Productivity impact of the Fourth Industrial Revolution

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Introduction

In most highly industrialized economies, productivity growth has slowed over the past two decades. One technology trend expected to re-ignite productivity growth is the Fourth Industrial Revolution (4IR). First described by the World Economic Forum, the 4IR has attracted widespread attention from academics, practitioners and politicians worldwide. The 4IR describes a trend toward technological innovation that increasingly substitutes human decision-making with systems of smart, interconnected objects. These systems build on new core digital technologies that underlie communication between objects. The development of enabling technologies, such as artificial intelligence (AI) or 3D printing, that enable a wide range of new applications encourages a feedback loop of further improvements to core technologies, as is characteristic of general-purpose technologies. This technology trend therefore has the potential to drastically change production and research and development (R&D) processes, business models and the organizational structure of companies across a broad spectrum of industries.[1] The 4IR is being driven in particular by the internet of things (IoT). The IoT describes a system of interrelated physical and virtual machines able to send, receive and exchange data over a network without requiring human-to-human or human-to-machine interaction. Even though the 4IR builds on the information and communication technologies (ICTs) of the Third Industrial Revolution, it sets itself apart by the breadth of its scope, its system impact, its speed of development and by allowing the automation of intellectual tasks. It not only makes it possible to build smart machines, it is centered around that very thing. The power of 4IR lies in the integration of physical, digital and biological advancements.[2] It envisions widespread automation and autonomous decision-making in production leading to fully autonomous, fast-adopting, self-organizing production plants, as well as far-reaching automatized or customized products. Although this trend started in the early 1990s, it has only gained momentum in recent years. And even if this vision is still far from becoming a reality, the trend in this direction is already underway.

In view of its far-reaching cross-industry importance, it is hardly surprising that the 4IR has stimulated a broad discussion in industry and politics with regards to its economic consequences and, in particular, its productivity impact. Techno-optimists like Brynjolfsson and McAfee consider the new digital revolution and its applications in production to be still in its installation phase and expect that major future productivity improvements are yet to come.[3] However, unlike previous industrial revolutions, the 4IR has also been the subject of much skepticism regarding its impact on productivity. Gordon, for example, argues that the technological opportunities for follow-up innovations are significantly less in the 4IR than they were in the first two industrial revolutions, which is why no growth effects and effects on living standards or ones nowhere near as large are to be expected.[4] Bloom *et al.* likewise point to declining or depleting technological opportunities and a concomitant decline in research productivity.[5] On the one hand, such depleting technological potentials can only be realized at a greater expense for companies and, on the other hand, are also associated with lower productivity growth. Others argue that the decline in observed productivity growth is the result of too little diffusion of new digital technologies, especially among laggard firms.[6]

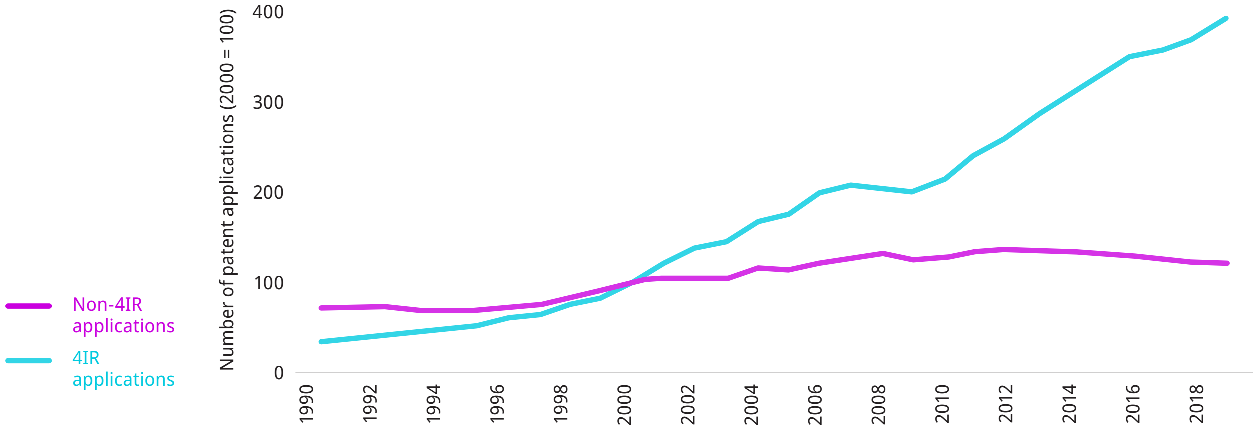
This paper sheds light on the recent development of 4IR technologies using patent data and summarizes some key findings on what has been learnt up to now about the impact of developing 4IR technologies, in order to assess whether this technology trend is likely to help revive productivity growth.

