The impact of digitalisation on labour productivity growth

The evolution of labour productivity is a key determinant of economic growth and prosperity. Over the past few decades, productivity growth in many industrial countries has been low in spite of the rapid diffusion of digital technologies, which is generally credited with having the potential to sustainably increase labour productivity. The question therefore arises as to what extent digitalisation actually leads to productivity gains.

Digital transformation can influence labour productivity through various channels. A frequently studied transmission channel focuses on investment in digital goods. Another transmission channel, which has received less attention to date, is that of digital intermediate inputs, which feed into numerous goods via production linkages. A multi-sector model shows that this channel plays an important role, and that the contribution of digital transformation to labour productivity growth is greatly underestimated if digital intermediate inputs are excluded. In addition, the analysis finds that efficiency gains in the digital sectors – measured in terms of the evolution of total factor productivity – are of key importance. Without these gains, labour productivity growth would have been significantly lower in several of the larger euro area countries, with productivity even stagnating, in some cases.

Nevertheless, it should be noted that the efficiency gains resulting from digital transformation have tended to decline over time. It remains to be seen whether the notable increase in the use and diffusion of digital technologies during the coronavirus pandemic marks a turning point in this regard. Surveys of firms, at least, arrive at a rather optimistic assessment of the situation.

Motivation

Question of the macroeconomic importance of digitalisation …

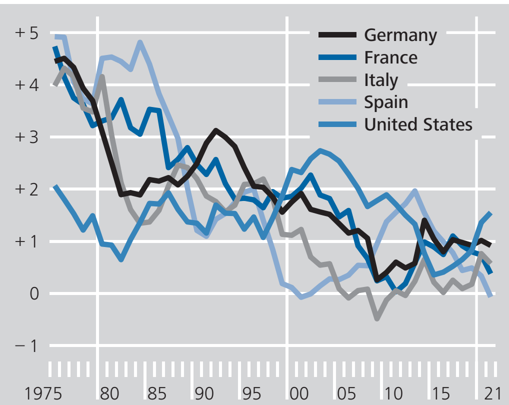
Similarly to the advent of electrification at the beginning of the 20th century, digitalisation can be regarded as the driving force behind a fundamental economic structural change. Digital transformation processes, such as the increasing automation of production processes and the growing use of robots and digital platforms, can trigger significant changes at the firm and industry levels. However, the actual macroeconomic impact of digitalisation is still being studied intensively (for more on this, see the box on pp. 48 f.). A key issue is the importance of digital transformation for labour productivity growth.[1]

… against a backdrop of declining productivity growth in the industrial countries

Given the increasing diffusion of digital technologies, it may seem surprising that labour productivity growth has been declining for some time now in many advanced economies, including the large euro area economies. On the one hand, there are a number of structural factors, such as demographic change and institutional and regulatory barriers, that may be hindering the potential efficiency gains of digital transformation.[2] Furthermore, there is evidence of measurement problems that could potentially lead to an underestimation of the productivity gains resulting from digitalisation.[3] On the other hand, however, there is also a group of "techno-pessimists", who regard digital technologies as being less transformative than generally assumed. In their opinion, digital technologies do not have the same potential to cause major leaps in productivity as previous waves of innovation, triggered, for example, by the development of the steam engine or electrification.[4] They also see signs that the development of digital innovations is becoming increasingly costly and therefore ever more difficult to achieve.[5] Additionally, in their view, it should be borne in mind that innovations do not enhance productivity until they are implemented. If new technologies – such as artificial intelligence or quantum computing – are not widely used, their productivity-enhancing potential will only be able to unfold to a limited extent.[6] Indeed, there are indications of a widening productivity gap between highly productive and less productive firms. This is also interpreted as a sign of weakening technology diffusion.[7]

Hourly labour productivity growth in selected industrial countries since 1975

%, five-year moving average of annual growth rates



Sources: OECD and Bundesbank calculations.
Deutsche Bundesbank

Focus is on the importance of digitalisation for labour productivity growth in the four largest euro area countries

This article studies the importance of the production and use of digital goods for the evolution of aggregate labour productivity in the four largest euro area countries compared with the situation in the United States. To this end, structural macroeconomic models depicting key transmission channels are used. In particular, production networks are modelled, as the impact of digitalisation on productivity can also arise from input-output linkages. First of all, however, the challenge of adequately capturing digitalisation must be addressed.

1 Labour productivity is defined as the ratio of production to labour input. Labour productivity trends can provide insights into economies' growth potential. Owing to its close link to per capita income, labour productivity is often also interpreted as a measure of prosperity. See also Deutsche Bundesbank (2021a).
2 See Deutsche Bundesbank (2021a).
3 See, inter alia, Byrne et al. (2017a, 2017b).
4 See, inter alia, Gordon (2016).
5 See Brynjolfsson et al. (2019) and Bloom et al. (2020).
6 See Brynjolfsson et al. (2019) and OECD (2020a).
7 See, inter alia, Berlingieri et al. (2020) and Deutsche Bundesbank (2021a).

Measurement and development of digitalisation

No clear-cut measure for degree of digitalisation

To quantify the macroeconomic effects of digital transformation, a delineation of digitalisation is needed. However, there is no clear-cut definition of digital transformation. Interpreted narrowly, digitalisation is the collection, storage and processing of information.[8] Broader definitions describe digitalisation as a range of new applications of information and communication technology (ICT) in business models and products.[9] Various indicators are therefore used to measure an economy's degree of digitalisation. In addition to findings on the diffusion and application of digital technologies among households, firms and the public sector, these indicators comprise investment expenditure on digital goods as well as output and efficiency gains in those sectors that predominantly provide digital goods and services. Although they do not necessarily produce a consistent picture, they do provide initial indications of the macroeconomic importance of digitalisation. Furthermore, a closer inspection of these indicators reveals key aspects that need to be taken into account when interpreting model-based analyses. This concerns, for example, measurement problems, which can limit the informative value of cross-sectional comparisons between countries.

Indicators on the diffusion and application of digital technologies

Indicators on the diffusion and application of digital technologies …

The European Commission uses the Digital Economy and Society Index (DESI) to capture the diffusion and use of digital technologies in the EU Member States.[10] This indicator, which is largely based on survey data, consists of four equally weighted components that assess the spread of digitalisation in terms of infrastructure ("connectivity"), the corporate sector ("integration of digital technology"), public administration ("digital public services") and the public's digital skills ("human capital").[11] As a result of conceptual revisions, the current version of the DESI is only available for the years 2017 to 2022.[12]

… show an increase for the EU as a whole …

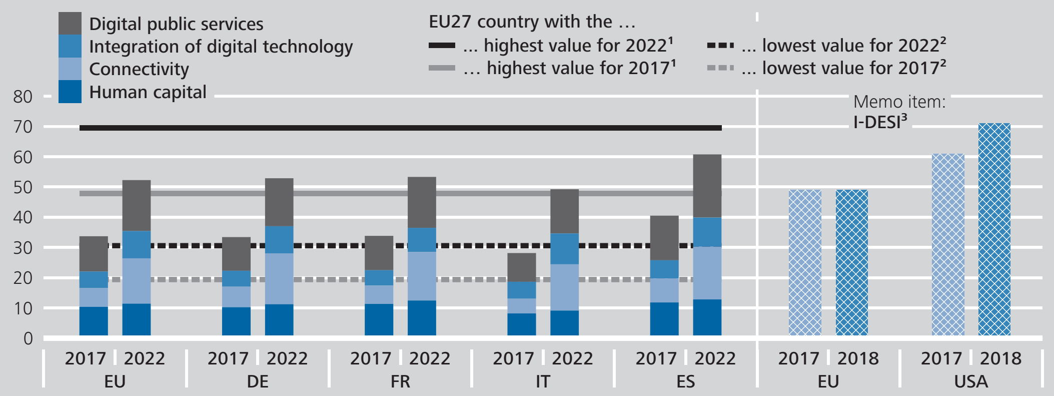
According to the DESI, the use of digital technologies in the EU has been increasing in recent years. This is particularly evident in the case of digital public services and connectivity. A comparison across countries produces a mixed picture, however. A clear discrepancy can be seen between the frontrunners, such as Finland, Denmark and the Netherlands, and countries with the lowest indicator values, such as Greece, Bulgaria and Romania.[13] While there has also been marked progress in the past few years among the countries that are lagging behind, the divide between them and the EU countries with the highest indicator values has widened.[14]

… and the four largest euro area countries

The four largest euro area countries are hovering around the EU average, with Spain most recently performing the best and Italy the worst. In all four countries, at times considerable progress has been made over time.[15] Particularly in the COVID-19 years, marked improvements were seen. The increase in the use of mobile

8 See, inter alia, Byrne (2022).
9 See, inter alia, International Monetary Fund (2018).
10 The indicator was developed in the context of the Digital Single Market Strategy. See European Commission (2015).
11 The "connectivity" component refers to the coverage of fixed and mobile broadband connections in an EU Member State and the corresponding prices. The use of digital solutions in the corporate sector – such as social media, electronic communication and accounting systems, artificial intelligence, cloud services and big data analytics – form part of the "integration of digital technology" component. The "digital public services" component captures the extent to which the services of public administrations are provided in a digital format. The "human capital" component incorporates the number of university graduates in ICT as well as ICT training measures. For a detailed description of the DESI, see European Commission (2022a).
12 The indicator largely uses data from the previous year. The main reference period for the DESI 2022 is therefore 2021.
13 See also European Commission (2022b).
14 Compared with the DESI 2017, the difference between the average of the three EU countries with the lowest indicator values and that of the three with the highest indicator values rose by 30% according to the DESI 2022.
15 During this period, the indicator rose by approximately 50% in Spain, by almost 60% in Germany and France and by as much as around 75% in Italy.

