980s in the United States, peaking at the end of the 1990s. ICT diffusion in the United States settled at a higher level than in the euro area, the United Kingdom and Japan.

Numerous studies provide explanations for these international differences in ICT diffusion.[15] Factors include the level of post-secondary education among the working age population as well as labour and product market rigidities. For example, an efficient use of ICT requires a higher degree of skilled labor than the use of other technologies. The required reorganization of the firm for effective ICT adoption can be constrained by strict labour market regulations. Moreover, low levels of competitive pressure, resulting from product market regulations, can reduce the incentive to exploit the most efficient production techniques. A number of empirical analyses have confirmed the importance of these factors.[16] Among others, Cette and Lopez (2012) show, through an econometric

15 See Schreyer (2000), Colecchia and Schreyer (2001), Pilat and Lee (2001), Gust and Marquez (2004), Van Ark *et al.* (2008), Timmer *et al.* (2011), and Cette and Lopez (2012).

approach, that the United States benefits from the highest level of ICT diffusion because of a higher level of post-secondary education among the working age population and less restrictive product and labour market regulations.

Our estimates indicate that a 1 percentage point increase in the ratio of ICT capital stock to GDP would lead to an increase of 1.56 per cent in the level of TFP. With this elasticity, it appears that, from 1913 to 2010, ICT diffusion as a production factor would have increased TFP by 14 per cent in the United States, 9 per cent in the euro zone, 11 per cent in the United Kingdom and 13 per cent in Japan. This impact is of course concentrated in the post-1950 period.

From these results, we build two new TFP indicators. TFP' is TFP corrected for the impact of the duration of education and changes in average capital equipment age. TFP'' is TFP' corrected for the impact of electricity production per inhabitant and changes in the ICT capital to GDP ratio. In Panels A to D of Chart 3, we present results for the four areas for the same benchmark years as in Chart 1, but starting in 1913 because of the high volatility of electricity production before that period and ending in 2010 because of the availability of education data.

From Chart 3, we see that variations in human capital and the age of capital are significant omitted factors in the estimation of TFP growth. Over the whole 1890-2010 period, human capital and the age of physical capital together account for 21 per cent of US TFP growth, 17 per cent in the euro zone, 25 per cent in the United Kingdom and 26 per cent in Japan. However, it appears that the amplitude of TFP' growth does not differ much from that of TFP. In particular, the 'one big wave' that occurred during the 20th century is still persistent with respect to the United States. This is also the case for the wave in the mid-1990s. This result is robust to different sets of credible values concerning the elasticity of TFP to the duration of education and to the average age of capital.

Nevertheless, education significantly contributed to the first TFP wave in the US, with a contribution of 0.42 percentage point per year during the 1913-1950 period, only slightly decreasing in the following periods (0.38 points in 1950-1974 and 0.34 points in 1974-1990), consistent with findings of Goldin and Katz (2008). Hence, the early opening-up of education to the masses in the US yielded a lasting contribution to productivity and partly explains the American lead. Indeed, the increase in the contribution of education appears one period later, in the 1950s, in the euro zone and the United Kingdom. In Japan, education posts a significant contribution throughout the century due to the initial very low level of education.

The age of capital makes a significant positive contribution mainly during the reconstruction period after World War II in the euro area and Japan, and also in the United Kingdom. Conversely, it has made a significant negative contribution since the 1970s in the euro area and Japan. In the four areas, equipment has aged from the 2000s, with a negative contribution to TFP growth.

The TFP growth waves are still evident in TFP', which is also corrected for the impact of the two General Purpose Technology shocks considered (electricity and ICT), especially as far as the 'one big wave' is concerned. However, the amplitude of this 'one big wave' has been reduced and is almost 40 per cent lower for TFP'' than for TFP' in the United States. Although the difference in contribution is not

16 See Gust and Marquez (2004), Aghion et al. (2009), Guerrieri *et al.* (2011) and Cette and Lopez (2012) who use country-level panel data, as well as Cette *et al.* (2017) who employ sectoral-level panel data.

very large across areas, the spread of electricity contributed significantly to the American advance on the euro zone, as its contribution peaked in the 1913-1950 period, while it increased during the 1950-1974 period in the euro zone. The United Kingdom appears not to have lagged in terms of the diffusion of electricity, with a very large contribution in the 1913-1950 period.

Broadberry and Crafts (1990) trace the productivity lead that the United States achieved over the United Kingdom during this period to barriers to competition allowing high-cost producers to remain in business. The contribution of ICT to TFP growth appears to be smaller than that of electricity in all four economic areas. This result seems consistent with results from Crafts (2002) and Jalava and Pohjola (2008). A possible explanation is that the diffusion of electricity was concomitant with the increasing skill of the labour force, robust post-war investments and a young population, which was not necessarily the case with ICT. The low contribution of ICT diffusion to the second productivity wave (the gap between TFP' and TFP" from ICT diffusion is not large) may be due to an underestimation of the productivity wave itself or of ICT diffusion.

