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A REVOLUTION IN THE MAKING? CHALLENGES AND OPPORTUNITIES OF DIGITAL PRODUCTION TECHNOLOGIES FOR DEVELOPING COUNTRIES

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A revolution in the making?

Challenges and opportunities of digital production technologies for developing countries

Antonio Andreoni
UCL Institute for Innovation and Public Purpose

Guendalina Anzolin
University of Urbino

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Abstract

The emergence, deployment and diffusion of new technologies clustered around the so-called Fourth Industrial Revolution (4IR) is increasingly altering the nature of manufacturing production, while blurring the boundaries between physical and digital production technologies and systems. Advances in fields such as intelligent automated systems, robotization and additive manufacturing as well as related data analytics—IoT, digital platforms and digital supply chains—generate significant opportunities to accelerate innovation and increase the value-added content of production in manufacturing industries. Yet the substantial requirements of the 4IR—particularly in terms of digital infrastructure, infratechnologies and digital skills—have led some observers to question whether industrialization is still a feasible or even desirable strategy to achieve economic development.

Against this backdrop, and with a specific focus on *digital production technologies*, this background paper provides insights on how these technologies are re-shaping the process of industrialization in developing countries, inquiring what is new about them and to what extent developing countries can benefit from their adoption in view of the fundamental binding constraints they face. Specifically, we focus on the role basic and intermediate industrial capabilities play in the productive absorption and deployment of new technologies and their diffusion along the supply chains.

Building on multi-country and multi-sectoral industry case studies, this background paper highlights the specific challenges associated with the incremental absorption, retrofitting and effective deployment of these new technologies and licensing of digital platforms in GVCs. The case studies and following discussion also challenge the view that industrialization as a development strategy is no longer feasible or even desirable. We conclude that developing countries will have to build a robust industrial system in which these technologies can release their productivity potential to continuously capture the "digital dividend" in a sustainable way. Moreover, by engaging in industrial activities, countries can build and strengthen the set of digital skills, organizational capabilities and new business models needed to compete and succeed in the new technological paradigm.

Keywords

Fourth industrial revolution; digital production technologies; production retrofitting; digital capability matrix; industrial policy

1. An introduction to the Fourth Industrial Revolution debate: developing countries' perspective

The so-called Fourth Industrial Revolution (4IR) encompasses different types of technologies that are altering production and service activities within and across sectoral value chains. In some cases, these technologies combine and merge the physical and digital realms of both production and products. For example, advances in fields such as robotization and additive manufacturing as well as related data analytics and systems (Internet of Things), digital platforms and digital supply chains, are unlocking new opportunities to accelerate innovation and increase the value-added content of production, especially across manufacturing processes and industries (OECD, 2017; WEF, 2017).

The debate around these new digital technologies has grown exponentially in advanced countries and late industrializers over the last decade. Even countries that have experienced premature de-industrialization since the mid-1980s (Andreoni and Tregenna, 2018) are captivated by the idea of an ongoing 4IR. The potentially disruptive impact of these new technologies on employment in mature industrial economies took centre stage in the academic and policy debates from the very start.

Two opposing views have dominated the debate so far, although more recent studies are suggesting the need for a more nuanced analysis of the impact of the 4IR on specific types of production tasks. The "optimistic view" perceives the 4IR as a new source of opportunities (also in terms of job creation) for both developed and developing countries. The more "pessimistic view", on the other hand, essentially argues that 'this time is different', i.e. the 4IR will not generate as many (good) jobs as workers who will be displaced, as has been the case in previous industrial revolutions.

The "optimistic view" maintains that the 'false alarmism' around the impact of digital production technologies (Atkinson and Wu, 2017) derives from overlooking the strong legacy between preceding technological shifts and the 4IR, thus advocating the prospect of the creation of more and better jobs. According to this perspective, we are currently experiencing the "unlearning the old and learning the new phase" (Freeman and Perez, 1989), but, just like in the past, a new golden age for job creation is on the horizon. Authors that support this perspective, such as Perez (2010), focus on the possibilities new technological opportunities offer to specific industries in developing countries, such as more effective use and management of natural resources.

Other authors assert that the impact of the new technologies on employment will depend on institutional factors – what is made of these technologies is what matters most. Gordon (2014), for example, perceives the progress in data computing and automation as less transformative than previous technological revolutions and does not associate the slowdown in job creation with computers (see also OECD, 2014). According to some scholars, therefore, the loss of jobs will be linked to more pervasive structural issues such as employment conditions and trade union disruptions, forcing down wages of low-skilled workers, as well as the financialization of corporations leading to a collapse in investments (Atkinson, 1999; Singh and Zammit, 2004; Lazonick, 2010).

According to the "pessimistic view", job creation will be insufficient for the growing population, particularly for low-skilled workers whose jobs are the most likely to be automated (Hawking, 2016). According to one of the most cited contributions to this strand of research (Brynjolfsson and McAfee, 2014), there has never been a worse time to be a worker with low skills and competences. Frey and Osborn (2013), for example, predict that automation will displace 47 per cent of jobs in the United States. The focus on low-skilled jobs and the notion of skills-biased technological change, developed by Acemoglu and others, builds on the conceptualisation of 'manual tasks' as being low-skilled, and thus most likely to be replaced (Goos et al., 2014).

Beyond this polarized discussion, recent studies provide a more nuanced assessment of potential job displacement. They focus on the type of tasks and specific skills that will be directly affected by 4IR technologies, particularly by robots. The findings of these studies are considered to be more accurate, due to the fact that a single job is made up of many different tasks and thus different skills, of which only a few can be replaced by computers or automation. By using the PIACC dataset (OECD), Arntz et al. (2016) examined task instead of job displacement, and estimate that 9 per cent of tasks will be displaced by 4IR technologies. Along the same lines, other contributions (Autor and Dorn, 2013; Autor, 2015) develop the concept of complementarity between automation and human tasks focusing on the so-called compensation effect. According to this task-based approach, some tasks are more likely than others to be displaced, which varies according to their degree of *routinization*. That is, we are facing 'routine-biased technological change', where only routine tasks will be substituted while cognitive tasks will be 'protected' from displacement. It is thus the degree of 'task routinization' that drives automation and not necessarily the fact that some tasks are manual. In fact, it might be difficult to routinize some of the manual tasks, i.e. it might be difficult to automate some of them (Sgobbi, 2018).

The small number of studies that has explored the impact of new technologies on manufacturing jobs in developing countries has primarily focused on the 'mediated impact' of the 4IR on employment generation (Chandy, 2016; Rodrik, 2018; WDR, 2019). These studies investigate to what extent the reduction in offshoring from industrialized to developing countries, driven by the increasing deployment of robots and additive manufacturing, can actually have an impact on job creation in low wage economies.

This reshoring of production[1] from developed to developing countries might also be coupled with another fundamental change. In the sphere of the third industrial revolution, developing countries can benefit from the so-called "flying geese" phenomenon, namely the fact that rapidly industrializing countries move from labour-intensive to more capital-intensive industries—say from garments to machinery—and thus relocate labour-intensive jobs to other developing countries. In today's 4IR world, rapidly industrializing countries like China might be 'capturing the geese', i.e. might replace jobs with robots and cease to move labour-intensive industries to low-wage developing countries. This is why some question whether the millions of jobs of fast growing late industrializers will ever reach Africa. Interestingly, while the potential disappearance of routinized manufacturing jobs has been widely decried, much less emphasis has been given to the fact that other technologies like data analytics and AI may potentially have a much larger impact on high and low value services, especially in countries like India.

Moving away from a debate that primarily centres around the impact of the 4IR on employment in advanced and rapidly industrializing countries, we argue that developing countries are indeed engaging with the 4IR in a much more diverse and context-specific way. Therefore, the direct and mediated impact of 4IR technologies on employment and industrialization across developing countries can only be understood in relation to:

(i) the *specific challenges* developing countries face (compared with more advanced economies) in engaging with the 4IR, especially digital production technologies; and
(ii) the *different forms of engagement with 4IR technologies* of countries at different stages of development, both with respect to companies' and governments' upgrading strategies and policies in different sectors.

When taking a closer look at the new digital technologies and their application in production processes across sectors and countries, we identify the need for a more incremental approach to the 4IR and a different policy focus, especially for developing countries. Instead of viewing the

[1] There is little evidence of reshoring mechanisms from emerging to developed countries due to automation and cost-saving technological change (de Backer et al., 2014).

ongoing technological change as a ‘disruptive revolution’, we argue that we are in fact witnessing an ‘evolutionary process’ in which companies are still sizing up many of the opportunities the new technologies offer, and face major challenges, especially in terms of effective adoption and retrofitting of their legacy systems.

What is more, 4IR opportunities are not equally distributed as companies and countries face different challenges. Effective adoption of these new technologies presupposes the existence of productive organizations endowed with basic and intermediate production capabilities, supported by enabling infrastructures such as reliable electricity, standardization and connectivity. These conditions, however, are largely missing in the majority of developing countries, as well as in many regions of emerging countries and mature industrial economies.

From this perspective, which does not undermine the potential future implications of the new digital technologies, we argue that it is more reasonable to focus on (i) the ways companies incrementally *integrate* the last generation of technologies to execute a number of production tasks within existing production systems, and (ii) how such integration requires a continuous process of *retrofitting* of these same production systems, and the development of new capabilities to run them effectively. This shift in the approach to the 4IR has profound implications for industrial policies, suggesting the need to move away from futurist technological discussions towards more targeted and grounded visions of what is feasible incrementally in different countries and sectors. The importance of focusing on these processes of integration and of retrofitting production tasks and systems, as well as the need for basic and intermediate production capabilities is crucial to escape the polarized discussion on the impact of digital technologies on employment.

1.1 Specific challenges for developing countries in engaging with 4IR

The specific challenges developing countries face in engaging with the 4IR can be clustered in five main groups. In sections 2 and 3, we analyse each of them in greater detail and exemplify them with a number of case studies in section 4.

a) Technology absorption, effective deployment and ‘capability threshold’

First, the basic and more advanced production capabilities required to absorb and effectively deploy the new digital production technologies and to diffuse them along the supply chains are scarce and unevenly distributed. Moreover, digital production technologies have also raised the ‘capability threshold’ that companies must reach to be able to effectively use the new technologies. This is not because parts of these technologies are completely new – for example, automated machineries go back to a least 2IR. That is, the 4IR is about the 'fusion of existing and new technologies' into complex integrated technology systems (Tassey, 2007). Managing complex integrated technology systems like a fully automated production line combining robots and IoT technologies is an extremely demanding task for productive organizations in a developing country.

b) Production system 'retrofitting and integration'

Second, industrialization is about the commitment of resources under uncertainty (Chang and Andreoni, 2019). Most of these commitments involve physical capital embodying certain technologies that cannot be re-moulded in any significant way to evolve into other technologies. Very often, the commitments are of an organizational nature as well and entail the specialization of individuals in developing specific skills. These commitments are critical because they raise productivity, resulting in benefits from economies of scale in production, for example. Depending on the investments' degree of reversibility, these commitments make future changes more difficult. This introduces a very specific challenge in developing countries. The existing companies that can make technology investments have already committed such resources and have to find ways to retrofit and integrate the new digital production technologies into their existing production plants. The establishment of brand new plants is fairly rare as it requires significant long-term investments and access to markets, and these new plants might be difficult to run given the lack of basic and digital infrastructure.

c) Basic and digital infrastructure

Third, digital production technologies are very demanding in terms of the infrastructure required to put their use in production into effect. Developing countries face considerable challenges in the provision of affordable and reliable electricity, as well as decent connectivity. In some cases, these infrastructural bottlenecks have been bypassed by off-grid energy technologies and wireless connectivity systems. While these solutions work in certain areas, they are not always able to provide the quality and reliable services needed to effectively run digital production technologies. As a result, the improvements in productivity and quality provided by digital production technologies are offset by these infrastructural bottlenecks and can make technology investments by individual companies too risky and ultimately, not economical.

d) Technology diffusion, '4IR islands' and the 'digital capability gap'

Fourth, despite the fact that '4IR islands' are found in nearly all developing countries, that is, companies that engage with some digital production technologies, many of these technologies remain contained within the company and their production cells. A few suppliers that have the basic production capabilities to make use of them might be linked to these 4IR islands (Andreoni, 2019). Moreover, 4IR islands often rely on enabling infrastructural capabilities (connectivity, electricity, etc.) built by the same company at its own costs for its own plants. Without such infrastructure, companies would not even be able to switch digital production technologies on. Surrounding these 4IR islands is a large majority of companies and sectors that are still fully operating within the third industrial revolution technology paradigm and thus unable to operate at the same standards of the island companies. In other cases, especially among least developed countries, companies are not yet even engaged with technologies from the second industrial revolution. This makes it extremely difficult for the leading companies—say an OEM—to link backward and nurture their supply chains. The “digital capability gap” between 4IR company islands and suppliers is so extreme and so costly to address (given the existing endogenous asymmetries – see below) that the diffusion of 4IR technologies remains very limited.

e) ‘Endogenous asymmetries’ in technology access and affordability

Fifth, digital production technologies are complex and controlled by a limited number of advanced countries and their leading companies. Developing countries heavily rely on the importation of such technologies from advanced economies, and in many cases, even when they are able to mobilize significant resources to access them, they are tied to their buyers with respect to both the hardware and software components. International buyers and OEMs control the source, type and utilization of the digital production technologies by setting the parameters of the suppliers’ engagement. Those who cannot meet these parameters are marginalized. The importance of using common protocols and software platforms for the deployment of digital production technologies bears the risk of verticalization and concentration of power. Moreover, many of these technologies are not “plug and play”, i.e. the acquisition of hardware goes hand in hand with the need for expensive technology services and royalties for the use of related software (Sturgeon, 2017; Piva and Vivarelli, 2017).

1.2 Different forms of engagement with 4IR across developing countries

Beyond these five general challenges, the following stylized facts are useful to capture how countries at different stages of industrialization and in different sectors are engaging with the 4IR. In section 4, we present case studies to highlight the different types of engagement, with a focus on the larger group of low and middle income countries for three sectors: automotive in South Africa, mining in Brazil and agriculture in Thailand.

Late industrializers

While the use of digital production technologies among late industrializers like China and India is speeding up, these technologies are still concentrated in a few sectors only (and in a few companies and supply chains within them) and the full automation of "routinized tasks" is far from diffused as many observers seem to suggest (see section 2 below). There are multiple reasons for this, including the infrastructural preconditions and trade-offs associated with digital production technologies, with respect to both the hardware and software of these technologies and, even more critically, the integration of their production system. Having said that, 4IR islands have started connecting with one another and cross-sectoral value chains using digital production technologies are gradually emerging, thanks also to governments' industrial policies such as in the case of Thailand and Malaysia.

Low- and middle-income countries

In low- and middle-income countries, like Brazil and South Africa, companies face more fundamental problems related to access to digital production technologies, their integration into existing production systems and retrofitting and, finally, sufficient availability of basic production capabilities and enabling infrastructural capabilities. In these countries, the lack of job creation is largely the result of structural and political-economic problems, including their premature deindustrialization, lack of productive organizations in key stages of GVCs and basic productive capabilities, more than the diffusion of digital technologies. In countries like Thailand and Viet Nam, where the political-economic configuration, namely developmental state coalition, has led to high levels of investments and an increasing number of export-led competitive companies, the countries' governments are pushing for the diffusion of digital production technologies beyond 4IR islands.