The trend toward a 4IR: Evidence from patent data

Recently, the European Patent Office (EPO) came up with a methodology for identifying 4IR technologies based on patent data.[7] Patents have been criticized as a measure for innovation, as not all inventions can be patented and not all inventions are patented, even if patentable, because firms have alternative measures they can take to protect their inventions. In addition, the use of patents may differ across 4IR technologies: for example, some enabling technologies may be more likely to be protected by copyright due to the nature of the technologies (e.g., algorithms). Finally, not all inventions lead to marketable innovations. Nevertheless, the availability of internationally comparable data over a long period of time and its rich technological content make patent data currently the best available proxy for studying the 4IR's evolution.[8]

4IR patents are identified in two steps. First, patent examiners identified a set of 368 technology Cooperative Patent Classification classes (CPCs) likely to contain 4IR technologies. In a second step, we performed a keyword search developed by the EPO, searching the patent texts of all EPO patents within these CPC classes. The keyword search identified patents containing a combination of terms for *data exchange* and terms for *communication* (e.g., internet, mobile, wireless), *computing* (e.g., big data, cloud, AI) and *intelligent devices* (e.g., sensor networks, IoT, smart homes).

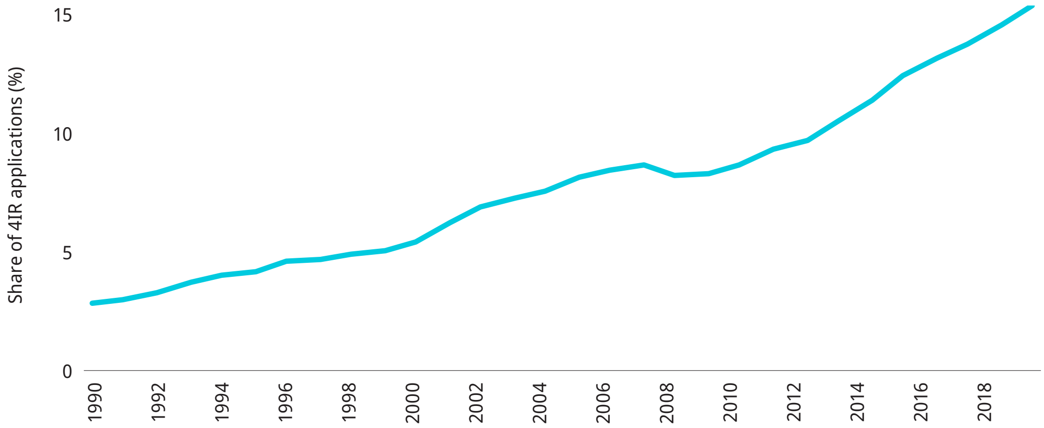
Figure 2.1 Trend in 4IR and non-4IR patents, 1990–2019



Source: Patstat, Spring 2021. Authors' own calculation.
Notes: Patents measured as patent applications at the European Patent Office. Index time series with base year 2000.

The trend toward new digital technologies is distinctive. In the early days of the internet in the early 1990s, 4IR patent applications – hereafter referred to as patents for short – accounted for about 3 percent of all EPO applications. Since then, their number has steadily increased. Since 2000, 4IR patents have more than quadrupled and the pace of growth continues unabated (Figure 2.1). For example, 4IR patents have doubled in each of the last two decades, most recently to around 15,500 in 2019. As for non-4IR patents, they increased initially, but then growth slowed significantly after the dot-com bubble burst and has even turned negative since 2013. However, with just under 88,000 patents in 2019, non-4IR patents are still in the majority. The discrepancy in the growth of 4IR and non-4IR patents is reflected in the share of 4IR patents in total patents. From just under 3 percent initially, this share had risen to over 15 percent by 2019, which means that, today, more than one in seven patents relates to 4IR. This shows clearly the growing importance of 4IR technologies in companies' R&D activities (Figure 2.2).

Figure 2.2 Share of 4IR patents, 1990–2019



Source: Patstat, Spring 2021. Authors' own calculation.
Note: Patents measured as patent applications at the European Patent Office.