Digital Economy and Society Index (DESI)*



Sources: European Commission and Bundesbank calculations. * Calculated as an equally weighted average of the following components: human capital, connectivity, integration of digital technology and digital public services. The maximum is 100. The minimum is 0. **1** Finland. **2** Romania. **3** International Digital Economy and Society Index (I-DESI).
Deutsche Bundesbank

internet and the integration of digital technologies by small and medium-sized enterprises was especially striking.

Diffusion of digital technologies in the United States has progressed further than in the EU

The International Digital Economy and Society Index (I-DESI), also published by the European Commission, makes it possible to assess the progress of digitalisation in the EU in a global context.[16] The latest published results show that the United States is well ahead of the EU in this respect. There are also indications that digitalisation in the United States is progressing more dynamically compared with the EU.

Investment expenditure on digital goods

Investment in ICT capital can also provide indications of the degree of digitalisation

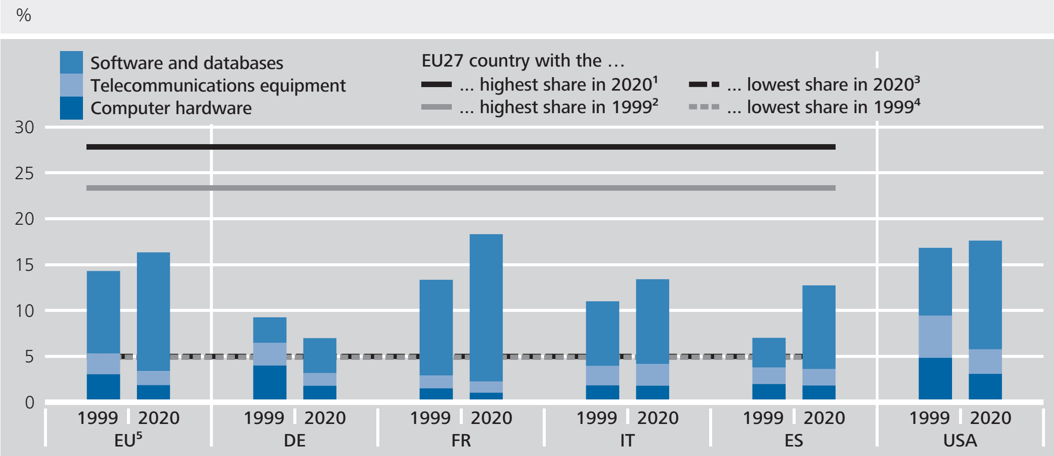
Another approach to capturing digitalisation looks at investment expenditure in the area of ICT as recorded in the national accounts.[17] ICT investment is considered to be a key transmission channel through which digitalisation can have a productivity-enhancing effect. This is achieved, on the one hand, by equipping more workplaces with ICT capital.[18] Moreover, the quality of the capital stock may improve. In this context, a number of studies stress the importance of capital-embodied technological progress that is only unleashed by investment.[19]

Marked increase in ICT investment in the EU

In the EU, ICT investment expenditure increased markedly in relation to total gross fixed capital formation between 1999 and 2020. However, this masks diverging developments. The share of investment in software and databases increased significantly, whilst investment in telecommunications equipment and computer hardware decreased markedly relative to total investment. In terms of individual countries, the picture is indeed mixed. While the share of ICT investment in gross fixed capital formation in France, Italy and Spain increased significantly in some cases between 1999 and 2020, it fell markedly in Germany. The relative importance of the individual categories of fixed ICT assets also differs between the four largest euro area countries. Investment in software and data-

16 The I-DESI, which is only partially comparable to the DESI due to methodological differences, covers the EU27 Member States, the EU as a whole and the United States, inter alia. See also Foley et al. (2020). The I-DESI additionally contains the component "internet use by the general public", which also comprises the use of social media, online banking and video calling. Furthermore, the weighting of the main components differs between the two indicators. The I-DESI was last published in 2020 and is based on data up to 2018. For information on the methodology used for the DESI and the I-DESI, see European Commission (2020a, 2020b, 2022a).
17 Here, ICT investment comprises telecommunications equipment and computer hardware as well as software and databases.
18 See also Deutsche Bundesbank (2002).
19 See, inter alia, Solow (1960), Greenwood et al. (1997), Hercowitz (1998), Cooper et al.(1999) and Greenwood and Jovanovic (2001).

ICT investment as a share of gross fixed capital formation



Sources: Eurostat, OECD and Bundesbank calculations. **1** Estonia. **2** Sweden. **3** Cyprus. **4** Latvia. **5** Excluding Denmark, Greece, Hungary, Ireland and Poland.
Deutsche Bundesbank

bases accounts for a much larger share of gross fixed capital formation in France, Italy and Spain than in Germany.[20]

High importance of investment in software and databases in the EU and the United States

In the United States, too, software and databases account for the bulk of ICT investment. Similarly to the development in the EU, their share in gross fixed capital formation increased significantly between 1999 and 2020, while the share of telecommunications equipment, computers and hardware decreased. The share of ICT investment as a whole increased slightly over the period under review.

Nominal perspective informative only to a limited extent

When looking at the share of ICT investment, it should be noted that there are specific price trends behind expenditure developments. These can differ considerably across categories of fixed assets. According to the official figures, the quality-adjusted price of ICT products in the United States halved between 1999 and 2020, while the deflator of total gross fixed capital formation increased by almost one-third. This implies that ICT investment grew by around 7% per year in real terms. By contrast, price-adjusted gross fixed capital formation as a whole rose by an average of around 2% per year. Qualitatively comparable developments are also evident for the EU, where real ICT investment rose by an average of 4% per year compared with an average growth rate of 1% for price-adjusted gross fixed capital formation as a whole.

Measurement problems hinder comparisons between countries

In these comparisons, it should also be noted that the national accounts metrics are fraught with a number of measurement problems, which hinder comparisons between countries. Digital goods are classified differently in some cases. Moreover, a meaningful cross-country comparison is made more difficult by the fact that statistical methods for measuring ICT investment are not fully harmonised. This is all the more important as the quantification of ICT investment poses particular challenges. For example, technical progress is often expressed in the form of quality improvements. In the case of ICT goods, however, these are, in some cases, insufficiently recorded in official statistics – as shown by a number of studies.[21] Finally, for several years now the recorded statistics for investment, particularly in intellectual property (which includes software and databases) have, in some countries, been greatly distorted by

20 The low share of investment in software and databases in Germany shown by official statistics is striking. It is not clear why it is so small.
21 See, inter alia, Byrne et al. (2016) and Byrne et al. (2017a, 2017b).

A comparison of online and offline prices in Germany

In the course of increasing digitalisation, trade via online stores and digital marketplaces has been growing more important, which can potentially affect price-setting behaviour. Everyday experience and academic studies show that the prices of many goods undergo only infrequent adjustments.[1] However, the rate of change of those prices that are adjusted is typically high when compared with the average inflation rate.

Against this background, the question arises as to whether increasing digitalisation has affected price setting, and if so, how. It is conceivable that online prices might adjust more frequently but less sharply owing to a lower cost of changing prices and greater transparency.[2]

This analysis is based on microdata which enter the German Consumer Price Index (CPI) and have been recently made available for research purposes.[3] The dataset comprises around 14.5 million price spells for the years 2015 to 2019. A distinction is made between eight outlet types, including internet trade.[4] There are online and offline markets for some 290 product groups, such as women's sports shoes. These product

1 See, for example, Dhyne et al. (2006) and Gautier et al. (2022).
2 For an overview of studies on differences in price setting between offline and online markets, see, for example, European Central Bank (2021). Cavallo (2017) finds no major differences in pricing behaviours by marketplace among multi-channel traders, while Gorodnichenko et al. (2018) report that online retailers change prices more frequently.
3 These findings are based on Bundesbank work within the ESCB research network "Price-setting Microdata Analysis Network" (PRISMA). See, inter alia, Strasser et al. (2023).
4 See Sandhop (2012).

Frequency and size of price changes in the German CPI*

Sources: Bundesbank calculations based on German CPI microdata. * Average values of monthly price spells for the 2015 to 2019 period for 288 product types (COICOP ten-digit level of the CPI). Points above (below) the 45° line indicate a higher (lower) value for a given offline product relative to its online counterpart.
Deutsche Bundesbank

groups make up approximately 16% of the consumer basket covered by the German CPI, mainly industrial goods, but also some processed food products such as frozen food and alcoholic beverages.[5] The price changes are calculated at the individual product level in a given store and subsequently aggregated.[6]

In fact, the data show that, overall, online prices are changed more frequently than offline prices (17% per month on average, compared with 11%), especially for industrial goods. By contrast, prices of processed food products are changed somewhat more frequently offline. Price changes due to sales are one reason for this. If sales are excluded, the prices of industrial goods are still adjusted more frequently online, and the frequency of processed food price adjustments becomes more similar between online and offline markets.