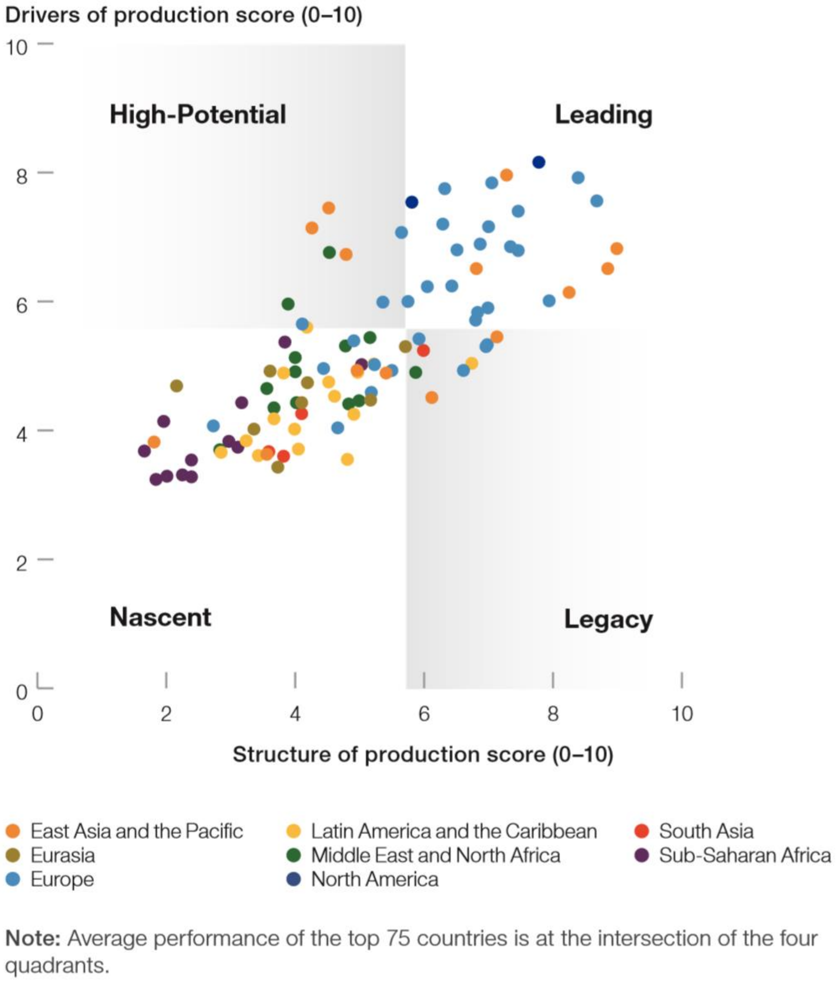
Least developed countries

In least developed countries, especially on the African continent, the lack of competitive productive organizations makes the deployment of these digital technologies in production even rarer. While some basic information and communication technologies (ICTs) have found some applications, for example, in managing money transactions (e.g. online finance platforms) or sharing some basic data (e.g. price data in agriculture), these applications were developed during the third industrial revolution and are thus not truly digital production technologies. A limited number of companies are experimenting with the use of digital production technologies to the extent they are involved in production activities. For example, we find some experimental applications in selected high value agricultural products, extractive processes and trade logistics.

Unfortunately, given the limited amount of manufacturing industries and competitive companies, these countries are still unable to capture the potential "digital dividend" of 4IR technologies.

The different levels of engagement of countries in different regions with the 4IR's digital production technologies is thus driven by their existing production structure and the extent to which they are equipped with the necessary basic capabilities and enabling digital infrastructures. Building on these two dimensions and two sets of composite indexes capturing the structure and drivers of production, Figure 1 illustrates that only a few East Asian countries have joined the group of advanced economies in the "Leading" quadrant of the next production revolution. These are countries where readiness in the engagement with 4IR technologies is higher. The majority of low- and middle-income countries are clustered in the group of "Nascent" countries, that is, countries with a limited production base and which will potentially face the most severe challenges.

Figure 1: Global map of readiness for the next production revolution, 2018



Source: WEF 2018. The Readiness for the Future of Production Report 2018

Given the major challenges developing countries currently face, and which will only increase in the future as a result of rapid technological change, especially in manufacturing industries, concerns have been raised regarding the extent to which developing countries should engage with the industrialization factor of the 4IR. The 2017 World Bank Report *Trouble in the Making*, for example, questions whether industrialization is still a feasible or even a desirable strategy to achieve economic development. The report acknowledges the fact that new technologies, including advanced robotics, industrial automation and 3-D printing, are changing the landscape of global manufacturing. Thus, it questions whether developing countries' traditional path to development, often driven by manufacturing, may be at stake because the criteria for becoming an attractive production location are changing. The report acknowledges that opportunities remain for developing countries, if governments take appropriate policy actions on the 3Cs: competitiveness, capabilities and connectedness.

In the following sections, we assess the *feasibility* (challenges) and *desirability* (opportunities) of investing in manufacturing industries and digital production technologies in developing countries, while the global economy is slowly advancing towards the 4IR.

In section 2, we look at the development of production technologies since the First Industrial Revolution (1IR) and investigate the role digital production technologies can play in developing countries. We will break down digital production technologies to better understand how developing countries are/can engage/ing with them. Specifically, we focus on the *hardware* and *software* dimensions of digital production technologies, as well as how these are connected (*connectivity*) and integrated (*production system integration*). Particular emphasis is placed on the opportunities industrial robots, additive manufacturing and digital platforms offer.

In section 3, we explore the basic and more advanced capabilities required in different functional areas of production to effectively deploy these digital production technologies – from production to retrofitting and integration. We develop a *digital capability matrix* highlighting the specific capabilities required to capture digital industrialization opportunities and to overcome the specific challenges developing countries face. Particular emphasis is given to the significance of developing capabilities for technological and organizational integration.

Three case studies highlighting the ways countries are engaging with the 4IR are presented in section 4. We focus on three middle-income countries—South Africa, Brazil and Thailand—across three main sectors – automotive, extractive and agriculture, respectively. The case studies provide insights on specific capabilities, as highlighted in sections 2 and 3.

The final section discusses why developing countries should develop their manufacturing industries to capture the digital dividend of the 4IR.

2. What role for digital production technologies (DPT) in developing countries?

2.1 Digital production technologies: evolution or revolution?

4IR is the first so-called revolution in history to be announced while it is 'still in the making', and certainly 'long before its completion'. The 4IR (also called the 'Next Production Revolution') entails several types of technologies of which *digital production technologies* are only a subgroup (OECD, 2017; Andreoni, 2017). Other technology clusters include advanced materials, biotechnologies and quantum technologies, just to mention a few. For example, the World Economic Forum Handbook of the Fourth Industrial Revolution identifies 12 key emerging technologies (Table 1). Some of them are sector-specific technologies, although the majority are platform technologies that can be deployed in multiple sectors. A number of them can be directly classified as production technologies, such as additive manufacturing and robotics.

Table 1: Twelve key emerging technologies

Technology	Description
Artificial intelligence and robotics	Development of machines that can substitute for humans, increasingly in tasks associated with thinking, multitasking and fine motor skills.
Ubiquitous linked sensors	Also known as the "Internet of Things." The use of networked sensors to remotely connect, track and manage products, systems and grids.
Virtual and augmented realities	Next-step interfaces between humans and computers involving immersive environments, holographic readouts and digitally produced overlays for mixed-reality experiences.
Additive manufacturing	Advances in additive manufacturing, using a widening range of materials and methods. Innovations include 3D bioprinting of organic tissues.
Blockchain and distributed ledger technology	Distributed ledger technology based on cryptographic systems that manage, verify and publicly record transaction data; the basis of "cryptocurrencies" such as bitcoin.
Advanced materials and nanomaterials	Creation of new materials and nanostructures for the development of beneficial material properties, such as thermoelectric efficiency, shape retention and new functionality.
Energy capture, storage and transmission	Breakthroughs in battery and fuel cell efficiency; renewable energy through solar, wind, and tidal technologies; energy distribution through smart grid systems; wireless energy transfer; and more.
New computing technologies	New architectures for computing hardware, such as quantum computing, biological computing or neural network processing, as well as innovative expansion of current computing technologies.
Biotechnologies	Innovations in genetic engineering, sequencing and therapeutics, as well as biological computational interfaces and synthetic biology.
Geoengineering	Technological intervention in planetary systems, typically to mitigate effects of climate change by removing carbon dioxide or managing solar radiation.
Neurotechnology	Innovations such as smart drugs, neuroimaging and bioelectronic interfaces that allow for reading, communicating and influencing human brain activity.
Space technologies	Developments allowing for greater access to and exploration of space, including microsatellites, advanced telescopes, reusable rockets and integrated rocket-jet engines.

Source: WEF, 2018

Despite the fact that 'technologies never work in isolation' and advancements in one technology—say a new polymer or composite material—is the result of *as well as* the precondition for innovation in other technologies—say injection moulding machineries or 3D printers—we focus our attention on production technologies only, as they have played a key role in driving productive transformation since 1IR (Rosenberg, 1969; Andreoni and Gregory, 2013; Andreoni, 2014; Andreoni and Chang, 2019). They are therefore a key subgroup of 4IR technologies developing countries must engage with.

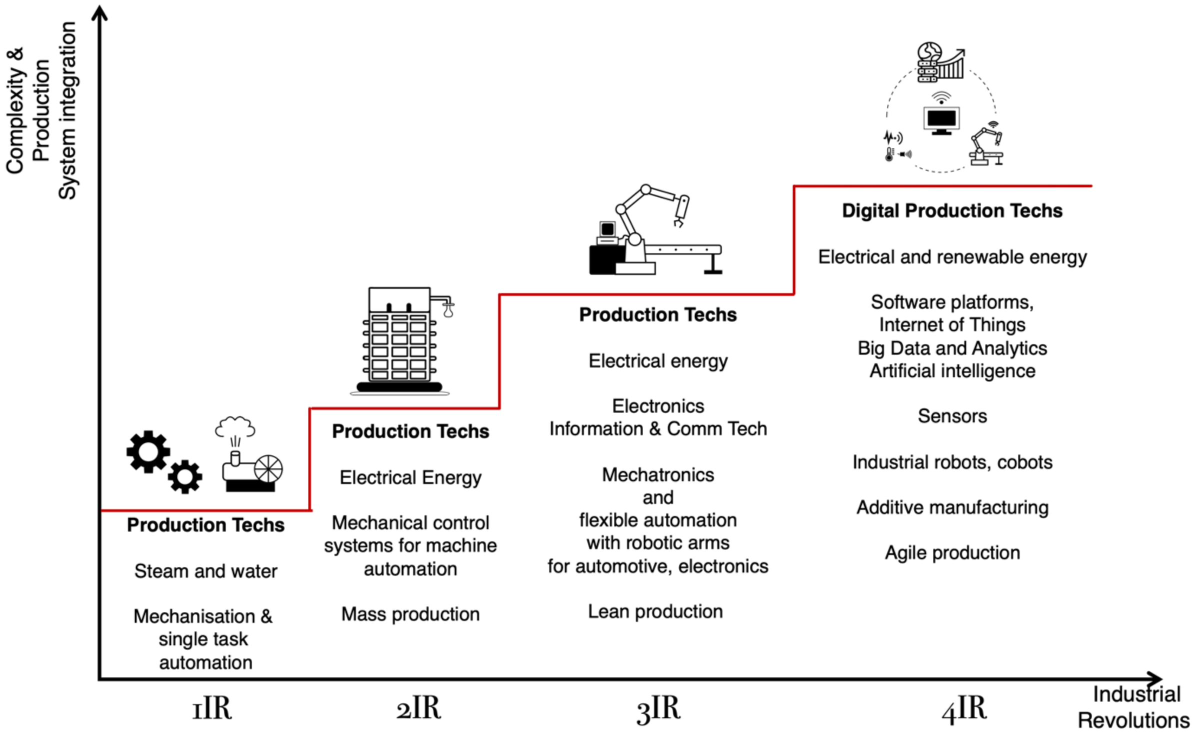
Production technologies encompass a wide range of machine tools and tooling and complementary equipment that operate in a coordinated and synchronized manner to execute a set of tasks to produce goods at the required volumes and quality. These machine tools, tooling and equipment range from simple hand-held tools, lathe machines, grinders, milling and injection moulding machines to highly versatile and complex machines with fixed hardware and fixed, but programmable, software to handle changes in the product's tasks, volume and quality. Production technologies can be used in different ways, following different manufacturing methods, from casting, forging, alloying, welding, soldering, brazing and moulding, up to the most recent additive processes and laser technologies.

Digital production technologies are the latest development of traditional industrial production technologies. They result from incremental changes in the *hardware* of these machines as well as their *software*—hence, their functionalities and data use in a cyber-physical space—and *connectivity* – hence, their integration with other production technologies (and products). Improvements in the hardware, software and connectivity of production technologies have enhanced the possibilities for *production system integration* – its virtual design, digital control and reconfiguration.

While often presented as disruptive technological changes, many of today's 4IR production technologies have evolved and emerged from the same engineering and organizational principles of previous revolutions. Figure 2 illustrates the evolution in production technologies since the 1IR, also in relation to the source of energy for production and the dominant co-evolving organizational model of production – from mass production to lean and agile manufacturing. This historical perspective suggests that in fact, we are facing an 'evolutionary transition' today rather than a 'revolutionary disruption'. Figure 2 shows, for example, how the idea of automating processes goes back to the 1IR, while the adoption of robots goes back to at least the 1960s. It also reveals how improvements in operational management and more recent system engineering have always relied on data collection, management and analysis.

Given that the idea of a 4IR has often been associated with robots and data, let us take a look at the historical evolution of these two technologies in more detail.

Figure 2: Revolutions and evolution in production technologies



Source: Authors

What robots? Industrial production has always been about automation

Despite the prevailing idea that robots are a new technology, automation dates back to the 18th century, and the first robotic arms deployed in industrial production to the 1960s. In 1785, Oliver Evans developed the first completely automated industrial process in the form of an automatic flour mill. Since then, automation technologies have evolved and found applications in almost all industries. In the early 1950s, machine tools were automated with the help of numerical control (NC) languages like APT, developed by MIT and Parsons Machine Tool Company. The term ‘automation’ was coined by D.S. Header from Ford Motor Co. when the first automation department was built. In the 1960s, the development of NC into computerized numerical control (CNC) allowed production technologies to increasingly rely on electronics for automation and robotization. The first implementation of a robot in industry occurred in 1960: the robot was manufactured by Unimate and implemented at Ford. In 1965, GM and IBM launched the first computer-controlled production line, which later evolved into computer integrated manufacturing (CIM) and geometric modelling and computer-aided design (CAD) systems.

Throughout the 1970s and 1980s, these new control systems allowed for programming machines to execute increasingly complex sequences of tasks with higher levels of precision. Industrial automation has allowed the replacement of decisions by and the manual operations of workers with logical programming commands and the use of mechanized equipment. For example, in 1974, the first minicomputer-controlled robot was commercialized by Cincinnati Milacron in the U.S. Since then, however, while industrial automation has spread across all economic sectors and countries with major impacts on productivity, the diffusion of robots has been relatively slow and has remained concentrated in developed countries (with the exception of Japan and the Republic of Korea first, and more recently in China). The reason behind the slow diffusion of robots is that they are powerful but demanding technologies. To deliver productivity gains, automated machinery and robots require significant capital investments and reliable power generation infrastructure. Robotized production, in particular, is only economical and cost-effective under very specific conditions, which are often not present in developing countries. Also, given the dramatic shortage of affordable electricity across developing countries, many companies have to rely on manual and semi-automated technologies, alongside second hand automated machineries from the 1980s.

What digital? Industrial production has always been about data

The availability of more and better quality data lies at the core of today's digital production technologies. Data are central in product and process design, process control, coding and the tracking of products within a firm and along its supply chain. Physical robots, for example, can only perform more flexible and intelligent tasks to the extent that the available software can extract the data collected, analyse them and give orders to robots and other machines connected through integrated systems.

Productivity improvements have been achieved through the availability of better and more reliable data since the 2IR. From Taylorism in the 20th century and Japanese lean production to the present 4IR, operation management and system engineering have always been based on data collection and use. Indeed, especially during the 3IR, the diffusion of measurements, standardization and interface standards, and the increasingly more sophisticated use of data have opened the door to a series of key production improvements, such as reliance on interchangeable parts, the development of infra-technologies, e.g. metrology systems, testing, scientific and engineering data.

Data technologies are being developed from the bedrock of information and communication technologies (ICTs) and data infrastructure within companies and across the globe in the form of the internet (OECD, 2017; Sturgeon, 2017; Dosi and Virgillito, 2019). The fragmentation of production that began taking place from the 1970s onwards was also facilitated by improvements in ICT (Baldwin, 2016). Even one of the key technologies of the 4IR's so-called *smart factory* can in fact be traced back to the application of physical sensors during the 3IR. Initially used to better monitor machine maintenance and operations, the data collected by sensors triggered the development of new intelligent platforms to make more effective use of the huge amount of data being produced. In more advanced countries like Germany, the *sensorization* of manufacturing plants have more recently led to the emergence of an ecosystem in which firms are connected with public and private institutions with the aim of accelerating technological transfer.