A virtue of patent data is their detailed technological content. Following the EPO methodology, we are able to distinguish between three 4IR technology areas: core, enabling, and application technologies. Each is positioned at a different spot in the 4IR technology space, fulfilling its own purpose, especially in the diffusion of 4IR technologies.

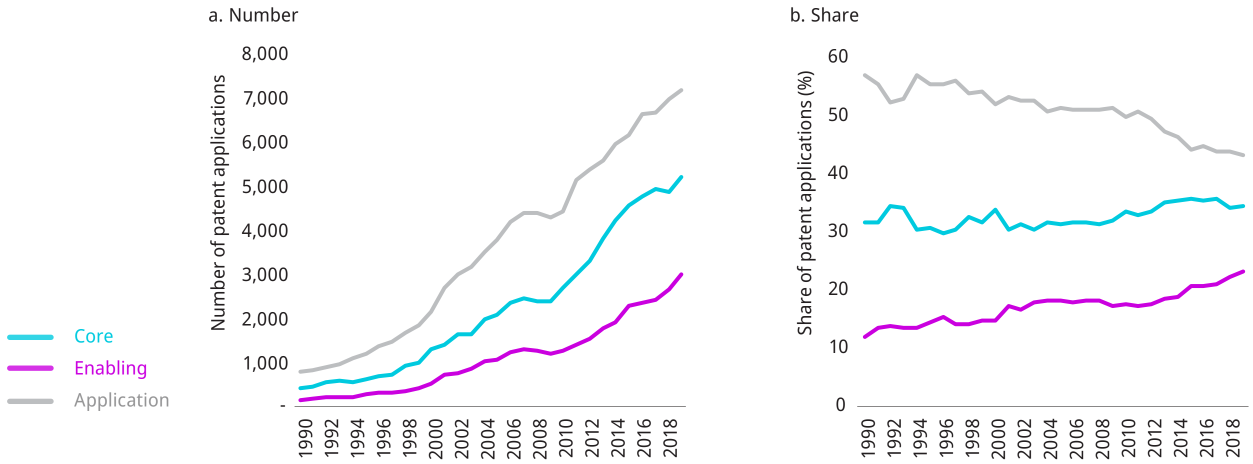
Core technologies are at the heart of the 4IR. They consist of IT hardware, software and connectivity technologies – such as processors, operating systems, network protocols and wireless technologies – on which all other applications of 4IR technologies rely. These technologies thus open the door to the development of any among the following technologies. Without them none of the applications of 4IR in either production processes or products would be possible.

Building directly on core technologies, there is a class of *enabling technologies* that uses the basic structures of the core technologies as an intermediary to specific applications. This area includes technologies such as AI, 3D printing, user interfaces, geo-positioning systems, smart power supply and data management systems. Each of these technologies can be built upon by developers of specific applications. Therefore, enabling technologies play an important role, acting as intermediaries between core technologies and applications, and enabling the diffusion of 4IR technologies into the economy.[9]

Application technologies are the most visible technologies. This area comprises final applications of automation technologies building on both previous blocks and represents the direct implementation of 4IR technology in the production processes and products of firms. The most prominent examples are smart factories, intelligent robotics, autonomous driving technologies, smart farming systems and smart personal devices.

The number of patents has steadily increased in each of the three 4IR technology areas outlined, with most patents being filed in the area of application technologies (Figure 2.3a). Core technologies is the second largest area, while enabling technologies represent the smallest technology area. Over time, however, 4IR activities have shifted significantly toward enabling technologies. Their share increased from around 12 percent to 23 percent during the period 1990–2019, while the share of core technologies remained stable at around 33 percent and the share of application technologies decreased from over 56 percent down to 43 percent in 2019 (Figure 2.3b).