Concerning the direction of price changes (share of price increases or decreases), there are no clear differences between online and offline products. Only in the "processed food" category is the share of price increases higher for online trade. With regard to the size of price changes, as expected, they turn out to be, on average, smaller in online stores than in offline stores – for both directions.

Overall, more frequent but smaller price changes are consistent with lower menu costs for online markets. As online trade gains a greater share of the market in the wake of increasing digitalisation, this could result in a higher degree of price flexibility.

5 The "processed food" category includes online shops as well as home delivery services for frozen food.
6 See Gautier et al. (2022).

the strategic activities of multinational enterprises.[22]

Production of digital goods

Shares in gross value added of the digital sectors

Evidence for the macroeconomic importance of digitalisation can also be found on the supply side of the national accounts. One standard indicator is the gross value added share of the digital sectors.[23] These economic sectors are characterised by a high concentration of digital goods producers.[24] However, their definition is generally not particularly clear-cut.[25] In addition, the industry composition may differ between countries. This, too, limits the informative value of comparative analyses.[26] When studying shares of value added, it should also be noted that these do not fully capture the economic significance of the digital sectors. For example, the output of digital goods producers feeds into a wide range of goods and services via intermediate products.

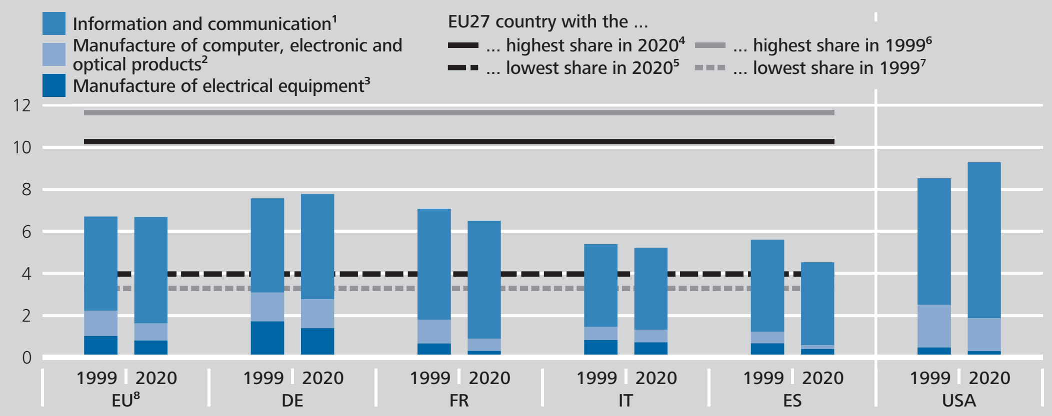
Share of digital sectors in gross value added broadly unchanged in the EU, …

In the EU, digital sectors accounted for around 7% of total gross value added in 2020. Their share was thus roughly as high as 20 years earlier. In Germany, the share of value added in the digital sectors was, in some cases, significantly higher than in the other three largest euro area countries. It also increased slightly in Germany

22 Level shifts and jumps in macroeconomic time series due to relocation of intellectual property rights – for example, licences – are likely to affect small economies in particular. Difficulties in conducting economic analyses can also arise for larger economic regions, however. See also Deutsche Bundesbank (2018).
23 See, inter alia, International Monetary Fund (2018), European Central Bank (2020a) and OECD (2020b).
24 In the following analyses, the digital sectors comprise the economic sectors "Manufacture of computer, electronic and optical products" (NACE division C26), "Manufacture of electrical equipment" (NACE division C27) and "Information and communication" (NACE section J). See also Anderton et al. (2020) and European Central Bank (2021).
25 Fintech activities, for example, are not explicitly mentioned in the classification of economic sectors still used today (NACE Rev. 2), and statistical registers assign the majority of fintech firms to the IT sector. See also von Kalckreuth and Wilson (2020).
26 See also European Central Bank (2021).

Shares of digital sectors in total gross value added

%



Sources: Eurostat, OECD and Bundesbank calculations. **1** NACE section J. **2** NACE division C26. **3** NACE division C27. **4** Czech Republic. **5** Greece. **6** Finland. **7** Bulgaria. **8** Excluding Ireland, Luxembourg and Malta.
Deutsche Bundesbank

between 1999 and 2020, whilst declining, at times distinctly, in France, Italy and Spain.

… but marked increase in the United States

In contrast to the EU as a whole, the value added share of digital sectors in the United States increased markedly between 1999 and 2020. This is all the more remarkable given that producer prices for digital goods fell by around 40% in this period. Real gross value added growth in the digital sectors was correspondingly strong. While total gross value added rose by an average of 2% per year in price-adjusted terms, this figure was 7% for the digital sectors.

Measures of efficiency

Conclusions on macroeconomic significance of digitalisation based on efficiency measures

The indicators presented above provide initial insights into the evolution and extent of digitalisation. However, the metrics do not deliver any direct conclusions on the implications of digital transformation for developments in aggregate labour productivity. These ultimately result from efficiency gains that are made possible by digitalisation.[27] Such efficiency gains cannot be observed directly. However, there are ways to measure them indirectly. Indicators for this include, for example, the relative price of investment in ICT and total factor productivity (TFP) in the digital sectors.

Changes in the relative price of investment …

The relative price of ICT investment is often measured by the ratio between the price index for ICT capital goods and that for consumer goods. A declining relative price is interpreted as an indicator of investment-specific technological progress, based on the idea that technological progress on the supply side leads to a decline in output prices. The development of prices for computer hardware is a fairly illustrative example of this. Relative to the consumption deflator, the price index for computer hardware, which also takes into account improvements in quality, fell around 190-fold in the United States between 1980 and 2021. A falling relative price stimulates demand for capital goods and thus enables technological progress to exert its productivity-enhancing effect via investment.

… as a measure of investment-specific technological progress

In the four largest euro area countries, the relative price of ICT investment has fallen, in some cases sharply, in recent decades.[28] This is particularly evident in Germany. By contrast, the decline in relative prices of ICT investment in France, Italy and Spain was considerably weaker. Nevertheless, in most of these coun-

27 Cost savings play a key role here. See Goldfarb and Tucker (2019).
28 ICT investment comprises telecommunications equipment and computer hardware as well as software and databases.

tries, this decline was, for the most part, still significantly more pronounced than for the rest of gross fixed capital formation (excluding construction investment).[29] Accordingly, investment-specific technological progress in the field of ICT would have been quite pronounced in the countries under review, especially in Germany.

Distortions caused by measurement problems

However, the differences between countries should also be interpreted with caution here, as the measurement of prices for ICT goods poses particular challenges and is not fully harmonised.[30] This should also be taken into account when comparing the relative price trend of ICT investment with that of the United States, where relative prices fell particularly sharply.

Developments in the four largest euro area countries and the United States have recently flattened

These restrictions aside, however, a noticeable flattening in the relative price decline of ICT capital goods can be identified in all countries under review in recent years. This suggests a slowdown in investment-specific technological progress in ICT goods across these countries.

Evolution of TFP in digital sectors …

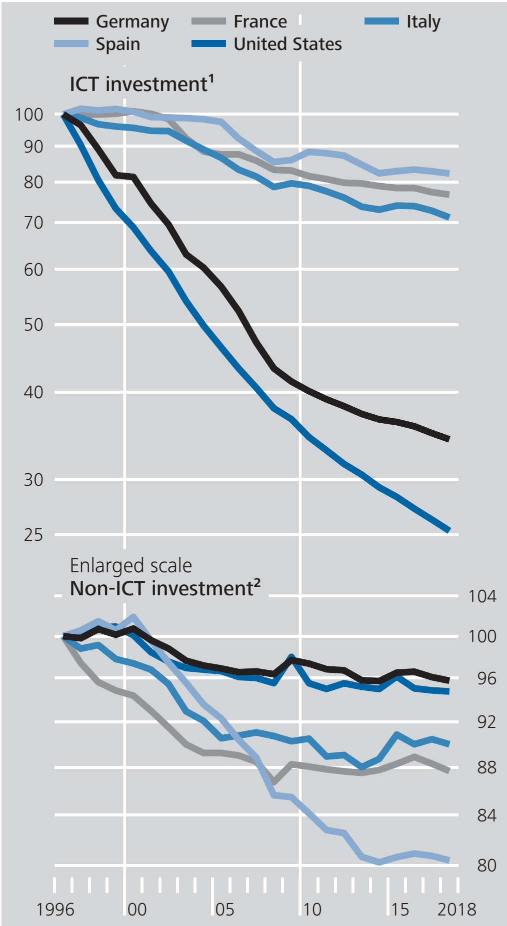
The evolution of TFP captures the part of output growth that cannot be explained by a change in labour or capital input. TFP thus represents a key indicator for the efficiency of production processes.[31] However, it cannot be observed directly; rather, it must be estimated (see also the box on pp. 52 ff.).[32] This can be done at the firm or industry level as well as for the entire economy.

… also signals a weakening of efficiency gains

Such estimates show that TFP growth in the digital sectors of the four largest euro area Member States has tended to flatten out over time.[33] Compared with the first five years after the establishment of the euro area, average TFP growth in the digital sectors was 3 percentage points lower in Germany and France and 4 percentage points lower in Italy between 2014 and 2018.[34] Only in Spain did TFP growth pick up slightly during this period, by 1 percentage point. In the United States, TFP growth has recently gained momentum, but has not come close to the strong rates seen at the start of the 2000s. Nevertheless, on average, TFP growth was still considerably larger in the

Relative price of ICT and non-ICT investment*

1996=100, log scale



Sources: EU KLEMS, Haver Analytics and Bundesbank calculations. * Investment deflator relative to consumption deflator. **1** ICT investment comprises computing equipment, communications equipment and software and databases. **2** Non-ICT investment comprises gross fixed capital formation excluding ICT investment and construction.