The widespread diffusion of data technologies across emerging economies and some developing countries has been enabled by the falling costs of sensors and the low power and bandwidth requirements for transferring data. Indeed, the actual exploitation of data in production cannot be fully pursued without reliable infrastructure connection. For example, the lack of high-speed data access was found to be one of the main obstacles for the deployment of predictive maintenance technologies in the machinery and equipment sector in South Africa (Kaziboni et al., 2018). In developing countries that lack data infrastructure, wireless transmission offers new opportunities. Wireless data transfer is the evolution of Ethernet communication based on field buses and provides much flexibility in terms of data collection from remote places.

2.2 Digital production technologies: what are they made of and what do they offer to developing countries?

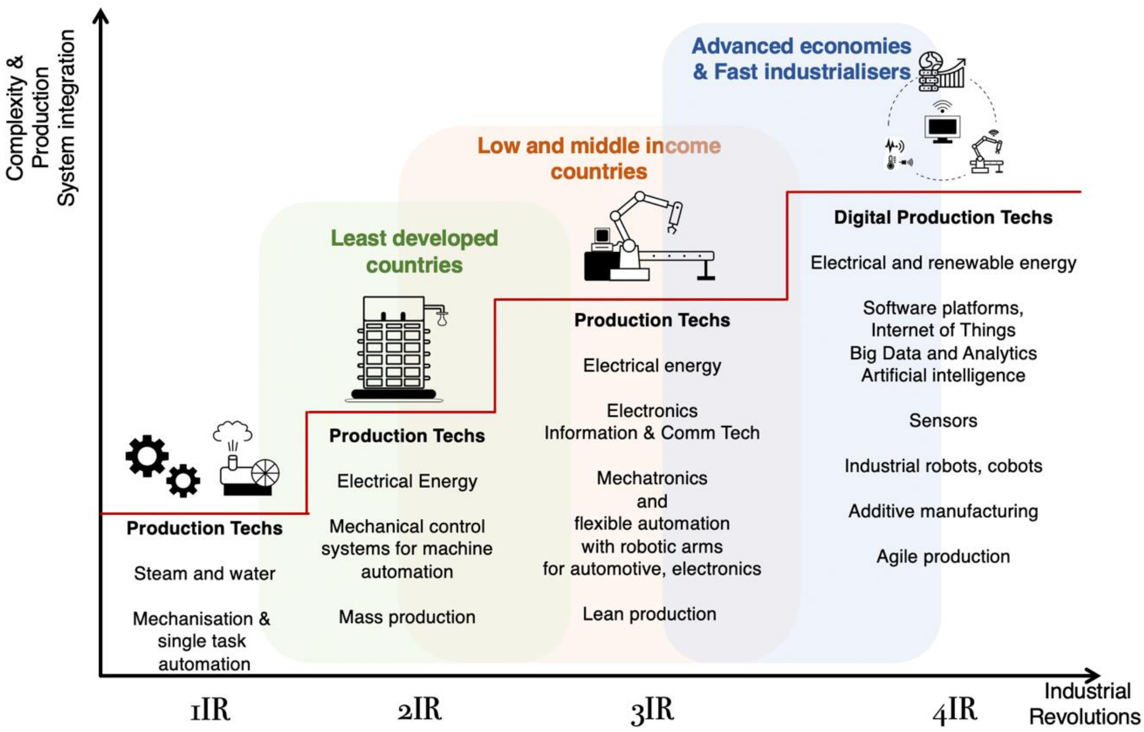
The notion of the 4IR as an 'evolutionary transition' more than a 'revolutionary disruption' is particularly relevant in two main respects, especially when we look at developing countries' engagement with the 4IR and the diffusion of 4IR technologies.

First, it shows how 3IR technologies coexist side by side with some initial 4IR technology applications in both developing and in most advanced countries. Companies in developing countries are still largely using—often ineffectively—3IR technologies. Moreover, their lack of command of 3IR technologies (automation, ICTs, etc.) also makes it difficult to fully exploit the opportunities of the 4IR. What is striking, however, is that despite sensationalistic announcements of an ongoing disruptive revolution, even among advanced economies and fast industrializers, only a few companies are incrementally engaging with 4IR technologies (Figure 3). Recent studies on the applications of 4IR technologies among SMEs in Germany and the

Republic of Korea suggest that only around 20 per cent of the companies have engaged with 4IR technologies (Yu, 2018; Sommer 2015).

Second, a focus on the evolution of today's production technologies and the realization of the co-existence of 3IR and 4IR technologies in all countries—even the more advanced ones—points to the importance of determining how 4IR technologies can be gradually integrated within existing 3IR production systems, and in what specific areas companies are retrofitting their production plants to make such integration possible. For example, capturing the opportunities offered by additive manufacturing in areas such as rapid prototyping (that is, making product design faster and more effective) or tooling (i.e. savings on expensive tools or retooling) cannot occur without an effective re-structuring of production operations, scaling up of technology and organizational processes. Against the backdrop of 4IR opportunities, technological and organizational integration (and thus retrofitting) are the key challenges that companies in developing countries face in everyday operations.

Figure 3: Revolutions still in the making



Source: Authors

The challenges companies face in integrating 4IR technologies and retrofitting their existing production systems can be better understood if we look at three main structural components of digital production technologies. Figure 4 provides a schematic model of the three main components of digital production technologies, that is, hardware, software and connectivity. We also show how in each of these technology domains there has been a development from the 3IR to the 4IR over time.

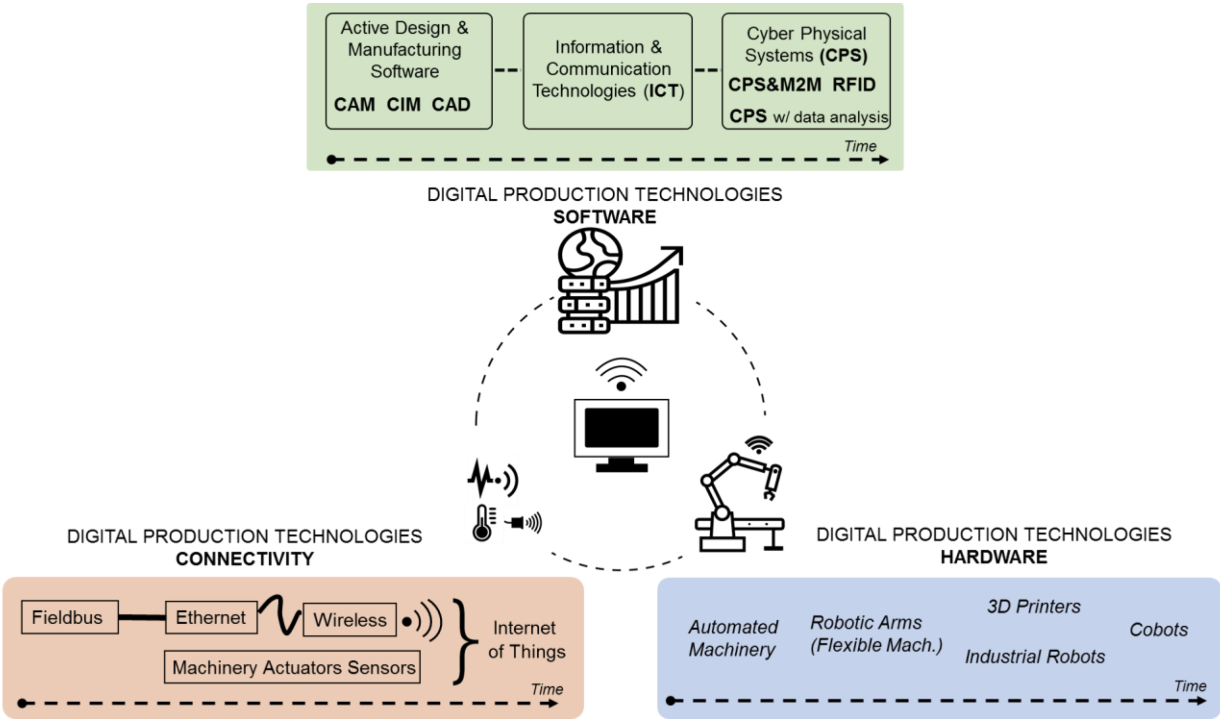
Hardware of digital production technologies

The hardware components of digital production technologies are made of the tools, tooling and complementary equipment of modern industrial robots and intelligent automated systems, as well as cobots (robots cooperating with workers in the execution of tasks) and 3D printers for additive manufacturing. This set of hardware production technologies is largely similar to their predecessors in the 3IR (despite functional improvements, even 3D printers and robotic arms of the 1990s have remained largely the same). What makes these machines different is their connectivity—that is, the fact that they are integrated within a complex production system—and their flexibility and functionalities in executing productive tasks.

Connectivity of digital production technologies

Machines have become more connected to other machines over the years (as well as workers and products) through their sensorization. The ‘sensorization’ of the hardware of production technologies is made possible by equipping machines and tools with actuators and sensors. Once machines and tools are able to ‘sense’ the production process and products—their components, material and functional properties—they are also able to collect data and transmit them through Ethernet and wireless connectivity systems. This type of connectivity can potentially open the way to a paradigm shift from centralized to decentralized production. Decentralized production, based on the creation of modules and the correlated division of tasks, is boosted by intelligent, fast and real time communication between both man-machine and machine-machine. The product is not simply processed by the machine, it is now able to communicate with the machine, instructing it exactly what to do. This is what is also commonly referred to as the Internet of Things (IoTs).

Figure 4: Digital production technologies



Source: Authors

Software of production technologies

Production technologies become fully digital once their connectivity is enhanced by software allowing for big data analytics, that is, analytical tools capable of processing vast quantities of data in near real time. Since the first such software like CAM, CIM and CAD was introduced (see section above), and the improvements initiated by ICTs during the 3IR, the software of the 4IR has opened the door to the cyber physical system (CPS). These are smart networked systems with embedded sensors, processors and actuators, designed to sense and interact with the physical world (including human users), and support real-time, guaranteed performances in applications.

Digital production technologies are the result of the integration of hardware, software and connectivity into an integrated production system. This integration is both technological and organizational and often requires retrofitting of existing production plants (see Section 3). Fully integrated digital production technologies can have a major impact along several stages of the value chain and for several functional areas of production.

The National Institute of Standards and Technology's research focusses on the potential benefits of the adoption of digital production technologies across firms operating in advanced industrial economies, in particular in the U.S., and for high-value capital intensive industries and is a useful methodology for analysing drivers of 4IR technology adoption and their impact. Four main impact groups—revenue improvement, cost reduction, fixed capital and working capital— are identified, driven by two main sets of rationales for 4IR technology adoption – profit and higher capital utilization (King, 2015).

The logic behind this approach is to establish a set of causational links between two broader 4IR technology drivers, i.e. reasons why firms would engage with digital production technologies, and four broader impact areas in which firms would be able to increase their competitiveness because of digital production technologies. For each of these areas, examples of the impact mechanisms are also identified.

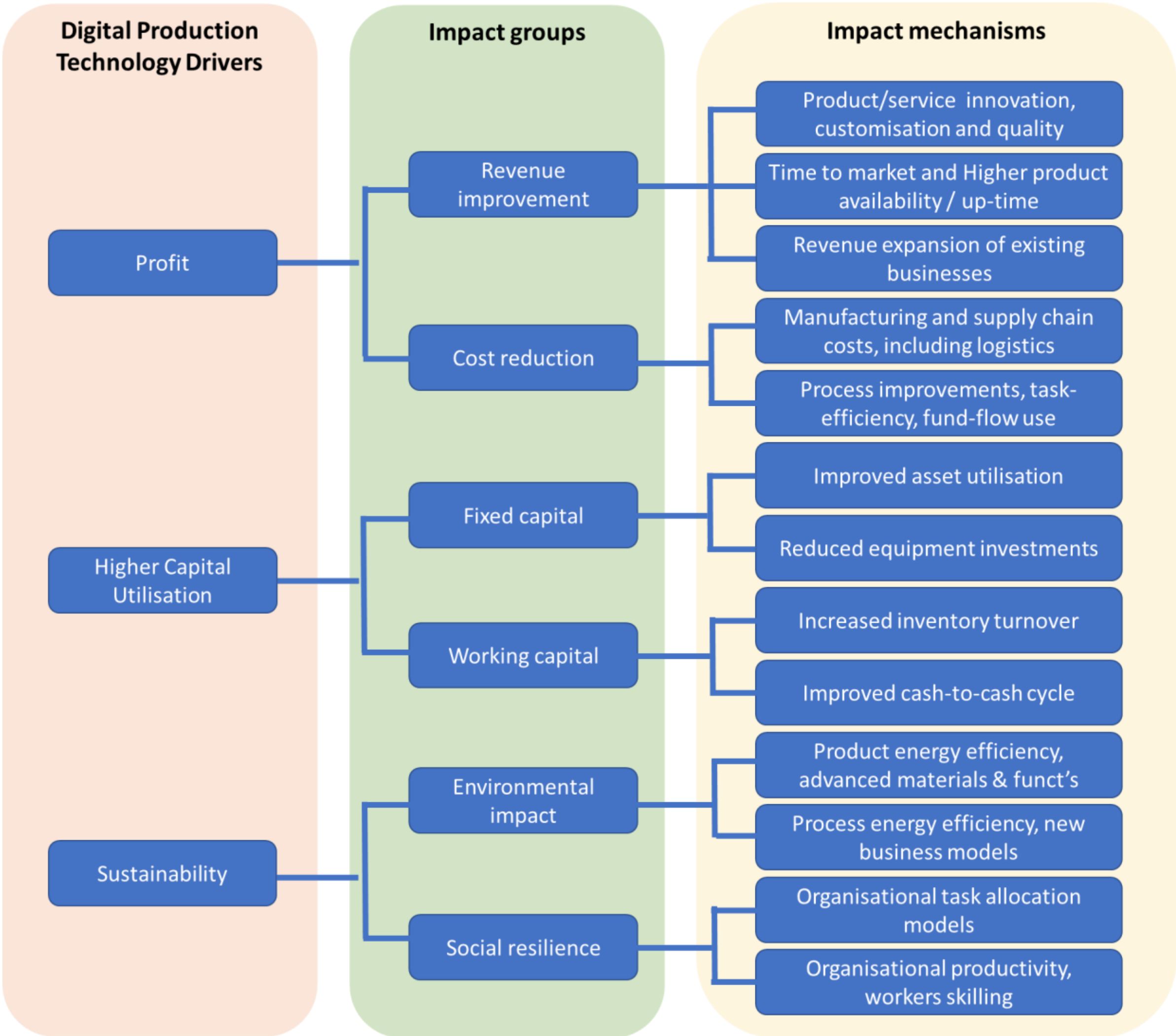
Drawing on this approach, we propose an augmented version of the NIST methodology in Table 2, which takes a number of other critical drivers of 4IR technologies into account, especially for companies operating in developing countries. We include a sustainability driver alongside the profit and higher capital utilization drivers presented by NIST, and cluster the impact of digital production technologies in six main impact groups. We provide examples of impact mechanisms for each of them. In the following, we look at each of these 4IR technology drivers, and the underlying impact groups and mechanisms.

Profit is a major driver for a company's choice of technology, as sustained profits are critical for investing in the firm's growth and competitiveness. This is particularly critical for companies in developing countries seeking to penetrate the international market both directly and indirectly through integration into GVCs. Digital production technologies enable companies to respond to their profit driver in two main ways.

First, digital production technologies can enhance product/service characteristics and functionalities which would result in higher revenue improvements—including product innovation, customization and time to market—and in a more competitive product/service package. In this specific case, digital production technologies impact revenue improvements by enhancing firms' competitiveness, that is, the firm's capacity to outperform its competitors with better products and services.

Second, revenue improvements can also result from cost reductions resulting from the use of digital production technologies for production and improvements in logistics processes, within the firm and along the supply chain. For example, the use of additive manufacturing can speed up critical stages in the scaling up of the product/technology, while reducing the costs of tooling and re-tooling for new product and process development. The introduction of IoT can also play a role in connecting different control processes, from components "just-in-time" inventory to product "predictive" maintenance.

Table 2: What digital production technologies have to offer



Source: Authors, based on the methodology proposed by King, 2015 (NIST)

Another major driver in the adoption of digital production technologies is the extent to which they impact efficiency in the use of capital investments, both with respect to fixed and working capital. This is a particularly important issue for companies operating in developing countries where capital constraints can be a major obstacle in the process of technological upgrading.