Figure 2.3 Number and share of 4IR patents by technology area, 1990–2019

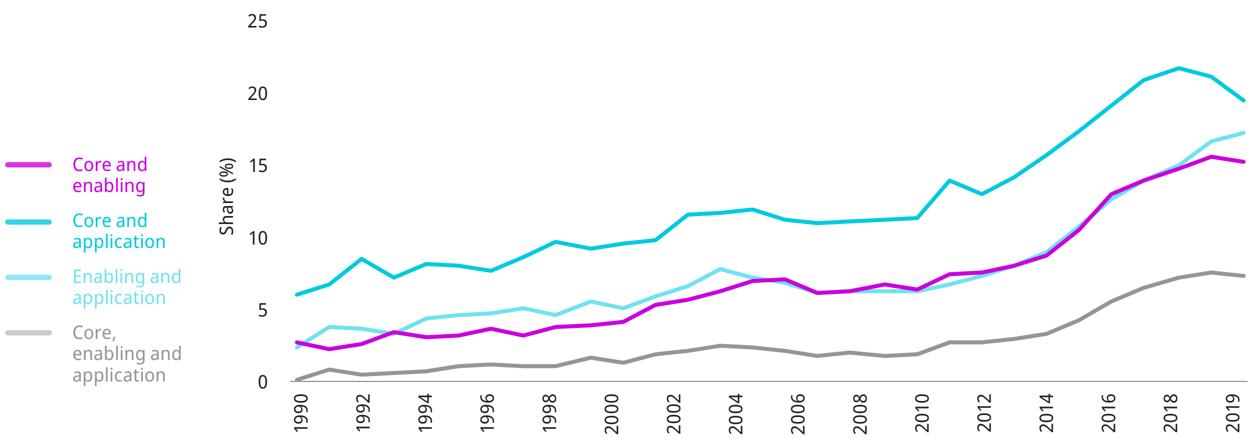


Source: Patstat, Spring 2021. Authors' own calculation.

Notes: Number and share of patent applications is based on fractional counts in order to account for patents belonging to more than one 4IR technology sector; that is, patents are weighted by the share of the respective 4IR CPC classes among all CPC classes of the patent application.

However, the shift from application to enabling technologies is only part of the story. We are also seeing an increasing share of 4IR bridging patents. These are patents that combine features of more than one 4IR technology area. In 1990, companies mainly filed inventions assigned to a single 4IR technology area. Back then, only about 11 percent of 4IR patents combined more than one 4IR technology area. This share had since grown very rapidly to reach 60 percent by 2018, doubling between 2011 and 2018 alone. Nowadays, about 20 percent of 4IR patents combine core and application technologies, while 17 percent are combinations of enabling and application technologies and 15 percent combinations of core and enabling technologies (Figure 2.4). Today, about seven out of every 100 4IR patents combine all three 4IR technology areas, whereas in the early 1990s this was only seven out of 10,000 4IR patents. All the patent indicators presented show impressively the increasingly dynamic trend toward the 4IR, especially within the last decade.

Figure 2.4 Share of 4IR bridging patents, 1990–2019



Source: Patstat, Spring 2021. Authors' own calculation.

Productivity impact of 4IR technologies

4IR technologies are expected to be an important source for increasing productivity. Productivity gains are predicted for many reasons, including cost and resource savings; increased flexibility in production; reduced uncertainty; the provision of better customized and personalized goods and services; better-informed decision-making; optimized delivery routes and a more efficient flow of material goods. On the other hand, the development and adoption of 4IR technology poses many challenges, as it involves making major changes to production processes and often requires that companies invest in new and different skills, knowledge and complementary assets. As a result, productivity gains may not be realized, or at least not immediately.

Despite the increasing usage of 4IR technologies and their expected impact on productivity, empirical evidence on productivity gains due to 4IR remains scant. However, studies available so far have shown the following key findings.