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29 With the exception of Spain, the relative price of investment in construction even increased between 1999 and 2019 in the group of countries under consideration, indicating efficiency losses in this area. See also Abdel-Wahab and Vogel (2011) and Sveikauskas et al. (2016).
30 See, inter alia, Federal Statistical Office (2018).
31 See also Deutsche Bundesbank (2021a).
32 These TFP estimates are based on data from the EU KLEMS database (https://euklems-intanprod-llee.luiss.it/). The estimation period covers the years 1997 to 2017 (Italy), 1997 to 2018 (Germany, France, Spain) and 1998 to 2018 (United States).
33 The noticeably weak dynamics in Italy from 2010 onwards can be attributed to developments in its telecommunications sector (for more on this, see the box on pp. 52 ff.).
34 The figure for Italy relates to the period 2013 to 2017, as no data are available for 2018.

Total factor productivity growth in digital sectors

Total factor productivity (TFP) is a key measure of the efficiency of production processes and a main driver of labour productivity. This box focuses on the evolution of TFP in the "digital sectors", i.e. industries that produce digital goods and services. Specifically, it looks at four sectors: the industry for computer, electronic and optical products as well as electronic equipment; the sector for the production and distribution of media products (publishing activities; motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities); the telecommunications sector; and, finally, the sector covering computer programming, consultancy and related activities as well as information service activities.[1]

A standard approach is to measure TFP growth by decomposing the growth rate of gross value added into the contributions of the primary production factors, labour and capital, as well as a residual component.[2] The latter, also known as the Solow residual, is interpreted as a measure of TFP growth. To obtain the most precise estimate of TFP possible, a two-step approach is used which extends the standard procedure by additionally controlling for the degree of utilisation of the factors of production.[3]

In a first step, the Solow residual (Δs_{it}) is calculated in sector i in year t as the difference between the growth rate of price-adjusted gross value added (Δy_{it}) and the annual growth rates of capital input (Δk_{it}) and labour input (Δl_{it}) weighted by the respective production elasticities:[4]

$$\Delta s_{it} = \Delta y_{it} - (1 - \alpha_{it})\Delta k_{it} - \alpha_{it}\Delta l_{it}.$$

In a second step, the Solow residuals of several economic sectors are regressed on the change in the average degree of capacity utilisation (Δu_{it}) and a sector-specific indicator variable (c_i):[5]

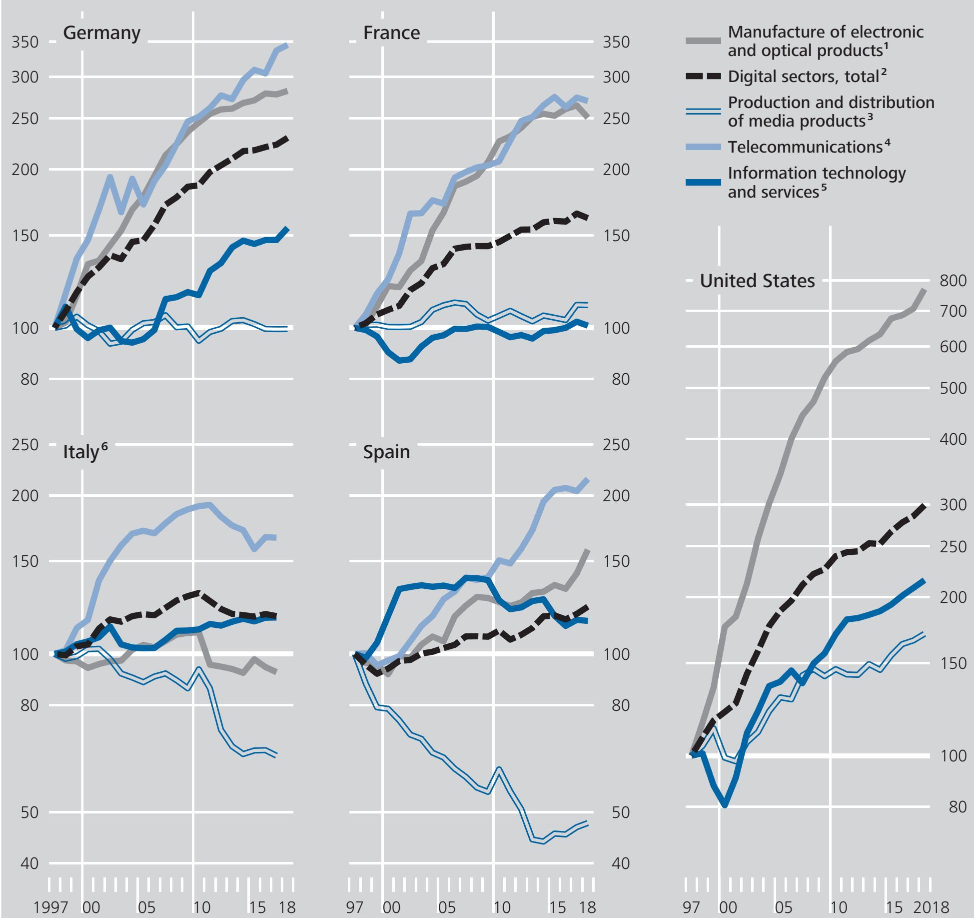
$$\Delta s_{it} = c_i + \beta \Delta u_{it} + \varepsilon_{it},$$

where ε_{it} is an error term. The estimations include data for 23 economic sectors in the four major euro area Member States and the United States for the years 1997 to 2018.[6] The sectoral data are taken from the

1 A proper alignment of efficiency changes with digitalisation trends requires a suitable classification of digital activities. Where such activities are innovative, the respective classification systems are naturally outdated. There is next to no explicit mention of fintech activities, for example, in the classification of economic sectors still used today (NACE Rev. 2 – 2008), and statistical registers classify the majority of fintech firms as IT firms. For Germany, see von Kalckreuth and Wilson (2020).
2 See Solow (1957).
3 If capacity utilisation is neglected, factor inputs and thus the TFP series may be recorded inaccurately. See Basu et al. (2006), Comin et al. (2020) and Deutsche Bundesbank (2021a).
4 The decomposition is based on a Cobb-Douglas production function with constant returns to scale. Assuming perfect competition on the factor and product markets, cost minimisation by firms implies that the factors of production are remunerated according to their marginal products. Labour elasticity (α_{it}) can therefore be determined by the ratio of the wage bill to gross value added, while the elasticity of capital is equal to $1-\alpha_{it}$. See Hulten (2010) and Deutsche Bundesbank (2012, 2021a).
5 See Basu et al. (2006), Comin et al. (2020) and Deutsche Bundesbank (2021a).
6 The model is estimated separately as a panel for each country and three sub-sectors. The latter comprise non-durable manufacturing (NACE divisions C10-C12, C13-C15, C16-C18, C20-C21 and C22-C23 and sections D and E), durable manufacturing (NACE divisions C24-C25, C26-C27, C28, C29-C30, C31-C33) and other economic sectors (NACE sections F, G, H, I, J, K, M, N and R-S); see Deutsche Bundesbank (2021a). In order to consider the digital sectors separately, NACE divisions J58-J60, J61 and J62-J63 are entered individually. Due to a lack of data, utilisation data for J62-J63 are used for divisions J58-J60 and J61 in Germany. The series for Italy end in 2017. Based on EU KLEMS data, TFP growth rates for the United States can only be obtained from 1998 onwards. In addition, for the United States, no data are available for NACE divisions J61 and C21, and sectors D and E are entered as one sector (D-E).

Total factor productivity in the digital sectors*

1997 = 100, log scale



Sources: EU KLEMS, European Commission and Bundesbank calculations. * Calculated using a prototypical Solow decomposition and an econometric model to adjust for changes in the degree of capacity utilisation. **1** NACE divisions C26-C27. **2** NACE divisions C26-C27 and NACE section J. **3** NACE divisions J58-J60. **4** NACE division J61 (not available for the United States). **5** NACE divisions J62-J63. **6** Series for Italy end in 2017.

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EU KLEMS database.[7] Data on capacity utilisation are derived from the European Commission's business surveys.[8]

As capacity utilisation itself can also react to TFP, an instrumental variables method is used to estimate the panel models. Economic variables which correlate with capacity utilisation but not with TFP serve as instrumental variables. These are an oil price shock, an international financial market shock and a macroeconomic uncertainty shock series.[9] Utilisation-adjusted TFP growth of an economic sector is then computed as the difference between the Solow residual

7 The data are available at https://euklems-intanprod-llee.luiss.it

8 The utilisation data are available for manufacturing from 1985 onwards and for services sectors from mid-2011 onwards (Italy from mid-2010); see European Commission (2020c). For the years prior to 2011 (for Italy prior to 2010), the capacity measures for the services sectors are extended backwards by using the growth rate of average capacity utilisation in the manufacturing sector; see Comin et al. (2020). For the United States, average hours worked are used as an indicator of the degree of utilisation; see Basu et al. (2006).