With respect to fixed capital investments such as investments in machinery, tooling, intelligent automated systems, the sensorization and robotization of processes, the capital expenditure decision, i.e. a company's capex equation, will be determined by two variables. First, the extent to which digital production technologies allow for improvements in the scale-efficient utilization of these fixed assets, thereby reducing idle times and under capacity utilization. Second, the extent to which digital production technologies reduce the need for certain types of fixed investments which cannot be fully recovered, especially when companies do not have an established or dominant position in the market. For example, more flexible robots or 3D printers can reduce investments in multiple automated production lines and the need for investment in tooling (and re-tolling).

With respect to working capital decisions and management, digital production technologies can have a major impact on increasing inventory turnover and in improving cash to cash cycles. For example, in a fully digitalized production line, sensors provide live information on efficiency in the use of production technologies, the inventory and MRO specific needs. These data can help better manage the life cycles of existing production lines and technologies, thus improving working capital management.

Sustained profits and efficiency in capital utilization are important company drivers. There are, however, new important "sustainability drivers" that companies are integrating into their strategic decision matrix. Digital production technologies can play a role in making some production processes more environmentally and socially sustainable, ultimately impacting on the two most traditional profit and capital utilization drivers. While the impact of these sustainability drivers is cross-cutting, that is, they may also have an indirect impact on revenue improvement, cost reduction and capital utilization, they also contribute to achieving a broader driver in itself. This is the extent to which a company is capable of becoming a major player in the transformation of the economy into a more inclusive and sustainable one.

Under the sustainability driver, we can identify two main impact groups. The first is related to the environmental sustainability of industrial production, and the second to the social sustainability of industrialization as a process of structural transformation of society as a whole.

As regards the environmental sustainability impact group, digital production technologies can play a role in improving both the product and process sustainability dimensions. The introduction of new business models that improve product functionalities by attaching customized services to it while reducing a number of environmental costs is one example in this respect. At the interface between product/service and process sustainability improvements, we also find several innovations in the area of energy sources and advanced materials. These innovations influence the extent to which companies use a sustainable energy technology mix and advanced materials fit for the purpose – for example, lighter materials for mobility solutions, such as improved automotive efficiency and a lower environmental impact. These improvements are of course not simply a sustainability matter, as they may also impact revenue generation and cost reduction.

As regards the social sustainability impact group, digital production technologies can play a role in improving working conditions in industrial production by introducing new work flow and task allocation models as well as by increasing the workforce's skills threshold. For example, automation solutions in the automotive sector have provided opportunities for the re-organization of production tasks, releasing workers from the most physically demanding tasks. As the introduction of lean manufacturing has revolutionized the workforce, process and quality control and other organizational models, if properly used digital production technologies can give companies an opportunity to improve workers' involvement and productivity.

While these represent potential benefits for all firms whenever they operate and whatever digital production technologies they use, the scope of these potential benefits in reality is both sector- and country-specific. Capturing 4IR opportunities to improve efficiency, effectiveness, speed, agility, full capacity utilization, etc. call for a specific set of capabilities and incentives to develop them. These capabilities and incentives are not equally distributed across sectors and countries. We will focus on these capabilities in Section 3, after having analysed the specific opportunities and challenges of three main sets of digital production technologies and their diffusion across countries and sectors.

2.3 Industrial robots: flexibility and sectoral applications

Technology opportunity

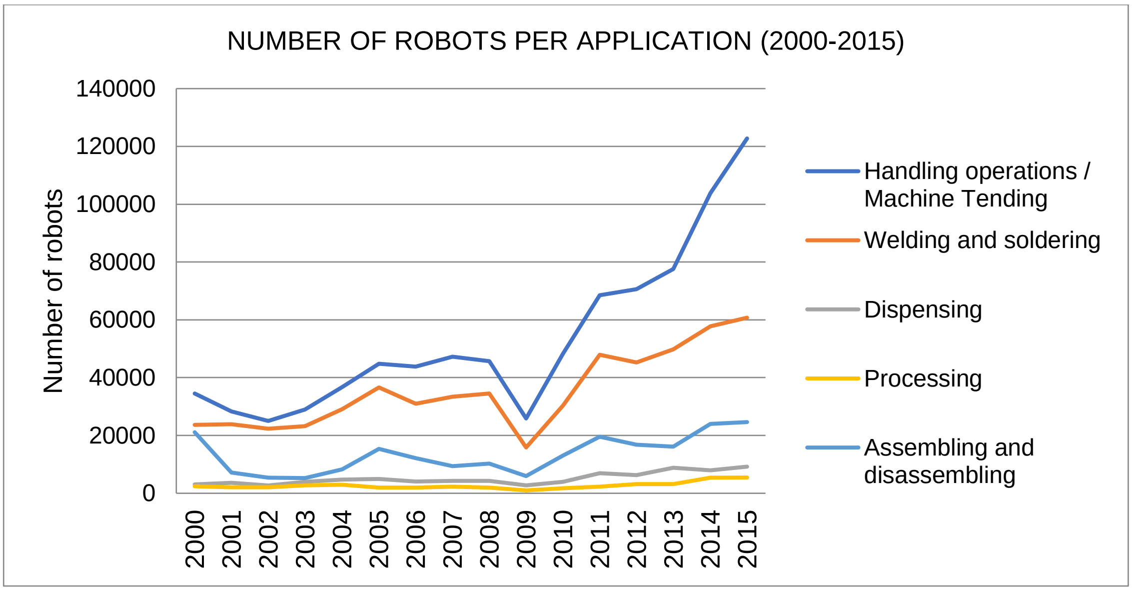
Industrial robots today are defined according to ISO 8373:2012 as "*an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*". This type of robot is an evolution of the robotic arm system, with more flexibility in terms of computer reconfiguration but older constraints in terms of task variety.

As already discussed, the use of industrial robots can be traced back to 1960, the year of the first robot deployment by Ford in the automotive sector (Mehrabi et al., 2000). What makes the latest version of industrial robots different from past ones is a mix of increased intelligence (problem-solving ability), flexibility and ability to perform complex tasks. The increasing flexibility of automated systems and industrial robots has opened the way to *reconfigurable automated systems* that allow for both flexibility of the product and quick adaptation of processes in a smart self-adjusting way.

Machine connectivity has also made the use of cooperating robots that carry out a common task possible. For example, we can find that the assembly and spot-welding operations in an automotive plant are performed by two robots that, respectively, pick up and hold the parts to be welded, while a third robot performs the spot welding (Michalos G. et al., 2010). Coordination has been developing both in terms of machine to machine and machine to human. New intelligent robots, so-called *cobots*, are being adopted to work alongside human workers on assembly lines, assisting them in a variety of manufacturing tasks (Calitz et al., 2017).

Despite these important innovations, the great majority of industrial robots deployed in the last decade have been used to perform simpler tasks. As Figure 5 shows, the two key tasks performed by industrial robots are machine handling & tending (43 per cent) and welding & soldering (27 per cent). These applications are strongly related to the automation of physically demanding tasks—e.g. handling heavy and voluminous materials and components—and precision critical tasks, e.g. welding or the application of a specific quantity of a material or chemical on another component.

Figure 5: Diffusion of industrial robots by production task



Source: Authors based on International Federation Robotics (IFR) dataset

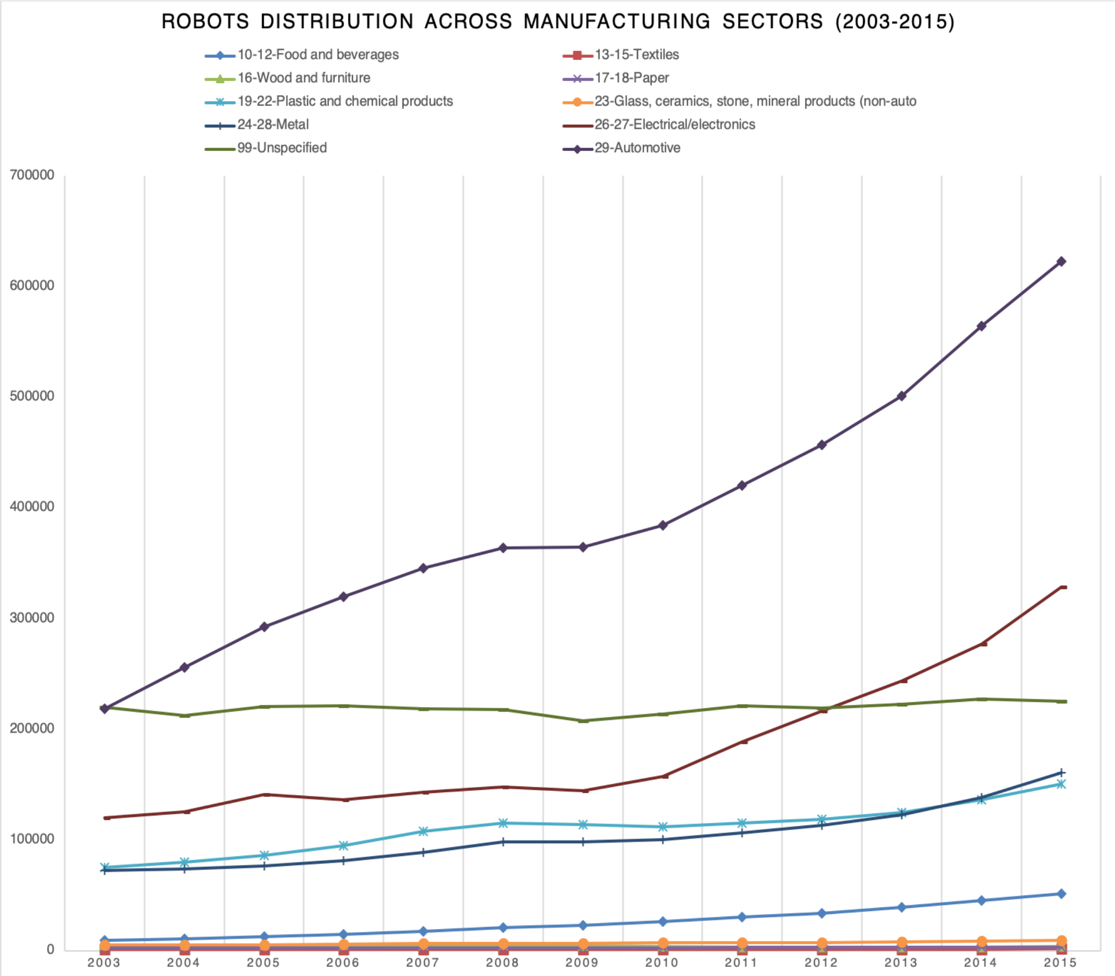
Technology diffusion

According to the International Federation of Robotics (IFR) dataset, there is a high sectoral concentration when we look at industrial robots deployment. A striking 99 per cent of industrial robots are used in the manufacturing sector, with the remaining 1per cent being used in the following sectors: agriculture, forestry and fishery, mining and quarrying, electricity, gas, water supply, education/research/development, construction and other non-manufacturing sectors. Within manufacturing, the greatest number of industrial robots is deployed in the automotive industry.

Automotive has benefitted from a continuous technology push, stemming from investments by major car manufacturers in production technologies. It has always been the bedrock of advances in manufacturing automation due to its high volume production, standardization and modularization that allow the production and assembly of different parts. Indeed, it is within downstream assembly operations, led by large OEMs, that the majority of robots can be found.

The electrical and electronics industry—the other leading sector in terms of adoption of robots—has experienced a huge increase in robot deployment mainly due to the demand pull of new and more diverse products and components. Moreover, the production of small parts at high speed, which characterizes this sector, has put workers under enormous pressure and makes them unable to compete with machines. Manufacturing robots are capable of handling screens and coat circuit boards, and of assembling connectors without error (IFR, 2015).

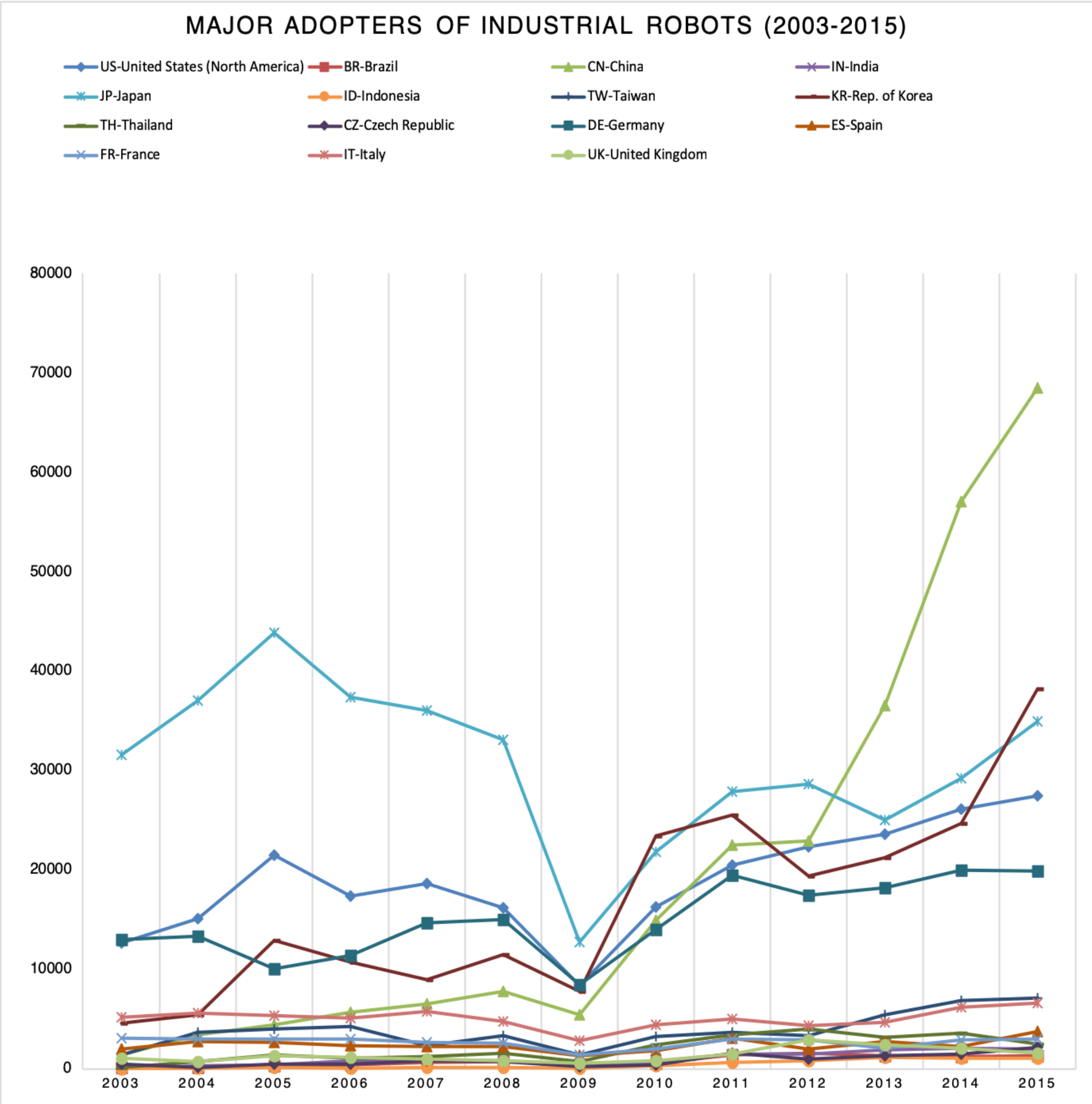
Figure 6: Distribution of robots across manufacturing sectors (2003–2015)



Source: Authors based on International Federation Robotics (IFR) dataset

Figure 7 presents the geographical distribution of robots across countries. The majority of robots can be found in developed countries and China, with a rising number also being used in emerging economies such as Thailand, Mexico and Brazil. The concentration of robots in major industrialized countries and a few fast-emerging economies reflects the structural characteristics and, more specifically, the sectoral composition of these economies. Again, the striking geographical concentration of industrial robots in a dozen countries suggests that the majority of countries—especially developing countries—are still very far from widespread diffusion of this production technology, and will remain so unless they start developing key manufacturing industries where robots can be implemented.