Indeed, due to the price decrease of this type of product, investment in ICT can accelerate the capital deepening process in ICT-using industries, leading to an increase in capital intensity and hence in labour productivity, but not necessarily in TFP. But, as already noted, national accounts take only partially into account the embodied technological progress in ICT investment price indexes, which means that it is not fully included in increases in investment volume and falls in investment prices (see the synthesis by Van Ark, (2016) on these aspects). Consequently, the accounting split between capital deepening and TFP within labour productivity growth is biased, the role of the capital deepening component being undervalued and, conversely, the role of TFP growth being overvalued.

ICT investment data compiled by national accountants (and taken into account here as ICT investment) underestimate productive ICT expenditure. Indeed, spending on ICT is regarded as investment only when the corresponding products are physically isolated. Therefore, generally speaking, ICT that is included in productive investment (for example machine tools or robots) is not counted as ICT investment but as intermediate consumption of companies producing these capital goods. Beretti and Cette (2009) and Cette *et al.* (2016) correct macro ICT investment data by considering intermediate consumption in ICT components integrated in non-ICT productive investment. Their main result is that the amount of 'indirect ICT investment' appears to be significant.

How can we further improve measurement of TFP in order to reduce the share of unexplained GDP growth? A first way would be to include the quality of the labour input in the production function, for example by trying to measure the quality of education. Second, spillovers from both capital and labour that we are not factoring in can be captured. Third, other fundamental innovations that are encompassed by TFP can be identified and estimated.

What to Expect for the Future?

Regarding the productivity slowdown observed during the 2000s, analyses carried out by the OECD at the firm level suggest that this slowdown does not appear to be observed for the most productive firms, in other words, at the productivity frontier (Andrews et al., 2015). The productivity slowdown appears to be a diffusion problem from the best performances at the frontier to the laggard firms. This diffusion problem seems to hinge on the nature of innovations at the current juncture, with intangible capital being more difficult to replicate, or on a winner-takes-all phenomenon in ICT sectors. The puzzle is why such innovation diffusion difficulties appear to have become worse simultaneously in all developed countries, which are at different stages of development.

Work in progress at the Banque de France on French firms confirms the OECD results but suggests complementary explanations. The cleansing mechanisms may indeed have become weaker. One explanation being tested is that this weaker cleansing mechanism could at least partly be explained by a decline in real interest rates and less expensive capital, which allow low-productivity firms to survive and highly productive firms to thrive. Less expensive capital lowers the return on capital expected from firms and allows innovative firms to take on more risks. But this could also contribute to capital misallocation, as financing becomes less selective on the main innovative projects. Recent researchers have found that such an explanation may be relevant for Southern European countries such as Portugal, Italy and Spain (see for example Reis, 2013; Gopinath *et al.*, 2015; Gorton-Ordonez, 2015; and Cette, Fernald, Mojon, 2016).

Nevertheless, the omitted factors in the estimation of TFP growth continue to remain largely a mystery. For this reason, future productivity and GDP growth is very hard to forecast and different scenarios are credible. Cette, Lecat and Marin (2017) develop a growth model calibrated to test various scenarios over the very long-run (up to 2100). They show how different perspectives on future trends in innovation and its impact on TFP can yield dramatically different outcomes. They stress the need to deepen our knowledge of the main drivers of GDP through examination of past trends.

Conclusions

Long-term explainations for trends in GDP per capita are needed to understand long-term developments in living standards. This article is a synthesis of several previous contributions based on an original database over the long 1890-2015 period for the four main developed areas: the United States, the euro area, the United Kingdom, and Japan. We decompose GDP growth into its main components through an accounting breakdown. These components are TFP, capital intensity, working time, the employment rate, and population. It appears clearly that changes in TFP growth are the main driver of changes in GDP growth. We then go further to explain changes in TFP growth.

We attempt to capture empirically the contribution of factor quality and technology diffusion to TFP growth. In other words, we refine the measurement of TFP to better explain changes in GDP and in particular low growth over the last sub-period 2005-2015. Two types of factor quality are considered: the average level of education and the average age of the capital stock. Two technological shocks corresponding to General Purpose Technologies are considered: electricity and ICT.

Our main contribution is to present estimates of the impact of changes in the quality of labour and capital, and the impact of technological shocks, on the measurement of TFP. But this is still not enough to explain a large part of TFP growth, and the productivity waves remains largely unexplained. This means that we have to go further in future analysis to explain growth. As we do not have complete knowledge and understanding of what drives GDP growth, forecasting the future course of growth is very difficult.

Policies can influence TFP and GDP per capita growth. Relevant policies are ones that support innovation and foster greater productivity benefits from technological shocks. Examples are policies to reduce anti-competitive barriers on the product market, introduce more flexibility into the labour market, and increase the education level of the working age population (see on these aspects Aghion and Howitt, 1998, 2006, 2009, and Aghion *et al*. 2008 for an empirical illustration). The challenge in the coming years for the four economic areas considered in this analysis will be not to miss the opportunities arising from a possible new TFP growth wave linked to a new technology shock. The increase of the participation rate in the euro area over the past two decades illustrates the large role played by policy. But compared to the United States, GDP per capita in the euro area still suffers from lower employment rates, which gives room for new policies.