9 The oil price shock is based on movements in the Brent oil price; see Basu et al. (2006). The uncertainty shocks stem from macroeconomic models; see Jurado et al. (2015) and Meinen and Röhe (2017). The financial market shock is based on the indicator introduced by Gilchrist and Zakrajšek (2012) for the non-predictable component of risk premia on US corporate bonds. Statistical tests certify that the instruments are sufficiently correlated with the change in capacity utilisation.

and the impact of changes in capacity utilisation:[10]

$$\Delta\widehat{tfp}_{it} = \Delta s_{it} - \hat{\beta}\Delta u_{it}.$$

The estimates show important similarities for the four largest euro area Member States, but also significant differences. The greatest efficiency gains occurred in telecommunications. On an average over the period from 1997 to 2018, TFP rose by around 2% per year in Italy and by 4% in Spain, 5% in France and as much as 6% in Germany.[11] The low average growth rate in Italy can be explained in part by the significant decline in TFP in the wake of the European sovereign debt crisis. TFP growth in the manufacture of electronic and optical products is similar to that recorded for telecommunications in the case of Germany and France. In Spain and Italy, however, growth was considerably weaker. Italy, in particular, saw hardly any efficiency gains in this sector. There are also marked differences between the euro area Member States under review in the area of information service activities, which includes software development, programming and data processing, amongst other things. Only in Germany have there been noticeable efficiency gains since 2007. In Spain, TFP in this sector decreased at the end of the observation period following initial increases. In the economic sector focused on the production and distribution of media products, efficiency is estimated to have remained broadly unchanged in Germany and France, while in Spain and Italy it even declined markedly.

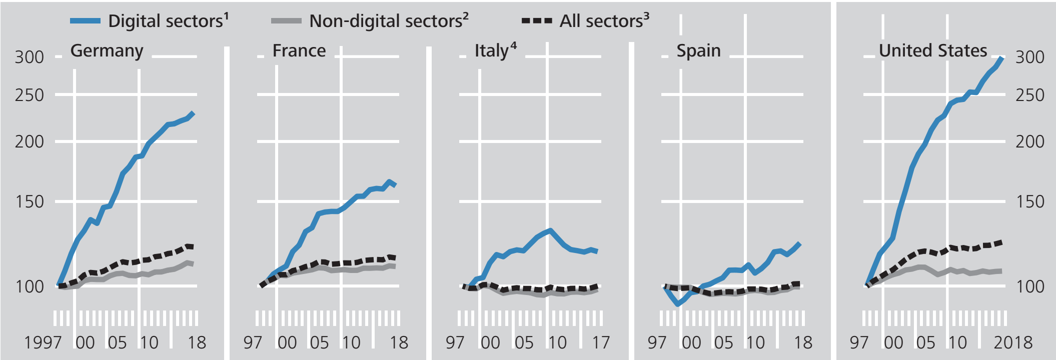
In the United States, TFP developments were broadly similar in the sectors under review, although the country recorded greater progress overall.[12] This applies in particular to the manufacture of electronic and optical products, which saw exceptionally strong TFP growth of almost 10% per year. Remarkably, there were also significant productivity gains in the United States in the print, film and audio media sector.

Combining the various digital areas yields a clear grading. Whereas efficiency gains in the United States are very large, Germany posts somewhat smaller growth. Growth in France comes in slightly further behind, while TFP advances in digital sectors are significantly weaker in Italy and Spain. However, this cross-country analysis is subject to the caveat that measurement problems may restrict the comparability of TFP series (see also pp. 49 ff.).

10 Capacity utilisation is only taken into account if $\widehat{\beta}$ is significant at the 90% level.
11 The data for Italy cover the years 1997 to 2017. The relatively fierce competition between service providers is a potential driver of TFP growth in the telecommunications sector. However, the government's influence in this area can still be pronounced. See Federal Statistical Office (2018).
12 Due to the lack of data, no conclusions can be drawn for the telecommunications sector (J61). This is the result of differences in the classification of economic sectors. There is no exact equivalent for NACE division J60 in the NAICS classification used in the United States. There are also slight differences for NACE division J60.

Total factor productivity between 1997 and 2018*

1997 = 100, log scale



Sources: EU KLEMS, European Commission and Bundesbank calculations. * Total factor productivity was calculated using a prototypical Solow decomposition and an econometric model to adjust for changes in the degree of capacity utilisation. **1** NACE divisions C26-C27 (manufacture of computer, electronic and optical products as well as electrical equipment) and NACE section J (information and communication). **2** NACE sections D, E, F, G, H, I, K, M, N, R-S and NACE section C (excluding divisions C26-C27 and C19). **3** Digital sectors and non-digital sectors. **4** Series for Italy end in 2017.

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digital sectors of the group of countries under review than in the other sectors of the economy. This is consistent with the picture obtained when looking at relative prices.

Digitalisation and labour productivity

Importance of digitalisation for labour productivity from the perspective of macroeconomic models

The various indicators considered here suggest, in part, a rapid pace of digitalisation. This is particularly true of the two presented measures of efficiency, although their development has, in some cases, weakened over time. The implications of this for the course of macroeconomic labour productivity can be examined using structural macroeconomic models. Traditional approaches focus mainly on the role of investments;[35] meanwhile, the importance of digital intermediate inputs is neglected. Recent studies suggest, however, that production linkages play a key role in the diffusion of technologies.[36]

Traditional analytical approaches

Traditional approaches focus on investment

Dynamic stochastic general equilibrium (DSGE) models are one tool that can be used to grasp the macroeconomic role of investment-specific technological progress.[37] Amongst other things, they make it possible to assess the contribution of this progress to trend growth in labour productivity.[38] A neoclassical baseline model[39] which takes into account various types of capital, including ICT capital, serves as the basis for this. Besides the evolution of TFP, investment-specific technological progress associated with the respective capital types is a key driver of the model.[40]

The total contribution of investment-specific technological progress to labour productivity growth is equal to the weighted sum of the technological progress associated with each of

35 See, inter alia, Byrne et al. (2013), Cette et al. (2015) and European Central Bank (2021).
36 See, inter alia, Foerster et al. (2022) and vom Lehn and Winberry (2022).
37 See, inter alia, Justiniano et al. (2011), Schmitt-Grohé and Uribe (2011) and Díaz and Franjo (2016).
38 See, inter alia, Greenwood et al. (1997), Bakhshi and Larsen (2005) and Rodríguez-López and Torres (2012).
39 A detailed description of this model framework can be found in Acemoglu (2009).
40 One particular feature of the model specification chosen here is the assumption of time-varying production elasticities. The calculation follows the approach in Eden and Gaggl (2018). In the above DSGE approach, exogenous stochastic shocks are implemented to capture the time-varying production elasticities. For more information, see Young (2004), Ríos-Rull and Santaeulàlia-Llopis (2010) and Lansing (2015).

Contribution of capital-embodied technical progress in ICT to labour productivity growth*

Percentage points

Sources: EU KLEMS, Haver Analytics and Bundesbank calculations. * Contributions of capital-embodied technical progress in ICT to average annual productivity growth per total number of hours worked derived from a DSGE model. The ICT capital stock comprises investment capital in the areas of computer equipment, communications equipment, and software and databases.

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Weight and dynamics of investment-specific technological progress determine its growth contribution

the respective types of capital.[41] Investment-specific technological progress can be approximated on the basis of the relative price path of the relevant categories of capital goods.[42] However, its importance for productivity growth is also determined by the relative weight of the corresponding type of capital in the production process.[43]

Declining growth contributions of investment-specific technological progress in ICT

According to this approach, the contributions of investment-specific technological progress in ICT to aggregate productivity growth in the four largest euro area countries has been lower in recent years than before the global financial and economic crisis. A similar picture emerges for the United States. This development is largely being driven by the flattening of the relative price paths of ICT investment. With regard to the size of growth contributions, note that the relative weight of ICT capital was comparatively small.[44] By this yardstick, the growth contributions of ICT-specific technological progress to aggregate labour productivity are quite high.[45] For example, in France and the United States, they were around 12 times higher in the period from 2013 to 2018 than the average contributions of technological progress associated with non-ICT investment (excluding construction). In Germany and Spain, the contributions of ICT-specific technological change were at least as high as the contributions made by technological progress in non-ICT investment. According to the model decomposition, the positive impulse from ICT in Italy was even counteracted by a negative contribution to labour productivity growth from non-ICT investment between 2013 and 2018.