Figure 7: Geographical concentration of robots in the global economy, 2003–2015



Source: Authors based on IFR dataset

Technology challenges

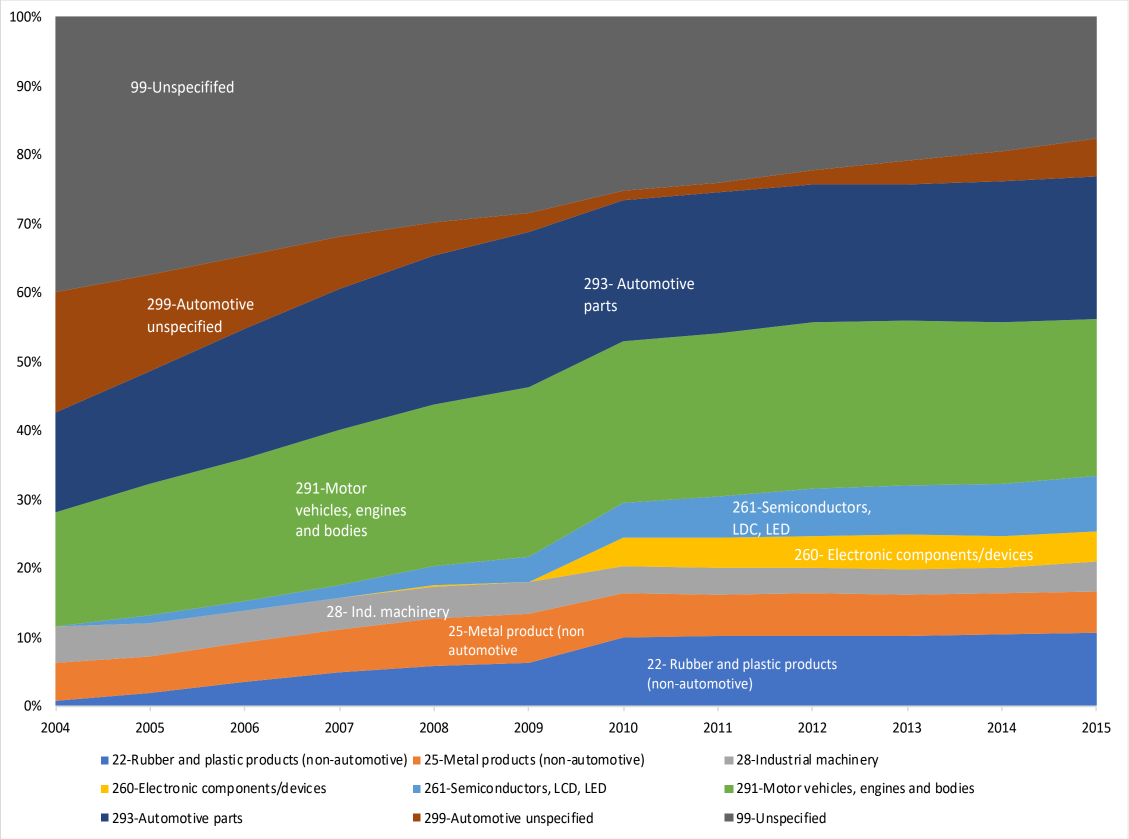
The sectoral and geographical concentration of robots in today's global economy reflects two major challenges for developing countries. First, some industrial sectors, because of their intrinsic characteristics, tend to attract more sophisticated digital production technologies like industrial robots. The presence of either an automotive or electric/electronics industry is a strong driver in the adoption of industrial robots. These two sectors combined encompassed over 60 per cent of total industrial robots in 2017 (IFR, 2018). The automotive sector deploys the greatest number of industrial robots, namely more than 1/3 of the total (36.81 per cent). The automotive sector has benefitted from a continuous technology push and has always been a bedrock of advances in manufacturing automation due to its high volume production, standardization and modularization, which allow for the production and assembly of different parts.

The electric and electronics industry has experienced a huge increase in robot deployment; interestingly, this trend has in particular been related to the production of semiconductors, as shown in Figure 8. This is primarily due to the demand pull of new and more diverse products and components and to the production of small parts at high speed. This has put workers under tremendous pressure and makes them unable to compete with machines. Manufacturing robots are capable of handling screens and coat circuit boards and of assembling connectors without error (IFR, 2015). The combination of these factors is responsible for the large diffusion of robots in this sector.

If, together with the two aforementioned sectors, we also consider plastic and chemical products as well as metal products, which have important linkages with automotive and electronics, the share of robots deployed increases to nearly 80 per cent of total robot use. The automation trend is also likely to continue because of the drivers that ultimately lead to automation. An increase in productivity and the importance to reduce errors, thus achieving higher quality, are the two most relevant drivers of robot adoption. Because of the precision of the tasks involved and the repetitiveness that characterizes high-tech manufacturing industries like electronics and automotive, they are expected to be major adopters of robots in coming years.

The food and beverages industry is growing at a more moderate pace (see Figure 6). In these industries, robots are primarily deployed in key stages of processing and packaging. Automated packaging machineries have increasingly evolved with the introduction of automated intelligent systems and operational robotic arms (see, for example, the industry study on a world leading packaging machinery company, IMA; Andreoni et al., 2017). The importance of building up spaces and capabilities within these sectors is a major challenge for developing countries.

Figure 8: Distribution of robots in manufacturing subsectors (operational stock), 2004–2015



Source: Authors based on IFR

Second, and related to the former point, countries that have invested in high-tech manufacturing sectors with selective industrial policies, as in the case of China and Thailand, are in a better position *vis-à-vis* countries that have remained anchored in low-tech manufacturing sectors. The high cost of new machinery and the complexity of integrating new machines in existing production systems calls for structured policy incentives. In this respect, the case of Thailand is worth mentioning because of its policy package and its impact on the absorption of automation technologies. The policy package promoted by Thailand over the last decade includes: digital infrastructure building within the Eastern Economic Corridor (USD 45 billion infrastructure investment), USD 6 billion Robotics Development Plan and a consistent commitment of universities and training centres to train high-skilled employees. The effectiveness of this industrial ecosystems promotion both from the demand and supply side has already had a positive effect: in the last two years, robotic giants like the Swiss ABB, Japan’s Nachi and the Taiwanese (Province of China) Cal-comp Electronics have set up plants in Thailand. Moreover, if we exclude China, Thailand is the developing country with the highest number of industrial robots in operation today.

2.4 Additive manufacturing: customization and rapid prototyping

Technology opportunity

Additive manufacturing equipment such as 3D printing (3DP) refers to a new paradigm of industrial production which consists of a layer by layer additive construction of three-dimensional objects. While this technology was already developed in the 1990s, its rapid development and diffusion was only realized in the mid-2000s. With the expiration of old patents, open source movements took off and promoted the diffusion of 3DP technology (OECD, 2017). The steady decrease in the price of the technology, alongside the development of 3D printers capable of operating with different materials and the integration of 3DP into prototyping machines also played an important role in the diffusion of this digital production technology (Laplume et al., 2017).

3D printing technologies open a number of opportunities in product design, especially prototyping, and in the production of highly customized components and products. The possibility of printing components in the early stages of development of new components and products is of major significance for the scaling up of manufacturing. Additive manufacturing technologies release companies from the need to develop expensive tooling for product and component design and engineering, while providing the possibility to physically test components' and products' functional properties. The cost of developing new components and products has thus been drastically reduced and improved. Given these properties and increasing affordability, 3DP technologies have registered a certain level of diffusion across developing countries, mainly in rapid prototyping processes. For example, during a field study conducted among lead firms in machinery and equipment industry in South Africa, Kaziboni et al. (2018) found that 3DP reduced the time spent on manufacturing and testing a prototype from between six to eight weeks to two to three days.

Customization of specific components in critical product system industries like aerospace and medical devices has also improved dramatically as a result of 3DP deployment, especially in advanced countries. The possibility of an integrated process of virtual customized design and production of components—for example, in prosthesis implantation surgery—has shifted the frontier of customization. If companies used to customize a product around a limited number of characteristics and functionalities, 3DP offers companies the opportunity to produce unique personalized tailored goods.

Technology diffusion

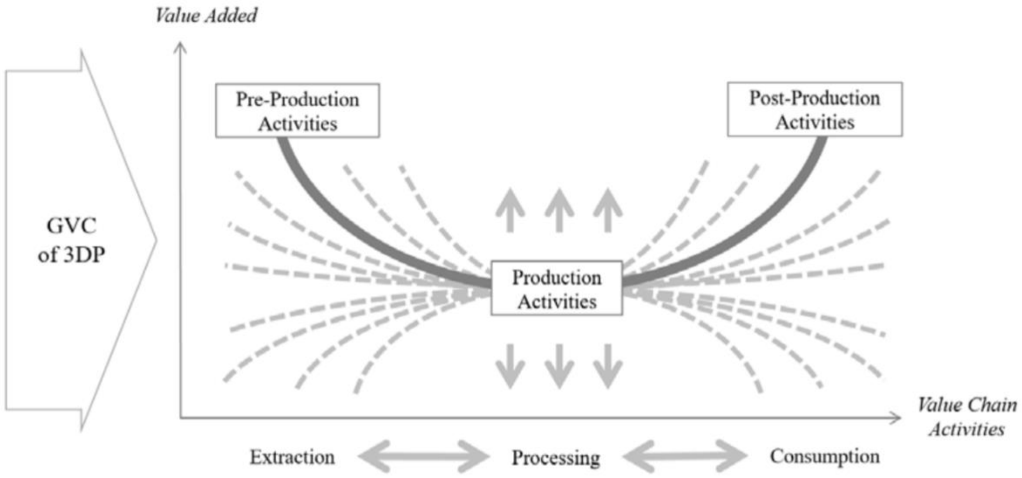
Despite widespread agreement that 3DPs will not replace high volume operations given the enormous economies of scale of more traditional production technologies (Paiste, 2014), 3DPs are being used in several other applications in some high-tech sectors. In particular, the automotive and aerospace industries use 3DPs not just for rapid prototyping, thus shortening the model-design phase, but also to produce high throughput. For instance, Airbus had a plan of 30 tonnes/month of 3DP parts for 2018 (Sturgeon, 2017).

Despite ongoing developments in advanced materials, most 3DPs are limited by the use of plastics and resins in their additive manufacturing processes. Thus, industries characterized by low volumes and the production of objects with few parts are found to be more suited for widespread deployment of 3DPs. In fact, sporting goods and toys, medical instruments, the manufacture and repair of machinery and equipment are industries where 3DP facilities are already being widely used (Laplume et al., 2017).

A number of recent studies has also suggested that 3DP technologies will lead to shorter and more dispersed value chains with a decrease in production and trade of intermediate parts (Laplume et al., 2016). As Figure 9 illustrates, the shortening of the value chain would occur due to the reduced need for assembly, packaging and transport, with a "rebundling" process effect on the value chain (Rehnberg and Ponte, 2018). Moreover, according to these studies, 3DP might have an increasingly stronger impact in pre-production activities due to rapid prototyping and post-production activities, given the need for high customer responsiveness and a shift towards just-in-time production. This trend is already visible in logistics giants such as UPS, DHL and Amazon. For example, UPS has already transformed several existing hub warehouses at airports into mini factories to "produce and deliver customised parts to customers as needed instead of shelving to vast inventories" (D'Aveni, 2015[2]).

[2] https://hbr.org/2015/05/the-3-d-printing-revolution

Figure 9: Potential GVC restructuring



Source: Rehnberg and Ponte, 2018

Technology challenges

Against the backdrop of several opportunities, especially for developing countries, there are also a number of challenges for the widespread adoption of 3DP. First of all, the diffusion of 3DP is constrained by the shortage of printing materials. Resins, plastics and sands are the most frequently used materials. The technology development and diffusion of 3DP will be shaped by the availability of new materials and their quality and functionalities. For instance, due to the dearth of materials and high customization of the sector, the electronics industry could see a revolution triggered by the possibility of printing conductive materials, to the extent that these materials become available and affordable. Second, the power shift towards pre- and post-production activities such as R&D, design and logistic post-sales could increase the concentration of decision-making and value added in these segments, leading to a reinforcement of 3DP "technological inseparability" (Laplume et al., 2017). Third, similar to the case of industrial robots, OEMs and global corporations control the industrial use of these technologies. For instance, a series of inter-chain upgrading opportunities are being offered by GE aviation which maintains close relationships with suppliers of 3DP through an annual hackathon where suppliers are invited to re-engineer existing GE products with 3DP. Proximity and investment opportunities led by large firms will continue to attract 3DP inventors to a few innovating poles.

2.5 Digital production systems integration: connectivity and software ` platforms

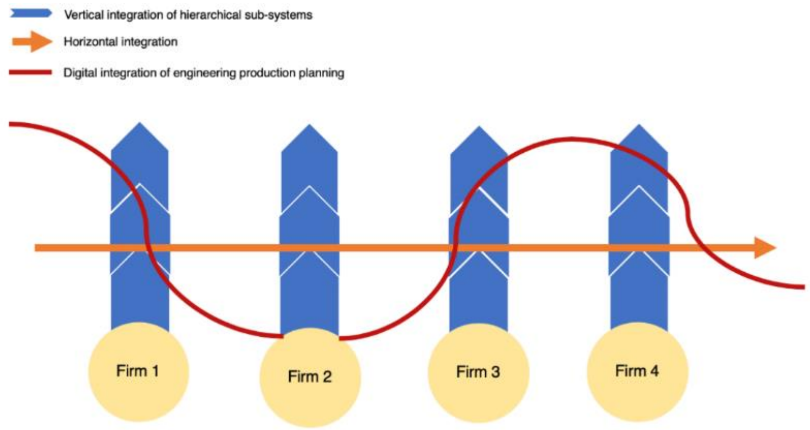
Technology opportunity

Industrial software has transformed into highly connected data platforms for managing and analysing an increasingly high volume and better quality data at a higher speed in almost real time – so called *big data* (OECD, 2017). As shown in Figure 4, digital production system integration is based on the IoT which, by definition, connects different machines with one another that interact through a common digital platform. Recent developments both in hardware and software systems have increased the potential of connectivity. Specifically, improvements in more sophisticated actuators and sensors and the development from an industrial ethernet to a wireless network has created the basis for high-speed, precise and continuous production of real-time data. The IoT is embedded in these enabling technologies and augmented by its integration with cyber physical systems (CPS). CPSs are the latest frontier of information flow software systems, and the latest evolution of software used for automating tasks in computer aided design and computer aided manufacturing.

These software technologies and their connectivity are opening a new array of opportunities in manufacturing production and digital integration. As illustrated in Figure 10, integration can take place at three levels: (i) *vertical integration* of flexible and reconfigurable manufacturing systems and their production of data (smart factory), ii) *horizontal integration* along the supply chain, and (iii) *product lifecycle integration* of digital end-to-end engineering activities (IfM, 2017). While each of these integration processes are independent, CPS software enables firms to capitalize from their full integration across the three levels. For example, it enables the integration of data collection, analytics and management on the maintenance of the equipment, together with stock level monitoring along the supply chain and with machine-to-product-to-machine communication. CPSs thus foster technologies that bridge the virtual and the physical world to create new production ecosystems where intelligent objects communicate, interact and support an automated self-adjusting process[3].

[3] For a review of German policies on 4IR, see Horst and Santiago (2018), "What can policy makers learn from Germany's Industrie 4.0 development strategy?" UNIDO Working Paper 22/2018.

Figure 10: Map of different integration levels

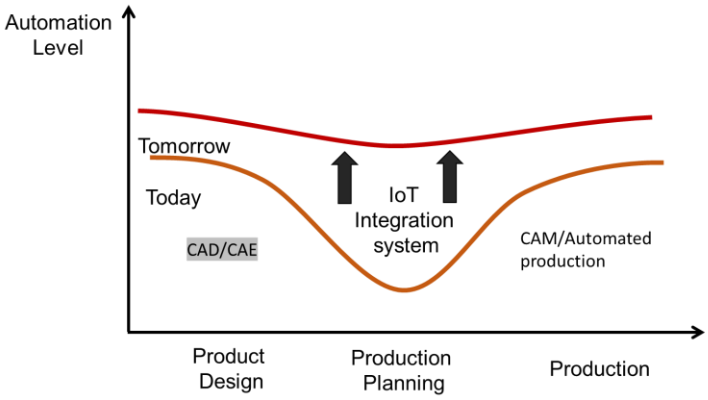


Source: Authors

Technology diffusion

CPSs have high potential in terms of productivity increases, better decision-making and more precise product cycle analyses and customer responsiveness. Nonetheless, the complexity of integrated IoT and CPSs makes their adoption and diffusion at present difficult, even within and between companies in more mature economies. This does not mean that other more traditional software such as CAD (computer aided design), CAE (computer aided engineering) and CAM cannot be deployed to support other stages of production. Indeed, as shown in Figure 11, CAD and CAE software are generally widely diffused in product design in companies in both developed and developing countries, and have allowed for high levels of automation of design processes and data communication. A design is created based on a drawing, digital design or scan and is then communicated to the machine. Similarly, automation in the production process (CAM) is also a well-established process, especially in advanced industries such as automotive, aerospace and electronics.