4IR technologies significantly increase productivity

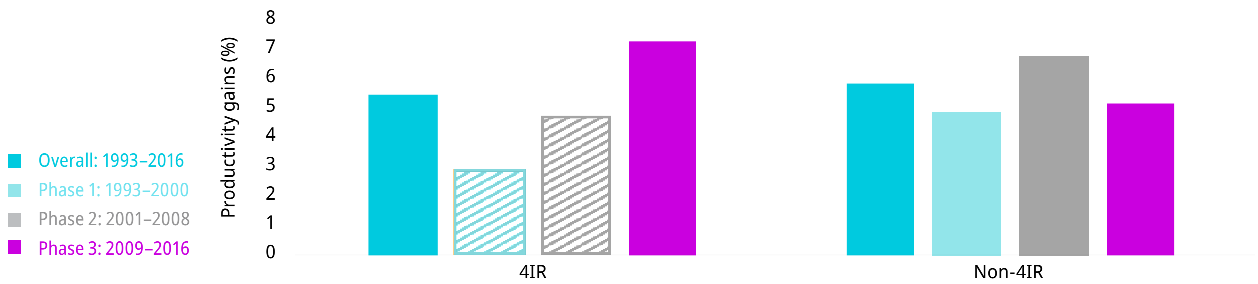
Two recent studies use patent data to examine the impact of 4IR technologies on productivity. Benassi and coauthors take a sample of around 500 large firms, with at least one 4IR patent filed at the EPO, drawn from 14 countries (including China, France, Germany, Japan, Republic of Korea, Sweden, the United Kingdom, and the United States). This study finds that a 10 percent increase in the stock of 4IR patents leads to an estimated increase in labor productivity of around 0.22 percent and total factor productivity (TFP) of 0.23 percent.[10] These effects appear modest; however, their observation period from 2009 to 2014 was when many companies started developing 4IR technologies either from scratch or a very low level. The average annual increase in the stock of 4IR patents has been around 67 percent, implying a quite large annual productivity gain of around 1.5 percent according to both productivity measures. The results also show a time lag of two years before companies start to reap benefits in terms of improved productivity. The second study by Peters and Trunschke focuses on a sample of high-tech manufacturing firms in Germany, the main producers of new 4IR patents.[11] For the period 2008 to 2016, the study shows that, within this group, those companies that developed new 4IR technologies were able to increase productivity by as much as 7.2 percent. Importantly, both studies find stronger productivity effects from 4IR patents than from non-4IR patents.

A limitation of both studies is that they only examine the productivity gains of those companies developing new 4IR technologies. However, many companies do not themselves develop such technologies, but instead adopt 4IR technologies developed by others. To complete the picture of productivity effects, two further studies – one by Acemoğlu and coauthors, the other by Czarnitzki *et al*. – provide additional insights by focusing specifically on the adoption of 4IR technologies. The first study shows that adoption of industrial robotics in a sample of French companies led to a 2.4 percent increase in TFP during the period 2010–2015.[12] The second focuses on the adoption of AI as a key 4IR technology.[13] This study shows that the adoption of AI in German companies has led to a productivity increase of between 4.4 and 6 percent in 2018. However, the proportion of firms that adopted AI in the study is still quite small at 7 percent. Furthermore, this second study shows productivity to increase in proportion to the intensity with which companies use AI methods in their business processes. AI intensity is measured based on 20 AI application areas in a company, with companies using AI on average in 2.5 of these areas. A shortcoming of both studies is their focus on a specific 4IR technology. As different 4IR technologies are being increasingly combined, this may lead to an overestimation of the productivity effect of a single 4IR technology.

Productivity increases have gained momentum

The positive effects found in the two studies referred to above are an indication that the 4IR is slowly moving beyond the installation phase and the first productivity effects of this new technology trend starting to be observed. This is supported by recent evidence showing productivity gains to have gathered momentum in just the last few years. Also, based on findings from German high-tech firms, it is very clear that, on average, no significant productivity gains were observed for first-mover firms in the early days of the 4IR (Figure 2.5). However, the effects have grown over time and were significantly positive for the first time in the last decade.

Figure 2.5 Productivity impact of 4IR and non-4IR patents by time period, 1993–2016

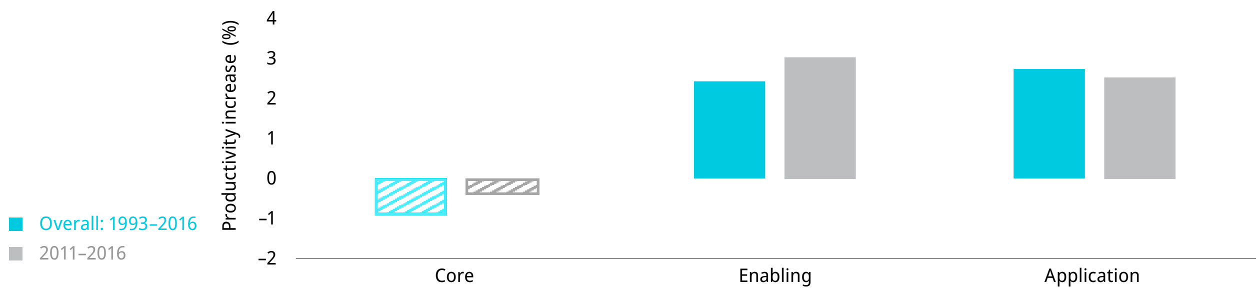


Source: ZEW – Mannheim Innovation Panel. Authors' own calculations.
Note: Solid and striped bars indicate significant and non-significant productivity effects, respectively.