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Appendix: Construction of the Series

In this appendix, we describe our dataset more in details and explain some of the choices we made regarding the estimation of TFP.

Background

The Bergeaud, Cette and Lecat (BCL) long term productivity database was created in 2013 as part of an effort to update the long-term TFP series used in Cette *et al*. (2009). The database is updated yearly. More countries are added when information becomes available. The latest vintage of the database can be downloaded from the website: www.longtermproductivity.com. In 2016, the current version of the BCL database includes 17 countries: the United States, Japan, Germany, France, the United Kingdom, Italy, Spain, Canada, Australia, the Netherlands, Belgium, Switzerland, Sweden, Denmark, Norway, Portugal and Finland. Series are available for labour productivity, GDP per capita, capital intensity, average age of equipment, and TFP, defined as the Solow residual of a Cobb-Douglas production function with two inputs: capital stock and total hours worked.

Main hypothesis

To calculate our TFP series we need data on real GDP (Y), total hours worked (H), employment (N), population (P) and real capital stock (K). Capital stock estimates are based on long-term information on investment (I). Series for GDP and capital are given in national currencies, expressed in constant 2010 prices, and converted to US dollars by purchasing power parity (PPP) estimates for 2010, with a conversion rate from the Penn World Tables.

The perpetual inventory method (PIM) is used to construct the capital series from data on investment. Equipment and building investment (IE and IB) and capital (KE and KB) are distinguished with different life expectancy. The annual depreciation rates, noted δ, have been chosen according to Cette *et al*. (2009 and 2015) as 10 per cent for non-ICT equipment, 30 per cent for software and computers, 15 per cent for communication equipment and 2.5 per cent for buildings. In addition, for each year, we updated the given capital stock with a war and natural disasters damage coefficient (d_t) (with $0 \leq d_t \geq 1$) in order to take into consideration capital destruction.

The PIM corresponds to the relation $K_{\tau+1}=(K_\tau\times(1-\delta)+I_\tau\times\sqrt{1-\delta})\times(1-d_{\tau+1})$ This relation assumes that the whole investment is done in one flow and in the middle of the year which explains that a part of it is slightly depreciated with a coefficient $\sqrt{1-\delta}$ at the end of the year.

In order to calculate K_t for every year, we need to initialize the capital stock at t_o. To do so, we considered that on the long run, the growth of capital follows the average growth of GDP. We calculated the average growth rate from the first year available to the data up to 1913 for each country. Let g be this growth (initial war and natural disasters damage coefficient is assumed to be null):

$$g=\frac{K_{\tau_{o+1}}-K_{\tau_o}}{K_{\tau_o}}=-\delta+\sqrt{1-\delta}\times\frac{I_{\tau_{o+1}}}{K_{\tau_o}}$$

or equivalently:

$$K_{\tau_o}=\frac{\sqrt{1-\delta}}{\delta+g}\times I_{\tau_{o+1}}$$

In the estimation of capital stock, we have made a strong hypothesis by assuming coefficient δ is constant in time over time for each of the two asset types: structures and equipment. This can be criticized, namely regarding the latter, as the increasing share of short-living ICT equipment in total equipment investment has put upward pressures to the depreciation rate of equipment. For this reason, we have used the ICT investment series from Cette *et al*. (2015) and divided series of investment into 5 assets: structures, communication equipment, computers, software, and other non-ICT equipment. Considering depreciation rates within a reasonable range for ICT capital, the differences in the aggregate capital stock growth rate are minor. Indeed, the bias implied by not separating ICT and non-ICT investment is equal to , $\left(K^{ICT}/K_M\right)(\delta^{ICT}-\delta^M)$ where δ^{ICT} is the depreciation rate of ICT and K^{ICT}/K_M is below 5 per cent.

From this PIM, we can derive the average age of equipment by using a recursive rule (see Bergeaud, Cette and Lecat 2016b for more details):

$$A_{\tau+1}=(A_\tau+1)\times\left(1-\frac{I_{\tau+1}}{K_{\tau+1}}\right)$$

Sources

Sources used in the construction of the investment series presented in the BCL database are mostly based on country specific studies that we have compared and updated using national accounts. Examples of such studies are Prados (2003) for Spain, Hjerppe (1996) for Finland, Villa (1994) for France.

GDP and population data mostly comes from Bolt and Van Zanden (2014) that have updated the seminal work of Maddison (2001).

Hours data comes from Huberman and Minns (2007), Clark (1957) and Maddison (2001) and employment series come from various sources.

The complete description can be found in www.longtermproductivity.com by downloading the latest version of the excel file

Education data have been kindly provided by Van Leeuwen and Van Leeuwen-Li (2014).