Figure 11: Production processes' integration level map



Source: Authors

The increasing deployment and diffusion of integrated IoT and CPSs will enhance companies in the critical production planning phase and establish a direct connection with the product design and production stages. By establishing this link, the integration of the digital production system allows for an acceleration and improvement of the design cycle, reducing time to market and linking design to smarter products. For example, in the automotive industry, the automation of the production planning phase will allow linking the product, process and resource data by defining which component should be manufactured based on which production steps (Schmidgall et al., 2005). Automation in the production planning phase is still limited, but improvements in IoT are increasing the opportunities to invest in this segment. Once this step is achieved, suppliers located in different parts of the world will be able to track the inventory levels of OEMs and when materials or components run low, the supplier will receive an automatic order to prepare the shipment. This synchronized just-in-time delivery made possible by IoT depends on a high level of internet connection, software and hardware integration.

Technology challenges

The complexity of these systems as well as the lack of reliable connectivity infrastructure constitute a major obstacle for their deployment. The adoption of fully integrated production systems, like the one described above, faces three main challenges.

First, CPSs entail the integration of a high number of operations. While the adoption of an industrial robot or the use of a 3DP in production involve a relatively limited number of operations and manufacturing units, CPSs and IoT technologies involve the full system of operations and thus require a high level of complexity and retrofitting of legacy systems.

Second, CPSs rely on the deployment of sophisticated tailor-made software that is in the hands of a few companies based in developed countries. The 4IR presents elements of networked openness and elements of power concentration. The theoretically endless elements of these systems and their modularity mean it is impossible for a single company/country to master all of the elements of the system and data. We are witnessing the development of "nested modules and platforms based on both *de jure* and *de facto standards*, stretching from discrete functional elements (technology platforms) to higher- mechanical systems, level tools, hardware systems, and software environments (core platforms) upon which developers" (Sturgeon, 2017:8). However, we are also increasingly realizing that this openness is not for everyone. Digital technologies will intensify value chain modularity and disintegration, but these technologies are at the same time integrated through protocols, software and machines that are mainly, when not exclusively, invented and produced in developed economies[4]. Interconnectivity also means that hardware producers, for instance, require customers to purchase proprietary design software by the hardware supplier (Berman, 2012).

Third, and related to the second factor, CPSs emerge from existing ecosystems. The 4IR, in the few advanced economies where it has already taken a foothold, is generating manufacturing ecosystems based on the integration of a set of technologies. Despite the physical disintegration of production, the emergence of ecosystems is likely to increase the concentration of power in a few hands of technology providers. This is particularly true for firms in developing countries, which, apart from a few isolated cases, tend to be followers of this technological wave. Moreover, within CPSs—being partially or fully integrated—there is a high generation of data. Due to a general delay in the legislations, the data produced raise concerns about data integrity and data ownership. Both of these aspects are particularly relevant for developing countries.

3. Capabilities for digital industrialization in developing countries: production, absorption, retrofitting and integration

In analysing the development and structural components of today's digital production technologies and the specific opportunities and challenges associated with robots, 3DPs and data platform technologies such as IoT (Section 2), we have documented how 4IR technologies are not emerging from a revolutionary disruption process. On the contrary, and to the extent that these technologies are diffused across sectors and countries, many of these 4IR technologies result from incremental developments of 3IR technologies.

[4] For a review of digital platform distribution, see Sturgeon, 2017.

The fact that 4IR technologies build on and co-exist with 3IR technologies in production means that companies in developing countries will have to equip themselves with a fairly broad array of capabilities from both the 3IR and 4IR, if they want to effectively capture the new opportunities the 4IR offers. To the extent that it is possible, it would not make any sense for a company in a developing country to try to develop advanced capabilities in data analytics, if it is still struggling to effectively deploy basic ICTs or its hardware production technologies have no sensors and thus no connectivity. Similarly, IoT would not be feasible without prior development of coding and standardization capabilities as well as access to reliable connectivity infrastructure. Another example is the introduction of robot cells and the effective use of robots for the execution of various tasks such as handling, welding, etc., which implies that companies have effectively arranged the production flow and supply logistics and that robots can be fed with intermediate components—say from forming presses—in time, in a fully controlled environment and without any disruption. These production conditions are very difficult to meet in companies operating in developing countries given limited access to high quality electricity supply and connectivity.

These examples suggest that a number of ***basic and intermediate capabilities*** are in fact *pre-conditions* for engaging with more advanced digital capabilities in a meaningful and effective way. These basic and intermediate capabilities are crucial for creating the micro-efficiency and reliability conditions required to effectively deploy new digital production technologies, as well as to embark on a learning journey of technology absorption and adaptation, which eventually results—where possible—in the retrofitting of the legacy production systems. These basic production capabilities and intermediate capabilities for technology absorption and retrofitting of legacy systems define what we refer to here as ***digital capability threshold***.

Companies in advanced countries are better positioned to capture 4IR opportunities, precisely because they have spent decades absorbing, improving and deploying 3IR technologies, such as automation and ICTs in manufacturing production, which are preconditions for 4IR technologies. In other words, companies in mature industrial economies have overcome the digital capability threshold more often than developing countries and can therefore focus directly on the development of the more advanced capabilities of digital production technologies. Not only are these companies better positioned to incrementally integrate 4IR technologies and rethink their organizational models. They also operate in industrial ecosystems in which companies—while equipped with different capabilities—have been integrated into supply chains for a long time. This higher level supply chain integration is critical when a company decides to engage with a new technology, its decision will have a cascade effect along the supply chain (Andreoni, 2017 and 2018). The closer companies are in terms of their basic and intermediate capabilities, the easier it is for them to respond to these technological changes. Hence, for an OEM in a developed country, it is relatively less challenging to introduce a new digital production technology as its local suppliers operate with similar software and hardware systems, are aligned in terms of their production standards and use the same connectivity infrastructure.

These conditions are usually not met in developing countries. That is, not only the majority of companies in developing countries have not yet reached the digital capability threshold, even the most advanced companies are negatively affected by the existence of a major ***digital capability gap*** between themselves and the rest. Given the dualistic structure of the industrial system in developing countries, a few major companies and international OEMs operate as production islands in a sea of often disorganized, semi-formal and small-scale company operations. This does not mean that these smaller companies have not found their own way of operating, the problem is that their approach to competitiveness differs from that of the large companies. What we refer to here as the digital capability gap is thus a major obstacle to the diffusion of 4IR technologies, especially those intrinsically based on networked systems and data. For instance, if the first and second tier suppliers have limited connectivity, the OEM will not be able to effectively synchronize their supply of components and materials for production.

The analysis of these country-specific conditions have profound policy implications. Instead of concentrating on cutting edge 4IR technologies, the promotion of digital production technologies in developing countries should begin by identifying the specific set of basic and intermediate capabilities that must be developed to attain the digital capability threshold within firms in specific industries, and reduce the digital capability gap across firms in the supply chains in specific regions.

Building on several firm-level studies conducted during the 3IR across developing countries (for a review, see Andreoni, 2011)[5] and capability theories of production (Andreoni, 2014), the ***Digital Capability Matrix*** proposed in Table 3 provides a framework to identify these basic and intermediate capabilities that companies in developing countries should develop to effectively engage with 4IR technologies. The matrix distinguishes three levels of firm capabilities—basic, intermediate and advanced capabilities—and one system level of country capabilities – enabling infrastructure capabilities. The distinction between basic, intermediate and advanced capabilities for different functional areas allows to identify the incremental process whereby companies can cumulate capabilities over time, from the basic until the most advanced ones, if they want to

[5] The empirical research conducted in Latin America in the 1970s—i.e. the so-called 'Katz Programme'—and in India include contributions by Stewart and James (1982); Katz (1987); Dahlman et al. (1987); Lall, (1987 and 1992); Bell and Pavitt (1993); Romijn (1999).

engage with increasingly more complex technologies and functions. Thus, the shift from basic to intermediate and advanced capabilities is the learning journey that companies must undergo to capture some of the advantages of digital production technologies.

In their learning journey, companies cumulate capabilities and specialize in certain functions more than others, thus developing increasingly advanced capabilities to competitively perform a certain set of functions. However, even when these advanced capabilities are developed, mastering the basic capabilities—often associated with production processes—remains critical for retaining efficiency, promoting innovative products and processes and effectively deploying new technologies.

This matrix should be read as a map of the cumulative process of learning that companies have undergone in different functional areas, and which critical capabilities, from basic to intermediate and ultimately to advanced, they need to develop (and retain) in order to remain competitive and innovative. This reading is coherent with the notion of technological change as an incremental evolutionary process, more than one punctuated by disruptions.

The proposed capability matrix also sheds some light on the fact that capabilities are function-specific and activity-specific, but more importantly, it suggests that even performing the simplest productive activities very often requires the activation and matching of interdependent clusters of capabilities. Among those capabilities that must complement firms' development efforts are many that are more closely related to the broader ecosystems within which firms operate. These capabilities of the ecosystem are often embedded in several institutions and result in a certain level of "social capability". Chang and Andreoni (2019b) propose an institutional taxonomy including six types of institutions that determine social capability: (i) institutions of production, (ii) institutions of productive capabilities development, (iii) institutions of corporate governance, (iv) institutions of industrial financing, (v) institutions of industrial change and restructuring, and (vi) institutions of macroeconomic management for industrialization. These general institutions are not included in the matrix as they can assume different forms in different contexts, and the same institutional functions can be performed by different institutional forms.

Table 3: Capability matrix for digital industrialization

FUNCTIONAL AREAS CAPABILITIES		Investment	Product design	Process engineering & production planning	Strategic control	Manufacturing production	Supply chain & linkages management	Post-production services
B A S I C	**Production capabilities**	Feasibility studies Market analysis Competitors analysis Production technologies procurement Recruitment of skilled personnel Reliable energy supply	Product design & definition (CAM/CAD) Product functionality definition Product specifications execution Product customization Product prototyping Product scaling up Product standards compliance	Process design & engineering Process scaling up Process optimization Process quality management Process standards compliance Demand forecasting Inventory & delivery management	Financial flows management Workforce flow & incentives Inventory control Production operations control	Material processing Intermediate goods assembly Machinery automation Machine operations monitoring Product quality management Testing, inspections & validation Packaging & logistics	Materials sourcing Intermediate goods sourcing Suppliers monitoring Product quality management	Distribution Marketing Waste management Maintenance management Product life-cycle management Service quality management Product services

INTERMEDIATE	**Technology absorption capabilities**	Seizing market opportunities Seizing technology opportunities Joint ventures development	New product design assimilation Product reverse engineering Re-definition of product functionalities	New process design assimilation New production technologies acquisition Software skills	Financial commitment Engineering skills acquisition and development	Automation skills CNC Information and communication technologies	Linkages development with science & technology institutions	
	Legacy system retrofitting capabilities	Software licensing management Reliable energy supply Reliable connectivity	Additive manufacturing for prototyping	Process re-modularization Process re-engineering & scaling up Software engineering skills development New process optimization	Medium-term financial commitment Re-organization of workforce flow & incentives Worker retraining Production operation and connectivity control	Automation systems development and use of robotic arms Additive manufacturing for customized production Technological collaboration with suppliers and actors downstream & upstream Sensors, actuators & embedded systems for data and process control		New product life-cycle management

A D V A N C E D	**Production system integration capabilities**	Seizing technology integration solutions Seizing organizational integration solutions Data analytics for decision-making	Product R&D Materials R&D for additive manufacturing Data analytics for product design Cyber physical systems for virtual product design	Process R&D Cyber physical systems for virtual process design Technology integration Agile production	Long-term financial commitment Organizational integration Digital skills development Software platform development Big data analytics Data analytics for inventory control	Industrial robots and cobots deployment Additive manufacturing for customized and agile production Internet of Things (ability to use horizontal & end-to-end integration systems) End-to-end engineering capabilities to engage with the industrial ecosystem Dynamic capabilities in supply chain management, with real-time production of data	Data analytics for distribution Data analytics for marketing Circular economy Internet of Things
S Y S T E M	**Enabling infrastructure capabilities**	Digital product engineering skills Digital process engineering skills Digital technology institutions infrastructure Data ownership policy and software licencing accessibility			Digital workforce skills	Reliable energy infrastructure Bandwidth connectivity infrastructure (ethernet and wireless) Software licensing affordability	Physical infrastructure Logistics infrastructure

Basic, intermediate and advanced capabilities differ according to the different functional areas of production along a standard value chain. In the matrix, we distinguish both capabilities internal to the firm—*investment, product design, process engineering and production planning, strategic control and manufacturing production*—as well as capabilities that the firm will have to develop in engaging with its suppliers (and institutions)—*supply chain and linkages management*—and its customers – *post-production services*.

Companies are highly heterogenous; they are unique bundles of capabilities and even when they have followed the same technological trajectory, they can extract different services from the same bundle of resources they are composed of. In other words, the digital matrix of capabilities points to clusters of capabilities that must be developed in different functional areas, although their deployment in a specific productive organization remains highly heterogenous.

Across developing countries and in specific sectors (as discussed above, Section 2), a number of companies are ahead in terms of their engagement with digital production technologies. Having developed the basic and intermediate capabilities required to engage with 4IR technologies, such companies are focussing on the development of more advanced specific capabilities, that is, *production system integration capabilities.* As shown in Section 2, digital production technologies are the result of the integration of hardware, software and connectivity into an integrated production system. This integration is both technological and organizational and often requires retrofitting of existing production plants.

Technological integration ensures that the different components are integrated, that is, that the companies have the right mix of hardware, software and connectivity to meet the 'digital capability threshold' required to operate each one of them individually and all of them together as a system in a cost and quality effective manner. To achieve technological integration, the basic and digital infrastructure must meet the conditions of each one of these components – hardware, software and connectivity. An improvement in wireless connectivity in a country where power shortages undermine the effective use of automated systems is meaningless. Similarly, the lack of adequate software capabilities and infrastructure data analytics dramatically reduce the potential gains from digital production technologies. Data ownership and software affordability can be a major bottleneck for companies in developing countries that want to achieve technological integration.

Despite being a critical factor, technological integration in itself does not suffice for delivering productivity gains from the 4IR. The problem—especially in companies across many developing countries—is that the effective deployment of these integrated technologies requires quite advanced capabilities for organizational integration.

Organizational integration is important both at the individual company and the supply chain levels. The digital capability gap between leading OEMs and first tier suppliers, on the one hand, and second and third tier SMEs can be such that the advantages offered by technological integration do not materialize or spread along the chain (even in high-tech sectors like automotive, aerospace, mining equipment and medical devices). In some cases, the digital capability gap discourages leading OEMs and first tier suppliers from linking backward domestically. Thus, a technology upgrading opportunity can turn into an industrialization bottleneck for local suppliers when system integrators and assemblers have to rely on importation of components more than local insourcing from developing countries.

The following set of case studies provide vivid illustrations of these different types of capabilities and how countries and companies at different stages of development are trying to enhance them. The learning journeys are company- and sector-specific, and often start from incremental steps, such as reverse engineering in the provision of maintenance and repair operations (MRO) or opportunities for incremental digital transformation in more traditional sectors.

4. Case studies

4.1 The digital capability gap: the case of the automotive supply chain in South Africa

Historically, the automotive sector has been a major driver of industrialization in several successful country experiences. The length and complexity of its value chain, alongside the development of production and technological complementarities, allowed countries involved in the automotive sector to achieve several goals. They include a general upgrading of the manufacturing sector, but also better balance of payment indicators and a strong employment multiplier (1:4 ratio being the overall industry benchmark). The automotive sector has been a fertile field for many improvements in production technologies, being a sector characterized by intensive economies of scale and the use of automated machines.

Over the years, several technological and organizational changes have reshaped production in this sector, and companies had to retrofit of their legacy systems. The transition from mass production to mass customization, for example, allowed the production of more variants with fewer resources and materials in the fastest way possible (Michalos et al., 2010). If customization and product management are enabled by the increasing modularization of vehicles, it is at the same time partially constrained by the availability of technologies and equipment used in the mass production system.