Consideration of input-output linkages

Little attention paid to the role of input-output linkages thus far

However, digital products are entered into production processes not only as capital goods but also as intermediate inputs. This transmission channel is rarely taken into account in conventional macroeconomic models. Yet digital goods, in particular, are used to a large extent as an intermediate input. The multi-sector dynamic stochastic general equilibrium (DSGE) model MuSe developed at the Bundesbank captures sectoral production linkages and thus enables the analysis of their macroeconomic

41 It is assumed here that the exogenous investment-specific technological progress can be described by a stochastic trend. See Schmitt-Grohé and Uribe (2011).
42 The model analysis assumes that there is an inverse relationship between relative price paths and investment-specific technological progress. See also Schmitt-Grohé and Uribe (2011).
43 Assuming a Cobb-Douglas production function with constant returns to scale, the weight is given by the ratio of the respective capital income to total labour income.
44 Average ICT capital income shares range between 2% (Germany, Italy, Spain) and 5% (United States) over the total reference period. By contrast, capital income shares for non-ICT assets vary from 9% (Spain) to 13% (Germany).
45 Several simplifying assumptions need to be made in model-based growth accounting. These include, in addition to the basic principles of the standard neoclassical model, the assumption of a closed economy and of labour being a homogeneous factor of production. The model furthermore presumes the existence of a direct inverse relationship between investment-specific technological progress and the relative price of the respective investment goods.

implications.[46] In the model, sectoral output is used not only for consumption or investment purposes but also as an intermediate input in various sectors of the economy.[47] It is assumed that different intermediate inputs can only be substituted to a limited extent. Furthermore, the intermediate input bundle can vary among the economic sectors. The model specification used here covers 19 economic sectors and was specified for each of the four largest euro area economies as well as the United States.[48,49]

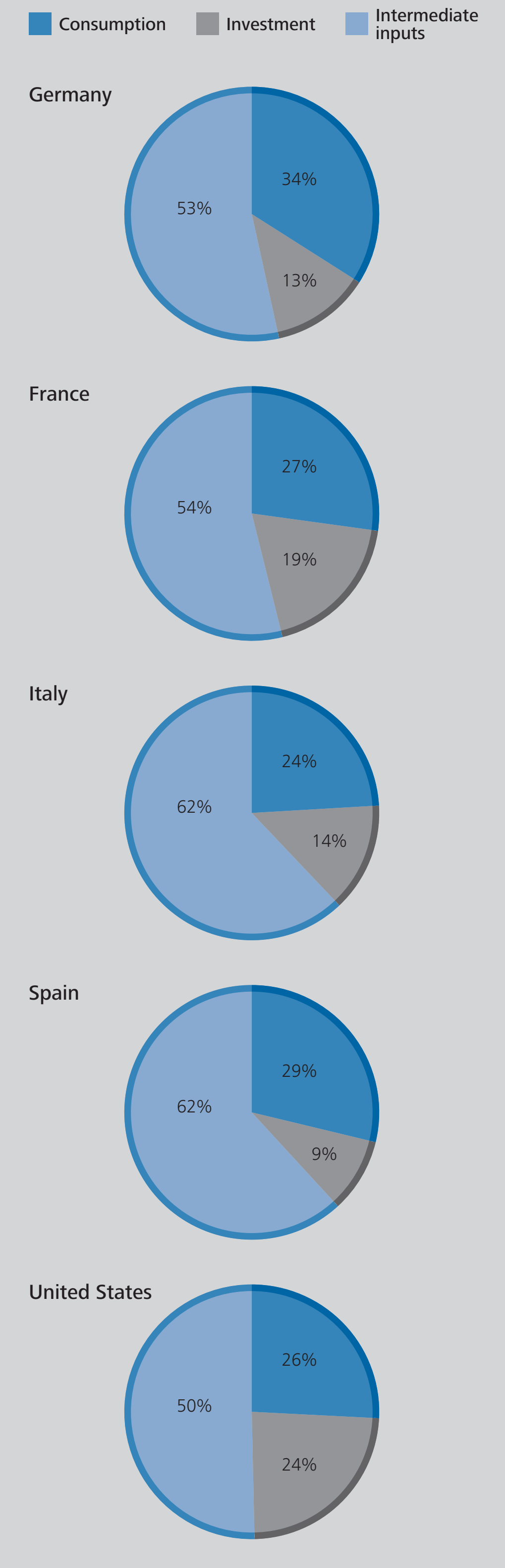
TFP growth in digital sectors as a key driver

In this model framework, digital transformation is triggered by TFP growth in digital sectors. An increase in TFP lowers marginal costs, as production can now take place with smaller factor inputs.[50] The prices of digital goods fall as a result. This, in turn, stimulates demand for these goods, both for consumption and investment purposes and as an intermediate input. As far as is possible, products from non-digital sectors are replaced by the comparatively cheaper digital goods. However, demand for other goods also increases due to complementarities. The growth in production in non-digital sectors calls for increased use of factors of production, which, when viewed in isolation, drives up factor payments, marginal costs and prices.

46 MuSe is a variant of the environmental multi-sector DSGE model EMuSe that does not include an environmental module. A detailed description can be found in Hinterlang et al. (2021, 2022, 2023).
47 The MuSe model is therefore an extension of prototypical models. In the latter, production is usually used only for consumption or investment purposes, as capital and labour are the only factors of production. See, inter alia, Christiano et al. (2018).
48 The model bundles NACE divisions C26-C27 (manufacture of computer, electronic and optical products and electrical equipment) and NACE section J (information and communication) into one sector. NACE divisions C10-C12, C13-C15, C16-C18, C20-C21, C22-C23, C24-C25, C28, C29-C30, C31-C33 as well as sections D-E, F, G, H, I, K, M, N, R-S are also depicted as separate economic sectors. For a detailed description of the NACE classification, see Eurostat (2008).
49 External trade links are excluded for the purposes of simplification. The production structure of the countries under review is modelled using country-specific datasets from the World Input-Output Database (WIOD). For more information on the WIOD, see Timmer et al. (2015).
50 The transmission channel of TFP growth in digital sectors described here is transferable to the other sectors depicted in the model.

Use of digital goods*

%



Sources: World Input-Output Database and Bundesbank calculations. * Digital goods comprise products from NACE divisions C26-C27 and NACE section J. Overall, NACE sections D-E, F, G, H, I, J, K, M, N, R-S and the divisions of NACE section C (excluding C19) in the year 2000 are considered.

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Assessing the role of digitalisation using a counterfactual analysis

In order to quantify the contribution of digitalisation to labour productivity, sectoral TFP paths, which were estimated separately (see also the box on pp. 52 ff.), are fed into the MuSe model. Specifically, two scenarios are compared here. In the reference scenario, the TFP paths for all sectors are considered.[51] In the counterfactual scenario, by contrast, it is assumed that TFP in digital sectors is constant and remains at its initial level. The differences between the two scenarios can then be used to assess the contribution to labour productivity growth made by digital sectors.

Overall accurate description of the actual path of labour productivity

The MuSe model quite accurately reproduces the actual path of labour productivity in the countries under review, with the exception of Spain.[52] This is also noteworthy given that labour productivity developments in this group of countries vary widely in some cases. Labour productivity in the United States rose considerably more strongly than in the euro area countries under review. Within this group, there was a marked difference between Germany and France, on the one hand, and Italy and Spain, on the other.

Predominantly large contribution of digital sectors to labour productivity growth …

If the changes in TFP in digital sectors are factored out of the simulation, the picture changes significantly. Labour productivity growth would be considerably weaker. For the United States, around seven-tenths of productivity growth would be lost, despite digital sectors accounting for a relatively small share of aggregate gross value added. The loss would be substantial in Germany and France, too, at roughly one-half and four-tenths respectively. According to this calculation, aggregate labour productivity in Italy would have stagnated. By contrast, differences compared with the reference scenario do not appear until the end of the simulation period for Spain. In accordance with this, there would have been only comparatively weak macroeconomic impetus coming from digital sectors in Spain in the years prior to 2012. Overall, the simulation results show the key importance of TFP growth in digital sectors for the developments of labour productivity. In line with this, less dynamic TFP growth in digital sectors – amid continuously weak impetus stemming from the other economic sectors – would have significant consequences.

… with input-output linkages representing an important transmission channel

In order to show the specific importance of input-output linkages for the transmission of digitalisation, a further scenario assumes that digital goods are used exclusively for consumption or investment purposes and not as intermediate inputs.[53] The simulation results suggest that digital intermediate inputs play a key role in aggregate productivity growth, since productivity gains were mostly significantly lower when digital intermediate inputs were excluded.[54] This is particularly evident for the United States, Germany and France. However, this transmission channel was also important in Italy. In Spain, on the other hand, relatively weak TFP growth in digital sectors also implies that the importance of digital intermediate inputs for labour productivity growth was lower.

Role of international linkages

For simplicity, this analysis looked at a closed economy. Digital goods are in fact also exported and imported.[55] However, it should be emphasised that the model incorporates the actual country-specific TFP paths, which also reflect external developments. A number of studies show that TFP progress is markedly in-

51 The simulation results are driven exclusively by the interplay between TFP paths in the individual sectors.

52 In Spain, labour productivity increased considerably as a result of the disproportionately large reduction in labour input in the wake of the global financial and economic crisis and the subsequent sovereign debt crisis. However, this dramatic development is not triggered by TFP adjusted for capacity utilisation and cannot therefore be inferred from the model. See also Deutsche Bundesbank (2021a).