Productivity increases are primarily driven by enabling technologies

The 4IR encompasses a wide range of different technologies. It is unlikely that productivity effects will be homogeneous across different 4IR technologies; rather, some technologies, such as AI, are expected to have a greater potential to increase productivity than others. Therefore, it is important to examine which technologies are likely to contribute most strongly to productivity growth. Indeed, we find that the positive productivity effects of enabling and application technologies are far stronger than those of core technologies; and, furthermore, that over the last decade the productivity effects of enabling technologies have overtaken those of application technologies (Figure 2.6). This is consistent with the results cited above showing the positive productivity effects produced by AI as a key enabling technology and from industrial robots as an important application technology in firms' production processes. Benassi's study cited earlier in particular points to the productivity effects from AI, cognitive computing and big data analytics, which are three times higher than the average effect of the 4IR on TFP.[14] Moreover, this same study also shows that wireless technologies – an important technology within the area of core technologies – have strong positive productivity effects. For cyber-physical systems (CPS), cloud computing/manufacturing, industrial IoT and augmented reality, on the other hand, the study finds no significant effects – or at least not as yet for the developers of these technologies.

Figure 2.6 Productivity impact of core, enabling and application technologies, 1993–2016



Source: ZEW – Mannheim Innovation Panel. Authors' own calculations.
Note: Solid and striped bars indicate significant and non-significant productivity effects, respectively.

Capabilities and complementary intangible assets are important contingencies for reaping productivity gains

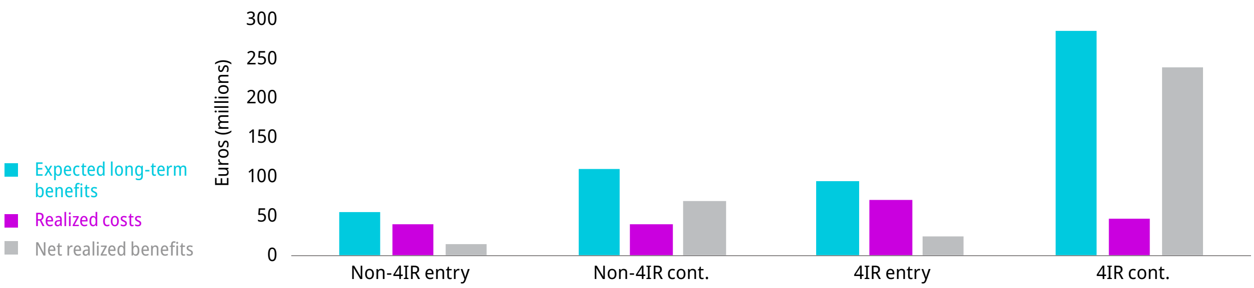
Despite positive results regarding 4IR productivity effects, it should however be said that achieving productivity gains is not a foregone conclusion. Initial results suggest there are important contingencies that enable companies to realize positive productivity gains. The importance of investing in human capital and AI-related skills, for example, is discussed in more detail in the GII 2022 Expert Contribution from Petropoulos. Skilled employees are also a vital constituent in building technological 4IR capacities within companies. The study by Benassi *et al.* has shown that a company's accumulated experience in developing 4IR technologies – and thus technological capabilities – matters immensely.[15] Currently, only those companies with a long experience of 4IR technology development (i.e., time since their first 4IR patent application) and highly persistent 4IR development activities dating from the first application are able to significantly increase productivity, whereas other companies are unable to achieve – or at least not as yet – productivity gains from their 4IR patent activities.

The role played by investments in complementary innovations and intangible assets in reaping the benefits of a general-purpose technology is also much discussed and has recently been illustrated by Brynjolfsson and colleagues in the context of ICT diffusion.[16] AI is likely to follow the same pattern. In the installation phase, digital technologies do not deliver what they promise in terms of productivity gains due to a lack of complementary innovations and intangible assets. Only once sufficient complementary innovations and investments in intangible assets are present can a continuous and steep increase in productivity be observed (J-curve). In the context of AI, a study by Behrens *et al.* highlights the importance of data and software investments as complementary assets to benefit from AI.[17] The authors use the same data as a study by Czarnitzki *et al.* on AI adoption, but enhance it with information on investments in internal and external databases and software made by firms.[18] This allows them to show that, among AI-adopting firms, only those that simultaneously invest in internal complementary intangibles, that is, internal data collection and software, are able to significantly increase productivity in the short term, with very high productivity effects of between 6 and 12 percent then achieved. The biggest productivity gains were observed for companies that developed AI jointly with external partners or acquired it by buying them, but at the same time invested in internal data collection (+12 percent). Positive but smaller gains were found for companies with internal AI development and investment in internal data collection (+6 percent), whereas companies that chose to simply adopt externally-developed AI and also acquire external data sources saw no increase in productivity. This confirms the importance of internal 4IR capabilities and investment in building internal data in achieving productivity gains.