Recent GVC developments have also reshaped the global organization of production in the sector and the relationships between global system integrators and their first, second and third tier suppliers. Being that the industry is characterized by producer-driven governance (Gereffi, 1994), OEMs' final assemblers and first tier suppliers play the most important role. The rise of mega first tier suppliers specialized in seats, braking systems and automotive semiconductors are increasingly creating oligopolies with revenues that could be compared to those of their automotive customers (Wong, 2018). This has implications on the upstream segments of the value chain that must undertake great efforts to continue to adapt to global standards and continuously changing dynamics.

The South African automotive industry is fully integrated in the global automotive value chain. According to OICA statistics, South Africa is the 22nd largest manufacturer of motor vehicles. It produces 600 000 vehicles[6], contributing 0.65 per cent of global vehicle output. Despite the government's target of achieving 1 per cent of global output by 2035[7], the output of South Africa's automotive sector has slowed down in recent years due to different constraining factors. Over the last two decades, the structure of South Africa's economy has remained fundamentally unchanged, and has in fact shown signs of premature de-industrialization (Andreoni and Tregenna, 2018). Manufacturing diversification has also remained limited in the country. The lion's share of output, productivity and technologies are controlled by big international OEMs and international Tier 1 suppliers, even in automotive, the spearhead of the South African economy. Due to the longstanding presence of international companies, South Africa has a complete supply chain from Tiers 3 and 4 to OEM assemblers. According to the AIDC[8] report, there are 120 Tier 1 companies that directly supply to OEMs and 360 companies that belong to Tiers 2 and 3.

Technological and productivity challenges are particularly acute between Tiers 2 and 3, and exacerbated by the so-called "missing middle" phenomenon. The lack of small and medium productive organizations able to link with big OEMs has constrained the development of the sector and its domestic value additions. When we look at the distribution of value added in different value chain segments, we find that OEMs produce 40 per cent, Tier 1 suppliers produce

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[6] 2016 data.
[7] South African Automotive Masterplan.
[8] Alternative Information and Developing Centers.

40 per cent and just 20 per cent of value added stems from the production of Tier 2 and Tier 3 suppliers (Monaco et al., 2018). Similarly, if we benchmark South Africa against other major recipients of FDI in automotive, we find that FDI related to automotive OEMs is almost three times that of FDI in components (Table 4)[9].

Domestic value addition and FDIs along the domestic automotive value chain are important indicators of the state of development of South Africa's automotive production system. FDI investments, in particular, are potentially important drivers of technological change, especially in new production technologies. According to the International Federation of Robotics, which collects data on the number of robotics applications with an indication of time, sector (and sub-sectors) and application, 86 per cent of total industrial robots in the automotive sector in South Africa are used in vehicle production, which mainly entails big OEM assemblers (Figure 12). If we benchmark South Africa against countries with a more developed supply chain, for example, Thailand, robots are much more widely distributed along the supply chain, with more first and second tier suppliers deploying this type of digital production technology. This indicates that the diffusion of digital production technologies like robotics critically depends on the level of development of the supply chain. Without such a development, suppliers involved in components production are cut off from the potential advantages of 4IR technologies.

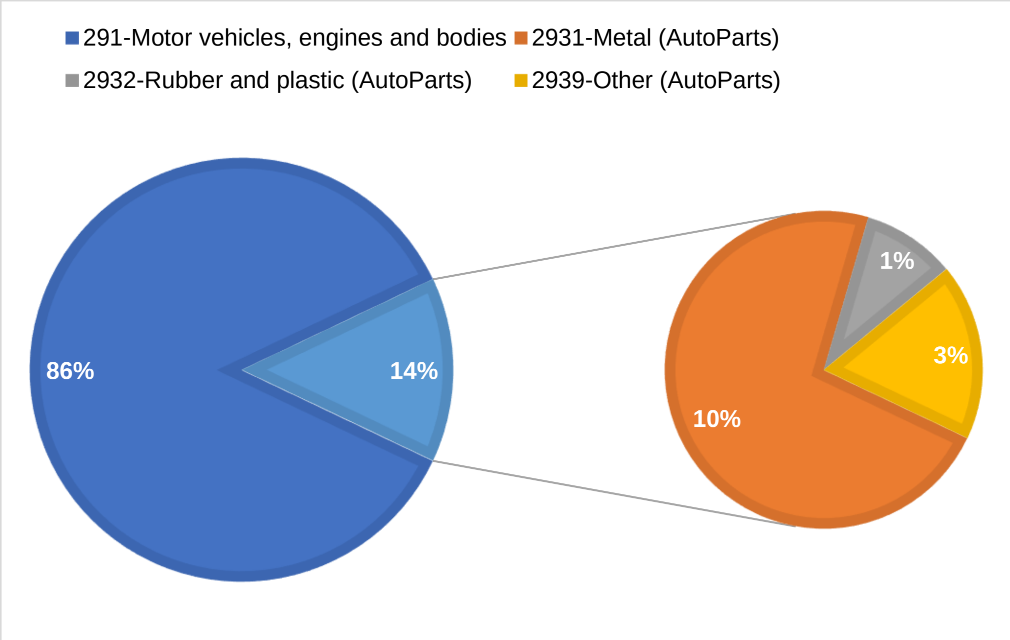
[9] Data on the first 22 countries per number of inward FDI between 2003 and 2015.

Table 4: Major recipients of automotive FDI (2003-2015)

Destination country	Automotive components	Automotive OEM	Total
Argentina	31	31	62
Brazil	99	114	213
Canada	64	38	102
China	660	241	901
Czech Republic	181	20	201
France	87	24	111
Germany	76	19	95
Hungary	150	19	169
India	274	163	437
Indonesia	60	51	111
Mexico	329	101	430
Poland	192	38	230
Romania	148	14	162
Russia	119	140	259
Slovakia	97	21	118
South Africa	18	50	68
Spain	66	58	124
Thailand	160	72	232
Turkey	41	47	88
UK	97	67	164
United States	706	159	865
Viet Nam	47	27	74
Total	**3,702**	**1,514**	**5,216**

Source: Authors based on fDi markets dataset.

Figure 12: Robots applications in the automotive sector in South Africa (2005-2015)



Source: Authors based on IFR data

Among the many and different types of suppliers, companies specialized in plastic components are particularly important in South Africa because of their potential link with the automotive sector and the horizontal linkages across other sectors of the economy. Acknowledging the importance of the plastic sector, the South African government has developed specific policies to promote the technological upgrading and integration of suppliers of plastic components into the local automotive value chain[10].

However, to exploit the new opportunities offered by digital production technologies, plastic companies have to commit significant resources and retrofit their existing production technologies and plants. Interestingly, those plastic firms that are closer to MNCs and OEMs appear to be relatively faster followers in terms of technology adoption and retrofitting. While all suppliers face significant constraints in terms of leveraging capital investments and access to basic and intermediate skilled workers, those with stronger links with OEMs are better incentivized and positioned to absorb new digital production technologies. The following two companies are illustrative cases of early engagements with 4IR technologies in South Africa[11].

[10] South Africa's Industrial Policy Action Plan (IPAP 2018/19-2020/21).
[11] The cases presented below are taken from a pool of studies conducted by the University of Johannesburg.

- ***Diemaster Industries*** is a South African plastic injection moulding company based in Johannesburg. The company is a Tier 2 supplier of plastic automotive components, with high potential in terms of expansion and integration of 4IR technologies. Despite being an early adopter of 4IR hardware systems like 3D printers for rapid prototyping, the company is now facing numerous challenges partially due to the continuous need for technology upgrading and the tight technical requirements and standards of Tier 1 companies. For instance, the company needs to replace its five year old printer with a more advanced multi-tasking one performing both milling and printing operations. This replacement is prevented by the high cost of the machine. The high cost of new technologies is found to be one of the major issues across different types of suppliers in the South African context. A regards the level of production system integration, Diemaster uses a CAD software which is connected to the moulding machines. Indeed, even relatvely advanced firms like Diemaster still use automation technologies only in relation to product design and/or production (Figure 11), lagging behind in terms of supply chain integrated systems based on IoT technologies.

- ***Plastic Omnium*** is a French MNC that is a leading first tier supplier of large automotive companies such as BMW, Volkswagen, Toyota and Renault. Because of its integration with big OEMs, Plastic Omnium considers automation to be a very important step forward. In the South African plants, robotics plays a crucial role since most of the moulding machines are last generation industrial robots. The main difference between other plants located in foreign countries is related to the next automation step, which is the integration of different units in a homogenous connected system. For instance, British and Thai manufacturing units are linked with development and sales centres in China, Japan and the U.S. Through the use of an enterprise resource planning (ERP) system to coordinate these different units, Plastic Omnium obtains real-time feedback on productivity, capacity and possible inefficiencies. Low capacity—both in terms of low productivity and lack of domestic skills—and geographic position are considered the main constraints for the development of these technologies in South Africa.

4.2 Overcoming enabling infrastructure capabilities bottlenecks towards full production system integration: The case of the mining sector in Brazil[12]

Mining was regarded as a capital-intensive, low-tech sector for a long time. Today, resourced-based industrialization (RBI) is recognized as a viable opportunity for developing countries to engage with digital production technologies and develop several linkages with the rest of the economy (Morris and Kaplinsky, 2011; Andreoni, 2015). The technological opportunity space (Perez, 2016) related to mining is particularly relevant: the sector entails numerous technological innovations from autonomous robots in Peruvian underground mines, to AI and machine learning in the exploration phases, up to integrated systems linking the mine to the beneficiation plant and logistics facilities. While these types of system integration technologies present great potential in terms of productivity increases and better quantity and quality of data through IoT applications, mining companies face several constraints because of the technological alignment and costs that stem from a fully integrated system.

The case study considered here is a prime example of an integrated system within a mining project, its potential and its challenges. The S11D is the largest iron ore mine in the world and was opened at the end of 2016 by the Brazilian MNC Vale in the Northern East state of Pará. The mine is considered a model both in terms of productivity and low environmental impact. The high technological standards required throughout the entire construction and its operations can be found in the hardware, connectivity and software components of the 4IR technologies being deployed. For example, two important innovations driven by the need to meet environmental standards are the belt system conveyor that saves up to 70 per cent of CO_2 emissions (which normally occur when transporting iron ore within the mine) and the dried sift system that saves 90 per cent of water consumption[13].

Vale contracted the leading company ABB both for the deployment of an automated electrical system and the *ABB Ability MineOptimize* application, which is used in the implementation of a fully integrated process linking the mine to the processing plant and the market. The collection and management of big data made possible by ABB digital production technologies had a dramatic impact on cost management along the iron ore value chain.

ABB Ability MineOptimize integration project materialized after the company won a contract to install the trackless belt system in 2014. This was the first time such a system was installed in a mine of this magnitude. First, ABB had to address a fundamental infrastructural bottleneck. ABB

[12] This case study is based on a skype interview with an ABB employee in the S11D.
[13] This innovation is particularly relevant after the collapse of the dam in the Brumadinho tragedy in January 2019. With the new dry method, the mine does not need a dam because there are no mud scraps to collect.

had to supply the electrical equipment needed within the mine, including a 230 kilovolt in-feed (primary) substation to connect the mine to the grid and 42 substations made of 88 units and 173 modules[14]. It is an incredible amount of energy, especially considering that the mine is in the middle of the Amazon. Once access to reliable electric power was achieved, ABB could start focussing on the creation of a digital platform for delivering a fully integrated production system.

First, capital equipment and sensors were provided by ABB and installed throughout the entire mine. The mine had to be equipped with 5 000 sensors capable of capturing data on machine temperature, positioning, electric power and tension, among other indicators. Machines are connected through wireless and via ethernet cable, depending on different needs. Sensors are applied in all machine equipment and along the 37 km belt conveyor system that transports the ore from the mine and the processing plant.

Second, 7 000 vibrating check stations had to be installed to report information to Emerson's CSI 6500 machinery health monitor. This was one of the biggest investment made by Vale – BRL 52 million (USD 13.5 million) just for the temperature and vibration system. Emerson was chosen to help ensure reliable operations of the pit-to-plant conveyor system as well as two crushers and a stacker-reclaimer that are part of the material handling system. Any disruption to this arterial system has the potential of bringing the 90 million tonnes/year operation to a halt – costing as much as USD 1.4 million per hour in lost production[15]. To avoid such a loss, the CSI 6500 collects sensor data from key conveyor components such as drives and primary pulleys. This technology is able to effectively pinpoint intensifying levels of machinery stress, weeks or even months before component failure. The stress is measured through vibrations which are reported through the 7 000 vibrating check stations installed and the 44 servers that monitor vibration and temperature. This system allows repair of machines when it is needed, without regularly sending out maintenance staff; nonetheless, applications of machinery health diagnostics are very costly and require time efforts to integrate, thus their application is still quite rare.

Third, the hardware (machinery, sensors, health machinery) is able to communicate and report information through the AssetVista software provided by ABB. This tailor-made software unlocks data, analyses it and makes it accessible to the maintenance staff. Thousands of real-time data are sent to the central room where three analysts are able to make better decisions in real time. Moreover, the system is based on alarms that are set off when vibrations recorded by the health machines are not constant; it is thereby possible to identify how much time

[14] https://www.australianmining.com.au/news/abb-wins-massive-truckless-mine-automation-contract-2/
[15] http://www.mining.com/web/emersons-machinery-health-technology-chosen-by-vale-for-truckless-mine-in-brazil/

maintenance staff has before the machine fails. The software allows integration between the different operations and the advanced control system: the High Level System (HLS) is a centralized system for the management and control of machine operations and plant facilities both in the factory and in the trackless mine. Predictive analytics, which is the main benefit gained from this kind of integration system, allows firms to reduce costs by preventing unplanned downtime and reducing manufacturing waste.

The level of automation reached by the S11D projects is already being taken as an example in the mining sector. It shows that through reliable power supply and internet connection, mining companies can remotely collect real-time data both on the status of the mineral and on the performance of the machinery. The ability to track ores—or concentrated—through the application of sensors, from extraction to downstream production, is something that could soon become a necessity, especially in high-technology sectors like automotive and aerospace where the importance of tracing back materials could impact their branding and sustainability standards.

Overall, the project has been very successful in terms of technological advances and high productivity. The low exposure to electrical hazard as well as the reduction of interruptions improved efficiency: in 2018, Vale estimated a gain of BRL 1 million due to losses prevented from machinery downtime. Despite the success of the mine, the other side of the story relates more to the sector's well-known enclave nature. This is a typical case of the rare 'setting up a brand new plant' which created a 4IR island; in a country where stable energy supply is still a problem in many areas, projects of this magnitude can take place without generating any significant spill-overs to the rest of the economy.

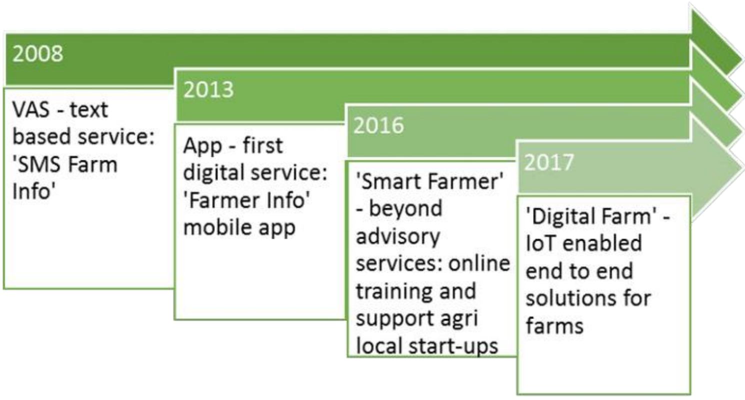
4.3 Scaling up ICT for data-driven production: the case of IoT in the agricultural sector in Thailand

Agriculture is another sector that is traditionally considered low-tech, with small margins for productivity increases and technology innovation. By industrializing agriculture, that is, by transforming agricultural processes with manufacturing technologies, there are several cases of high-tech agriculture today across developing and emerging countries. In particular, digital production technologies have found specific applications in critical stages and processes in the agricultural value chain. The following case study highlights one of these 4IR opportunities for technological upgrading in agriculture.