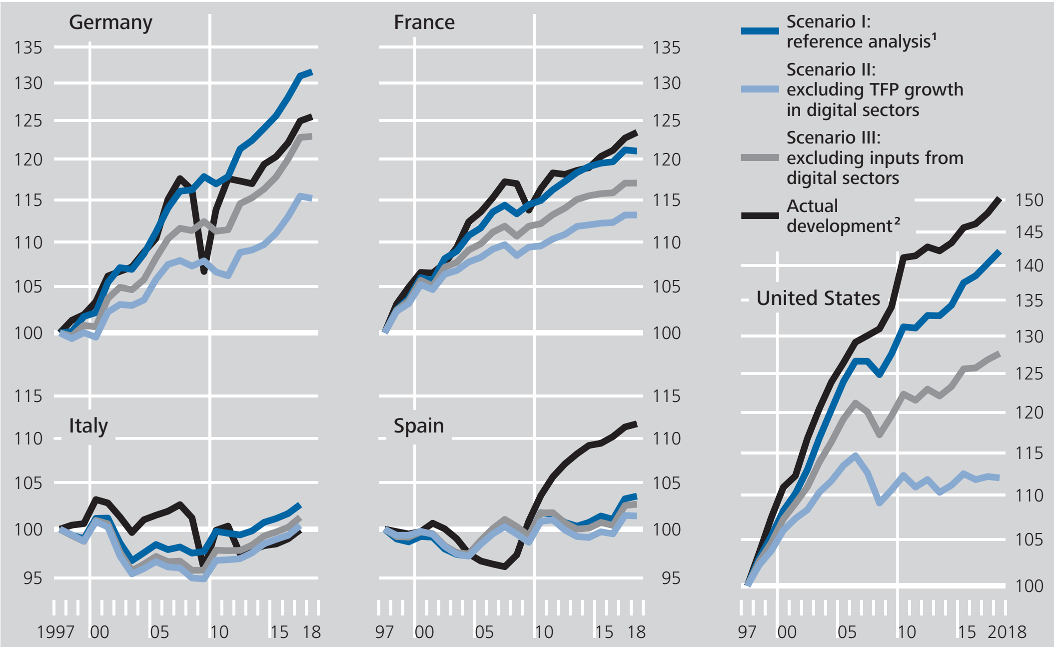
53 To this end, digital goods are excluded from the intermediate input bundles of all sectors.

54 For a more detailed discussion of the prominent role of input-output linkages, see, inter alia, Foerster et al. (2022) and vom Lehn and Winberry (2022).

55 According to WIOD data for 2014, the share of imported digital intermediate inputs in total intermediate inputs was recently around 3% in Germany, 2% in France and Italy and 1% in Spain and the United States. The share of imported digital consumer goods stood at around 1% in all countries under review. The share of imported digital capital goods in total gross fixed capital formation was close to 7% for Germany, while this share was 5% for Spain, 4% for the United States and 3% for France and Italy.

Importance of digital sectors for aggregate labour productivity*

1997 = 100, log scale



Sources: EU KLEMS, World Input-Output Database and Bundesbank calculations. * The simulations are based on a multi-sector DSGE model. The simulation period covers the years 1997 to 2018 for Germany, France, Spain and the United States and 1997 to 2017 for Italy. The digital sector comprises NACE divisions C26-C27 (manufacture of computer, electronic and optical products and electronic equipment) and NACE section J (information and communication). NACE sections C (excluding divisions C26-C27 and C19), D-E, F, G, H, I, K, M, N, R-S are also covered. **1** Depicts labour productivity developments based on the sectoral TPF paths and a model version with 19 sectors. **2** Aggregate hourly labour productivity of the 19 sectors the reference analysis is based on.

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fluenced by international research and development, especially in open economies.[56] Foreign direct investment and imports of intermediate goods can also have an impact on a country's TFP growth.[57]

Summary and outlook

Important role of digital intermediate inputs …

Digitalisation affects aggregate labour productivity developments in a variety of ways. Standard analytical approaches typically focus on the importance of digital capital goods. By contrast, the role of digital intermediate inputs is often neglected. Analyses using a macroeconomic multi-sector model show the key importance of digital intermediate inputs. If sectoral interlinkages are neglected, production growth resulting from digitalisation is often significantly underestimated. Furthermore, it can be seen that efficiency gains in digital sectors have a decisive impact on labour productivity developments. Without progress in digital sectors, productivity growth in the largest euro area countries would have been considerably lower or productivity would have even stagnated. The same applies to the United States. Here, too, labour productivity developments are driven largely by TFP growth in digital sectors.

… but diminishing impetus from digitalisation over time

Nonetheless, it becomes apparent that the efficiency gains resulting from digitalisation have tended to decline over time. Whether a turning point will be reached in view of recent developments is a matter of dispute.[58] The European Commission's indicators on the application and diffusion of digital technologies indicate a significant increase during the coronavirus pandemic. This suggests that changes in the framework conditions can have significant incentive

56 See, inter alia, Coe and Helpman (1995) and Coe et al. (2009).
57 See, inter alia, Borensztein et al. (1998) and Acharya and Keller (2009).
58 See, inter alia, van Ark et al. (2021).

effects. It is not yet possible to gauge the extent to which this leads to measurable efficiency gains. However, surveys of firms arrive at a rather optimistic assessment of the situation.[59]

59 In an ECB survey, more than 35% of the surveyed enterprises reported that they expected an acceleration of digitisation in their enterprise in the long term as a result of the coronavirus pandemic; see European Central Bank (2020b). Survey results suggest a digitalisation boost in Germany, especially for large enterprises; see Deutsche Bundesbank (2022). The majority of German enterprises surveyed are also hoping for productivity gains from the increased use of remote working; see Deutsche Bundesbank (2021b).

List of references

Abdel-Wahab, M. and B. Vogl (2011), Trends of productivity growth in the construction industry across Europe, US and Japan, Construction Management and Economics, Vol. 29 (6), pp. 635-644.

Acemoglu, D. (2009), Introduction to Modern Economic Growth, Princeton University Press.

Acharya, R. C. and W. Keller (2009), Technology transfer through imports, Canadian Journal of Economics, Vol. 42 (4), pp. 1411-1448.

Anderton, R., V. Jarvis, V. Labhard, J. Morgan, F. Petroulakis, and L. Vivian (2020), Virtually everywhere? Digitalisation and the euro area and EU economies, ECB Occasional Paper Series, No 244.

Bakhshi, H. and J. Larsen (2005), ICT-specific technological progress in the United Kingdom, Journal of Macroeconomics, Vol. 27 (4), pp. 648-669.

Basu, S., J. G. Fernald and M. S. Kimball (2006), Are Technology Improvements Contractionary?, American Economic Review, Vol. 96 (5), pp. 1418-1448.

Berlingieri, G., S. Calligaris, C. Criscuolo and R. Verlhac (2020), Laggard firms, technology diffusion and its structural and policy determinants, OECD Science, Technology and Industry Policy Papers, No 86.

Bloom, N., C. I. Jones, J. Van Reenen and M. Webb (2020), Are Ideas Getting Harder to Find?, American Economic Review, Vol. 110 (4), pp. 1104-1144.

Borensztein, E., J. De Gregorio and J.-W. Lee (1998), How does foreign direct investment affect economic growth?, Journal of International Economics, Vol. 45 (1), pp. 115-135.

Brynjolfsson, E., D. Rock and C. Syverson (2019), Artificial Intelligence and the Modern Productivity Paradox: A Clash of Expectations and Statistics, in Agrawal, A., J. Gans and A. Goldfarb (eds., 2019), The Economics of Artificial Intelligence: An Agenda, pp. 23-60.

Byrne, D. M. (2022), The Digital Economy and Productivity, Board of Governors of the Federal Reserve System, Finance and Economics Discussion Series, No 2022-038.

Byrne, D. M., J. G. Fernald and M. B. Reinsdorf (2017a), Does Growing Mismeasurement Explain Disappointing Growth?, Federal Reserve Bank of San Francisco, Economic Letter, No 2017-4.

Byrne, D. M., S. D. Oliner and D. E. Sichel (2017b), Prices of high-tech products, mismeasurement, and the pace of innovation, Business Economics, Vol. 52 (2), pp. 103-113.

Byrne, D. M., J. G. Fernald and M. B. Reinsdorf (2016), Does the United States Have a Productivity Slowdown or a Measurement Problem?, Brookings Papers on Economic Activity, pp. 109-157.

Byrne, D. M., S. D. Oliner and D. E. Sichel (2013), Is the Information Technology Revolution Over?, International Productivity Monitor, Vol. 25, pp. 20-36.

Cavallo, A. (2017), Are Online and Offline Prices Similar? Evidence from Large Multi-Channel Retailers, American Economic Review, Vol. 107 (1), pp. 283-303.

Cette, G., C. Clerc and L. Bresson (2015), Contribution of ICT Diffusion to Labour Productivity Growth: The United States, Canada, the Eurozone, and the United Kingdom, 1970-2013, International Productivity Monitor, Vol. 28, pp. 81-88.

Christiano, L. J., M. S. Eichenbaum and M. Trabandt (2018), On DSGE Models, Journal of Economic Perspectives, Vol. 32 (3), pp. 113-140.

Coe, D. T., E. Helpman and A. W. Hoffmaister (2009), International R&D spillovers and institutions, European Economic Review, Vol. 53 (7), pp. 723-741.

Coe, D. T. and E. Helpman (1995), International R&D spillovers, European Economic Review, Vol. 39 (5), pp. 859-887.

Comin, D., J. Q. Gonzalez, T. G. Schmitz and A. Trigari (2020), A New Measure of Utilization-adjusted TFP Growth for Europe and the United States, NBER Working Paper, No 28008.

Cooper, R., J. Haltiwanger and L. Power (1999), Machine Replacement and the Business Cycle: Lumps and Bumps, American Economic Review, Vol. 89 (4), pp. 921-946.

Deutsche Bundesbank (2022), Digitalisation in the German corporate sector since the onset of the coronavirus pandemic, Monthly Report, September 2022, pp. 54-55.