Long-term benefits of developing 4IR technologies

Given its high potential productivity gains, the question arises as to why many more companies have not yet joined this new technology trend by investing in the development of 4IR technologies themselves. Interesting answers to this question are provided by a recent study examining technology choices – investments in the development of new technologies, products and processes based on 4IR or non-4IR technologies – for German companies during the period 2008–2016.[19] The study finds that companies will invest in the development of 4IR technologies only if the long-run expected benefits are greater than the associated development costs. Greater short-term productivity gains from 4IR as compared to non-4IR technologies are only one building block for long-run net benefits and thus for choosing to develop 4IR technologies. In addition, it also matters how quickly such productivity gains depreciate over time and how high the development costs are for each respective company. The study shows development costs for 4IR to be significantly higher than for non-4IR technologies, and, furthermore, significantly higher for companies without 4IR experience (Figure 2.7). This means that, while experience with 4IR is an important contingency for achieving productivity gains, the barriers to entry for investment in 4IR development are at the same time high. Such high development costs turn the expected net benefits for many companies negative, meaning there is no incentive to invest in the development of 4IR technologies. This leads to an overall finding of strongly skewed long-run net benefits. The high barriers to entry provide an argument for public support. In a policy simulation, the authors of the study examine how a 25 percent subsidy on 4IR development costs might affect companies' technology choices. They conclude that such a subsidy would encourage more companies to develop 4IR technologies, while at the same time lessening the incentive for non-4IR technologies, with the induced technology switch associated with an overall increase in innovation.

Figure 2.7 Long-term benefits of developing 4IR technologies



Source: Peters and Trunschke (2021).

Note: The graph depicts the average expected long-term benefits, realized costs and net realized benefits of firms that invest in developing 4IR and non-4IR technologies. 4IR and non-4IR entry denotes firms without experience in the respective technologies. 4IR cont. and non-4IR cont. denote firms with prior experience in the respective technology classes.

Conclusion

The 4IR is expected to make a significant contribution to the productivity revival. At the same time, it is known that during the installation phase of a new broad technological development, productivity gains tend to be small. Once 4IR technologies are further developed and become more widespread, the productivity benefits are likely to increase significantly. Most recent evidence suggests that at least some 4IR technologies are about to progress – if they have not done so already – beyond the installation phase, with studies showing significant productivity gains from those 4IR technologies that have gathered momentum in recent years. But important differences still exist across technology fields. Moreover, achieving productivity gains through the development and adoption of the 4IR is by no means a foregone conclusion. Investing in complementary intangible assets, such as data, software and skills, is an important prerequisite for realizing the 4IR productivity potential. In addition, 4IR technological capability, that is, accumulated experience, is important to benefitting from the 4IR. At the same time, this represents a high barrier to entry for those companies starting to develop 4IR technologies. Subsidizing the development and adoption of 4IR technologies seems a promising solution to encouraging more companies to switch technologies toward the 4IR and innovate more. Subsidizing investment in complementary assets should also be considered where financial constraints are a major factor, especially for small companies.

Notes

1 Cockburn *et al.*, 2019.
2 Schwab, 2017.
3 Brynjolfsson and McAfee, 2011, 2014; and McAfee and Brynjolfsson, 2017.
4 Gordon, 2012.
5 Bloom *et al.*, 2020.
6 Andrews *et al.*, 2016.
7 EPO, 2020.
8 Martinelli *et al.*, 2021.
9 Teece, 2018.
10 Benassi *et al.*, 2022.
11 Peters and Trunschke, 2021.
12 Acemoğlu *et al.*, 2020.
13 Czarnitzki *et al.*, 2022.
14 Benassi *et al.*, 2022.
15 Benassi *et al.*, 2022.
16 Brynjolfsson *et al.*, 2021.
17 Behrens *et al.*, 2021.
18 Czarnitzki *et al.*, 2022.
19 Peters and Trunschke, 2021.

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