Farm Man Yum (which means precision farming) is a service developed by *dtac,* Total Access Communication Public Company Limited, the third largest GSM mobile phone provider in Thailand. Farm Man Yum is the most recent agribusiness innovation *dtac* has promoted in partnership with public actors. Public private partnerships developed in Thailand in response to the Thai government's intention to boost productivity in agriculture. In fact, despite employing one-third of the population (around 6 million people), the agricultural sector generates only 10 per cent of GDP. To overcome this lack of productivity, *dtac* established a partnership with NECTEC (Thailand's National Electronics and Computer Technology Center). As a result of this partnership, an IoT-based solution to help farmers deal with climate change, plant disease and soil moisture control was developed.

dtac's experience in agriculture started in 2008 with the first mobile agricultural advisory system 'SMS Farmer Info'. Through free SMS, *dtac* customers received daily updates on weather forecasts, farming techniques and market prices. This service was introduced after an assessment study whereby *dtac* discovered how the lack of access to information was responsible for low yields and increased the gap between urban and rural farmers. In 2013, a new app 'Farmer Info' was launched with improvements such as farming tips through video clips and advice on how to reach the market. At the end of 2016, already looking at intelligent agricultural systems, 20 devices were installed and tested by farmers across Thailand. As a result of this first pilot, farmers harvested more crops and recouped the initial cost after only one harvest.

Figure 13: Evolution of dtac agribusiness technologies



Source: dtac Sustainability Report, 2017

The latest step in this technological upgrading journey led by *dtac* was the 'Digital Farm' project. It consists of a *precision farming set* whereby sensor boxes are installed around greenhouses and a solar powered system monitors different parameters (light, humidity, temperature, water, wind and pH level). The *set* is linked to a router where a *dtac* SIM card places information in the cloud[16]. This solution enables targeted advisory to farmers based on farm-level granular data.

[16] https://www.gsma.com/mobilefordevelopment/programme/magri/dtac-enabling-digital-transformation-thai-farmers/

Personalized weather forecasts, health monitoring through satellite imagery and crop advice are the main features of the service. The system, for instance, helps monitor and automatically adjust temperature in a storing room depending on the crop's specificity; when setting up a greenhouse maximum temperature of 35 degrees, there is a sensor that sends an alert to the farmers in case of rising temperatures, allowing them to activate a sprinkler or open an air tunnel. These applications work because of internet signals from the *dtac* SIM cards router through which data are sent to mobile phones. Opportunities for data-driven decision-making will increase once all the data stored in the cloud are consolidated. Pakuna Boonkorkua, a melon farm owner in Chachoengsao province, said the agritech helped increase her farm yield by 27 per cent compared to the years before she adopted the digital technology[17].

A complementary part of the project involves the final users of the services. Being aware of the digital literacy challenges, especially among rural users, *dtac* set up the 'Internet volunteer' project, where *dtac* employees can dedicate time to teach farming communities about smartphones and the related benefits. Starting from this project, *dtac* in collaboration with government agencies organizes trainings to educate farmers on knowledge and information services. The actors involved in the implementation of the agribusiness solutions have recognized the importance of focussing on a specific segment of the farming population. *dtac* decided to focus on young farmers more prone to learning and adopting the latest technologies. Even in this case, *dtac* has collaborated with the Department of Agriculture, which already had knowledge about farmers' segmentation based on previous research.

This case is particularly interesting because it highlights the importance of three interrelated aspects: technological infrastructure, knowledge and public investment. The service provided by *dtac* can rely on its communication infrastructure and on a wide net of customers; specifically, the use of the same infrastructure and part of the same applications (e.g. SMS) shows the incremental nature of many applications related to the 4IR. Moreover, *dtac* builds on a ten-year experience in the agribusiness sector and on a government-led collaboration for the development of the service. In this sense, the 'pooling feature' of the 4IR is visible: the complexity of technologies underlying digital platforms and their functioning means that no single company or actor can control/own all of the elements of the system (Sturgeon, 2017). At the same time, this collective action poses issues in terms of data ownership.

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[17] https://elevenmyanmar.com/news/thailands-digital-transformation-to-reach-macroeconomic-scale-in-2019-the-nation

5. The digital dividend: discussion and policy implications

The so-called 4IR is an evolutionary (more than a revolutionary) phenomenon, characterized by country, sector and technology-specific dynamics. In the previous sections, we have established why and how the 4IR is in fact "evolutionary" and "heterogenous", and in particular what the opportunities and challenges associated with digital production technologies are for developing countries. We have also shown that key digital production technologies, for example, robotics, 3DP and IoT systems, are far from widespread, especially if we look at companies in todays' emerging and developing countries.

Contrary to the dominant narrative, which suggests an imminent disruption caused by the 4IR across all countries and sectors, we have also highlighted how the diffusion of digital production technologies is a diverse and lengthy process. Consequently, we have pointed out how 3IR and 4IR technologies will continue to co-exist for a long time and how a large part of companies—especially across developing and low-middle income countries—is still fully engaged in learning and effectively deploying 3IR technologies.

The diffusion and effective deployment of digital production technologies will be determined by several factors, including the extent to which they are the most cost effective way to produce a certain component or product (still not always the case), and the extent to which the majority of companies meet the digital capability threshold, that is, have a sufficient bundle of capabilities in several functional areas (definitely not the case, especially across developing countries). Without developing basic and intermediate level capabilities, i.e. basic production capabilities and technology absorption and retrofitting capabilities, the new advanced forms of technological and organizational integration will remain a technological mirage.

The advancement of this more nuanced perspective has twofold implications, especially if we look at the 4IR from a developing and low middle-income country perspective.

First, it suggests the importance of questioning a number of increasingly dominant narratives related to the 4IR, in particular those suggesting that:

(i) The 4IR poses an *existential threat to manufacturing jobs* across almost all sectors and countries, and therefore, countries that must employ a growing population might have to look elsewhere;

(ii) There are several 'problems in the making', especially in the new 4IR world of production and thus, *alternative non-manufacturing-based development pathways* might be a less risky bet for developing countries;

(iii) Governments have no principal way of *managing technological change and industrial restructuring*, that is, incremental ways to engage with the opportunities offered by 4IR technologies, while managing the conflicts, developing the capabilities and incentivizing changes across sectors of the economy.

Second, and related to the last point above, the more nuanced perspective we advance here points to the fact that while technological change has reshaped the relationship between workers and production, sectors and society at large since the 1IR, what matters is the use of the technology more than the technology in itself. For example, training institutions have been created to retrain workers in the use of technologies and to reduce the impact of technological change-led unemployment. In some countries like Japan, the establishment of certain types of industrial relations and other welfare state provisions have made it possible to manage the potential conflicts arising from the increasing robotization of the automotive industry. In a nutshell, as in past industrial revolutions, and to the extent that we buy the idea of an ongoing 4IR, *industrial policies can shape the technological change process within sectors and across society*. The experience of today's successful industrial economies and the experience of late industrialization points to this historical evidence (Andreoni, 2016; Andreoni and Chang, 2018).

In what follows, we challenge these dominant narratives (the first two sets of issues above) and in doing so, we suggest alternative industrial policy implications (second argument raised above).

Does robotization pose an existential threat to manufacturing jobs and challenge the comparative advantage of low-wage developing countries?

The direct and mediated impact of 4IR technologies—especially robots—on employment generation has dominated large parts of the 4IR academic and policy debate. As discussed above, based on a general understanding of 4IR technologies, two critical points have been made. First, that mature industrial economies will be increasingly relying on robots in industrial production (thus, reducing job absorption in these sectors) while at the same time, re-shoring large parts of labour-intensive processes from developing countries (thus, reducing opportunities for developing countries to exploit their low wage comparative advantage). The scenario emerging from this line of thinking is one in which developing countries are kicked off the industrialization ladder (again) and mature industrial economies and fast industrializers "reverticalize industrial production".

The empirical evidence, however, seems to point in three different directions.

First, based on the evidence and analysis provided in Section 3, it seems that over the last decades, intelligent automation has been penetrating industries slowly and robotization has remained concentrated in a few sectors. The relatively slow diffusion of robotization, especially across developing countries (but also some mature economies with a small manufacturing base), is due to the fact that the technology is costly, demanding and not always the best technology option vis-à-vis labour. Despite their increasing flexibility, to justify a certain capex and to be cost effective, robots have to operate at their full capacity and in a highly controlled environment—robot cells—once they have been set up. Also, investments in robots is only justified if a certain production threshold is met. This means that robot deployment and diffusion are bound by the quantity and quality of demand for a certain component or final product. In a nutshell, companies' decision to robotize a production plant is not a straightforward one. In some cases, companies have no choice but to automate and robotize. In other cases, while technologically feasible, robots are not deployed and human labour remains the most flexible and cost-effective choice. Finally, there are several areas in which companies strongly depend on human decisions, problem -setting and -solving and relational capabilities.

Second, the evidence of the negative impact of robotization on employment is mixed, country-specific and, in some cases, we face an interesting robots-employment paradox. That is, in those regions and countries where robots have found the highest application relative to others, total employment has not dropped, and in some cases, workers in robot-intensive industries were even found to have a substantially higher likelihood of remaining employed than others employed in non-robot-intensive industries. For example, in a study focussing on Germany, it was found that contrary to the U.S., robotization does not have a negative total employment effect (Dauth, et al. 2017). Paradoxically, they also found that "[t]he raw correlation between robots and local employment growth is even positive, but this is strongly driven by the automobile industry which is highly spatially concentrated and has by far the most industrial robots" (p. 7). During the period 1994–2014, the estimated replacement of certain jobs with robots in Germany was fully offset by job gains in other sectors, thus changing the composition of total employment. Moreover, by looking at detailed data for individual work biographies, the same authors found that workers from more robot-exposed industries are even more likely to keep a job in their original workplace. This means that workers in these industries were moved to other functional areas of production, more than being displaced by robots. Thus, in a nutshell, the equation 'more robots = less jobs' is not so straightforward. Several other factors affect this relationship and countries like Germany or Japan, where manufacturing employment shares have remained stable compared to comparators like the U.S. or other European countries, seem to have found ways to manage these factors better.

Third, if we look for evidence of massive reshoring trends, we do not find any significant evidence for a specific sector or country (see de Backer et al., 2016). On the contrary, low wages remain a major driver of production off-shoring from developed to developing countries (Olhager, 2018[18]). The shift of global demand towards fast emerging economies has also played a key role in attracting investments across developing and middle income countries, thus making offshoring or new investments in these countries still preferred options. Closeness to markets in certain industries is key, for instance. This is particularly the case in industries with rapid production-market cycles and high levels of customization. Similarly, to the industrial automation experience of the 3IR and contrary to expectations, flexibility maintains and in certain cases increases the optimal scale of production and the need for cost effective locations, thus generating mixed results in terms of concentration of production and new opportunities (Alcorta, 1995). These arguments suggest that far from witnessing a massive re-shoring of production, developing countries can still be the most attractive option for a number of labour-intensive industries, and thus for manufacturing employment creation.

Are there alternative non-manufacturing development pathways in the new 4IR world? Why manufacturing still matters for capturing the digital dividend

The rise of the 4IR narrative has re-opened a never-ending debate on the extent to which developing countries need manufacturing industries for their development. While certain types of service industries, that is, high value production-related services, and high-tech industrial agriculture can deliver productivity and value addition gains comparable to (and in some cases even higher than) manufacturing, the critical role that manufacturing industries play in embarking on the 4IR learning pathway and capturing its digital dividend has been overlooked and a too rosy picture of 4IR in services depicted.

First, manufacturing companies remain the main learning houses of any industrial revolution, especially if we focus on the development of production technologies and their latest digital permutation. This is due to the complex nature of manufacturing processes and widespread adoption of an interdependent set of machines, tools and equipment as well as a broad range of specialized skills and R&D required in manufacturing production. Manufacturing industries are

[18] Presentation at the Cambridge International Manufacturing Symposium 2018, "Designing and redesigning international manufacturing networks", available at: https://cimsymposium.eng.cam.ac.uk/previousevents/2018symposiumfolder/JanOlhagerLundUniversity.pdf/at_download/file

thus central in developing the set of basic and intermediate productive capabilities that companies need to efficiently deploy, effectively organize and incrementally absorb new technologies. What is also unique about manufacturing is that it allows the development of complex ‘collective capabilities’, resulting from the concentration and need for the organization of a broad range of closely complementary but dissimilar capabilities in production (Andreoni and Chang, 2016; Chang and Andreoni, 2019). These collective capabilities are particularly critical in technology and organizational integration, as highlighted in the Digital Capability Matrix above, and are perhaps the scarcest resource in today’s developing countries.

Second, when non-manufacturing sectors are able to capture the digital dividend, it is because 3IR and 4IR technologies are used to manufacture their transformation (Andreoni and Chang, 2018). The three case studies across sectors and countries presented in Section 4 have provided illustrations of the learning journey companies have embarked on, the potential digital dividend they are trying to capture and the barriers they face. Strikingly, all three cases point to the fact that the 4IR ultimately stems from technologies—hardware, software and connectivity—and organizational principles of manufacturing production. Indeed, independently from the sector considered—automotive, mining or farming—companies have been able to engage with 4IR opportunities and thus increase their productivity and value addition, only because they have introduced the manufacturing principles and technologies of process automation and the productive use of data for product design, process control and the efficient use of resources.

Third, across developing countries, the application of 4IR technologies to services has so far remained concentrated in a number of activities that do not necessarily deliver the type of structural transformation countries need. For example, the increasing use of ICTs in mobile communications and financial transactions, especially in countries like Kenya and Nigeria, has played an important role in providing important services to communities. However, the use of these technologies in production has remained quite limited, with a few exceptions in the agricultural value chain. The productivity gains from automation and data use in production have been relatively limited as the performances of these countries show, despite the rise of the ICT service industry. While the servisification of manufacturing literature (Nubler, 2016; Hallward-Driemeier and Nayyar, 2018) has pointed out how services can complement and augment value creation and capture opportunities stemming from manufacturing, it is also evident that the digital dividend will be higher when 4IR technologies are used in production-related services closely linked to manufacturing, such as engineering design services, market analysis, logistics and e-commerce. To the extent that services are embodied in manufacturing, there will likely be a symbiotic relationship between the two sectors (Hallward-Driemeier and Nayyar, 2018) and thus a higher chance of capturing the digital divided of the 4IR. Manufacturing industries must be developed to establish this symbiotic relationship.

Why, what and how industrial policy can shape 4IR

Since the first industrial revolution, industrial policies have always shaped and driven the transformation of the economy, particularly when engagement with new technologies has required coordination and the commitment of resources under uncertainty (Chang, 2002; Andreoni and Chang, 2018). The nuanced perspective advanced in this contribution has pointed to the fact that the opportunities associated with 4IR technologies are very heterogenous, in some cases sector- and process-specific. Therefore, countries will need incremental and targeted industrial policies to capture these opportunities and overcome their digital capability threshold and gap. The Digital Capability Matrix presented above suggests how, from a simple digital skills policy or investments in futuristic technologies, developing countries must identify and incrementally develop basic and intermediate capabilities towards effective technological and organizational integration. This means that instead of investing limited resources in scattered 4IR innovation initiatives, governments should concentrate their efforts in creating the capability preconditions required for technology absorption and legacy system retrofitting, and establish the appropriate enabling infrastructural capabilities

Given the different applications and potential digital dividend of certain 4IR technologies, a number of manufacturing industries remain the main target of industrial policy investments. However, while some of them—the machine tool industry, for example—will play a key 'technology push role', others—such as high-tech agriculture and production-related services, in particular—will play a key 'demand pull role'. For example, the application of manufacturing principles to agricultural production could deliver dramatic productivity gains and better international market access, while creating demand for a modern agricultural equipment industry. The enormous potential of the digitalization of mining could similarly be another demand pull factor towards the development of global leading mining equipment industries in countries like South Africa and several others in Latin America. By targeted investments at the intersection of these demand pull and technology push dynamics, developing countries can also manage to decrease their reliance (and related trade burden) on pre-made machinery from advanced industrial economies (Andreoni and Chang, 2016; Piva and Vivarelli, 2017). Investing in these intersections of emerging industrial ecosystems can also be a way of laterally entering those manufacturing industries where the digital capability threshold might be too high for certain types of developing countries. The penetration of most advanced industries in which 4IR technologies promise to deliver the highest digital dividend might become feasible if the right entry point in the GVC is found and the right companies are supported. Indeed, precisely because of the significant capability challenges countries face in their industrialization journey, and the fact that 4IR productivity and value addition gains are nested in specific processes and activities, industrial policy will have to be grounded, smarter and more agile: grounded in the reality of digital production technologies, smarter in climbing the technology ladder and agile in picking opportunities.

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