Deutsche Bundesbank (2021a), The slowdown in euro area productivity growth, Monthly Report, January 2021, pp. 15-46.

Deutsche Bundesbank (2021b), Remote working and its impact on labour productivity, Monthly Report, October 2021, pp. 58-59.

Deutsche Bundesbank (2018), Activities of multinational enterprise groups and national economic statistics, Monthly Report, October 2018, pp. 65-78.

Deutsche Bundesbank (2012), On the technical relationship between the trend rate of hourly productivity, the trend growth of total factor productivity and capital deepening, Monthly Report, April 2012, pp. 24-25.

Deutsche Bundesbank (2002), Productivity developments in Germany, Monthly Report, September 2002, pp. 47-61.

Dhyne, E., L. J. Álvarez, H. Le Bihan, G. Veronese, D. Dias, J. Hoffmann, N. Jonker, P. Lünnemann, F. Rumler and J. Vilmunen (2006), Price Changes in the Euro Area and the United States: Some Facts from Individual Consumer Price Data, Journal of Economic Perspectives, Vol. 20 (2), pp. 171-192.

Díaz, A. and L. Franjo (2016), Capital goods, measured TFP and growth: The case of Spain, European Economic Review, Vol. 83, pp. 19-39.

Eden, M. and P. Gaggl (2018), On the welfare implications of automation, Review of Economic Dynamics, Vol. 29, pp. 15-43.

European Central Bank (2021), Digitalisation: channels, impacts and implications for monetary policy in the euro area, Occasional Paper Series, No 266.

European Central Bank (2020a), The digital economy and the euro area, Economic Bulletin, Issue 8/2020, pp. 128-150.

European Central Bank (2020b), The long-term effects of the pandemic: insights from a survey of leading companies, Economic Bulletin Issue 8/2020, pp. 72-75.

European Commission (2022a), Digital Economy and Society Index (DESI) 2022 – Methodological note, July 2022.

European Commission (2022b), Digital Economy and Society Index (DESI) 2022 – Thematic chapters, July 2022.

European Commission (2020a), International Digital Economy and Society Index – Final report, SMART 2019/0087.

European Commission (2020b), Digital Economy and Society Index (DESI) 2020: Questions and Answers, June 2020 (Digital Economy and Society Index (DESI) 2020: Q&A (europa.eu)).

European Commission (2020c), The Joint Harmonised EU Programme of Business and Consumer Surveys – User Guide.

European Commission (2015), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions "A Digital Single Market Strategy for Europe", COM(2015) 192 final.

Eurostat (2008), NACE Rev. 2 – Statistical classification of economic activities in the European Community, Methodologies and Working Papers.

Federal Statistical Office (2018), Erzeugerpreise für Dienstleistungen: Information zum Preisindex Telekommunikation (WZ 2008:61), DESTATIS, Strukturerhebung im Dienstleistungsbereich – Fachbericht Rechts- und Steuerberatung.

Foerster, A. T., A. Hornstein, P.-D. G. Sarte and M. W. Watson (2022), Aggregate Implications of Changing Sectoral Trends, Journal of Political Economy, Vol. 130 (12), pp. 3286-3333.

Foley, P., D. Sutton, R. Potter, S. Patel and A. Gemmell (2020), International Digital Economy and Society Index 2020 – SMART 2019/0087, Publications Office of the European Union.

Gautier, E., C. Conflitti, R. Faber, B. Fabo, L. Fadejeva, V. Jouvanceau, J.-O. Menz, T. Messner, P. Petroulas, P. Roldan-Blanco, F. Rumler, S. Santoro, E. Wieland and H. Zimmer (2022), New facts on consumer price rigidity in the euro area, ECB Working Paper, No 2669.

Gilchrist, S. and E. Zakrajšek (2012), Credit Spreads and Business Cycle Fluctuations, American Economic Review, Vol. 102 (4), pp. 1692-1720.

Goldfarb, A. and C. Tucker (2019), Digital Economics, Journal of Economic Literature, Vol. 57 (1), pp. 3-43.

Gordon, R. J. (2016), The Rise and Fall of American Growth: The US Standard of Living since the Civil War, Princeton University Press.

Gorodnichenko, Y., V. Sheremirov and O. Talavera (2018), Price Setting in Online Markets: Does IT Click?, Journal of the European Economic Association, Vol. 16 (6), pp. 1764-1811.

Greenwood, J. and B. Jovanovic, Accounting For Growth, in C. R. Hulten, E. R. Dean and M. J. Harper (eds., 2001), New Developments in Productivity Analysis, University of Chicago Press, pp. 179-224.

Greenwood, J., Z. Hercowitz and P. Krusell (1997), Long-Run Implications of Investment-Specific Technological Change, American Economic Review, Vol. 87 (3), pp. 342-362.

Hercowitz, Z. (1998), The "embodiment" controversy: A review essay, Journal of Monetary Economics, Vol. 41 (1), pp. 217-224.

Hinterlang, N., S. Moyen, O. Röhe and N. Stähler (2023), Gauging the effects of the German COVID-19 fiscal stimulus package, European Economic Review, 104407.

Hinterlang, N., A. Martin, O. Röhe, N. Stähler and J. Strobel (2022), Using energy and emissions taxation to finance labor tax reductions in a multi-sector economy, Energy Economics, Vol. 115 (106381).

Hinterlang, N., A. Martin, O. Röhe, N. Stähler and J. Strobel (2021), Using energy and emissions taxation to finance labor tax reductions in a multi-sector economy: An assessment with EMuSe, Deutsche Bundesbank Discussion Paper, No 50/2021.

Hulten, C. R., Growth Accounting, in B. H. Hall, and N. Rosenberg (eds., 2010), Handbook of the Economics of Innovation, Ed. 1, Vol. 2, pp. 987-1031.

International Monetary Fund (2018), Measuring the Digital Economy, IMF Staff Report, February 2018.

Jurado, K., S. C. Ludvigson and S. Ng (2015), Measuring Uncertainty, American Economic Review, Vol. 105 (3), pp. 1177-1216.

Justiniano, A., G. E. Primiceri and A. Tambalotti (2011), Investment shocks and the relative price of investment, Review of Economic Dynamics, Vol. 14 (1), pp. 102-121.

Lansing, K. J. (2015), Asset Pricing with Concentrated Ownership of Capital and Distribution Shocks, American Economic Journal: Macroeconomics, Vol. 7 (4), pp. 67-103.

Meinen, P. and O. Röhe (2017), On measuring uncertainty and its impact on investment: Cross-country evidence from the euro area, European Economic Review, Vol. 92, pp. 161-179.

OECD (2020a), Artificial intelligence, digital technology and advanced production, in The Digitalisation of Science, Technology and Innovation: Key Developments and Policies.

OECD (2020b), A roadmap toward a common framework for measuring the Digital Economy – Report for the G20 Digital Economy Task Force.

Ríos-Rull, J.-V. and R. Santaeulàlia-Llopis (2010), Redistributive shocks and productivity shocks, Journal of Monetary Economics, Vol. 57 (8), pp. 931-948.

Rodríguez-López, J. and J. Torres (2012), Technological Sources of Productivity Growth in Germany, Japan, and the United States, Macroeconomic Dynamics, Vol. 16 (1), pp. 133-150.

Sandhop, K. (2012), Geschäftstypengewichtung im Verbraucherpreisindex – Wirtschaft und Statistik, March 2012, pp. 266-271.

Schmitt-Grohé, S. and M. Uribe (2011), Business cycles with a common trend in neutral and investment-specific productivity, Review of Economic Dynamics, Vol. 14 (1), pp. 122-135.

Solow, R. M., Investment and Technical Progress (1960), in K. J. Arrow, S. Karlin and P. Suppes (eds., 1960), Mathematical Methods in the Social Sciences, Stanford University Press, pp. 89-104.

Solow, R. M. (1957), Technical Change and the Aggregate Production Function, Review of Economics and Statistics, Vol. 39 (3), pp. 312-320.

Strasser, G., E. Wieland, P. Macias, A. Błażejowska, K. Szafranek, D. Wittekopf, J. Franke, L. Henkel and C. Osbat (2023), E-commerce and Price Setting: Evidence from Europe, ECB Occasional Paper Series, forthcoming.

Sveikauskas, L., S. Rowe, J. Mildenberger, J. Price and A. Young (2016), Productivity Growth in Construction, Journal of Construction Engineering and Management, Vol. 142 (10).

Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer and G. J. de Vries (2015), An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production, Review of International Economics, Vol. 23 (3), pp. 575-605.

van Ark, B., K. de Vries and A. Erumban (2021), How to not miss a productivity revival once again?, National Institute Economic Review, Vol. 255 (1), pp. 9-24.

vom Lehn, C. and T. Winberry (2022), The Investment Network, Sectoral Comovement, and the Changing U. S. Business Cycle, The Quarterly Journal of Economics, Vol. 137 (1), pp. 387-433.

von Kalckreuth, U. and N. Wilson (2020), Fintech and statistics – the challenge of classifying something that hasn’t existed before, Irving Fisher Committee on Central Bank Statistics, IFC Report No 12: Towards monitoring financial innovation in central bank statistics, Bank for International Settlements, pp. 126-139.

Young, A. T. (2004), Labor’s share fluctuations, biased technical change, and the business cycle, Review of Economic Dynamics, Vol. 7 (4), pp. 916-931.