Natura non facit saltus: Challenges and opportunities for digital industrialisation across developing countries

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Abstract

In this paper, we discuss the challenges and the opportunities faced by developing countries that want to join the so-called Fourth Industrial Revolution (4IR). We first point out that the current discourse on 4IR is often based on poor understanding of the true nature of the phenomenon. Emphasising that many of the so-called 4IR technologies have been there and evolving rapidly in the last half a century, we argue that what defines 4IR is the fusion of these technologies. Given this, we argue, rather than trying to master particular 4IR technologies, developing countries should first focus on acquiring what we call the foundational capabilities, that is, the capabilities to learn new technical and organisational solutions and apply them in creative and flexible ways. Using this perspective, we then discuss in great detail how different 4IR technologies are re-shaping each industry and creating new industries through technological fusion, while discussing how these changes are affecting the opportunities and challenges faced by developing countries for industrial development. We conclude the paper by discussing the implications of our findings for industrial policy in developing countries. (182 words)

Keywords: Fourth Industrial Revolution; Developing Countries; Leapfrogging; Foundational Capabilities; Technology Fusion; Industrial Policy.

1. Introduction

Over the last two decades, the global industrial landscape has been dramatically reshaped. The changes in global value chains have restructured national and regional industrial systems as well as the geography of production and international trade. Emerging technologies and their integration into complex technology systems are redefining value creation and capture dynamics in production, especially manufacturing production. In particular, the increasing application of automation, robotics, and digital technologies – coupled with new developments in nanotechnologies and biotechnologies – are altering manufacturing processes and production technologies, increasingly blurring the boundaries between physical and digital production systems – the so called ‘4th industrial revolution’ (4IR).

Against this background, developing countries face a number of challenges as well as opportunities. Those pointing out the challenges ahead have been questioning the future of manufacturing-led development and pointed to a number of new “troubles in the making” caused by technological disruptions and the related new competitiveness requirements (World Bank, 2018). On the other hand, those focusing on the opportunities have seen digital industrialisation as a new ‘leapfrogging chance’ for developing countries, in particular a chance to jump straight to the technology frontier of the ‘next production revolution’ (OECD, 2017). Both these perspectives have been often translated into digital policy frameworks in which, first, the role of manufacturing production in capturing the digital dividend is under-estimated in favour of post-industrial digital sectors; second, the leapfrogging perspective has led to the concentration of resources on technological jumps, much less on incremental technological learning.

This paper aims to challenge both these discourses and their policy implications by providing a new analytical framework and systematic evidence to identify specific challenges and opportunities of digital industrialisation for developing countries.

First, we highlight the role that the development of general – as well as sector-specific – production, technological and organisational capabilities play in enabling countries to capture digital industrialisation opportunities. In particular, we argue, these *foundational capabilities* are critical for the incremental absorption, retrofitting, and effective deployment of these new technologies. This integration of the new technologies into the existing production system involves the management of both the software (e.g. data, IoT, etc.) and the hardware (e.g. machinery, tools etc.) components, and the interfaces between the two (e.g. sensors and connectivity). This integration also requires adaptation not only at the individual firm level but also at the level of interface between firms in the production system – e.g. data software platforms. Retrofitting, retooling, and system integration changes the skill set that firms need.

Second, we claim that these foundational capabilities have become even more important in the context of the 4IR. This has to do with a very particular ‘revolutionary’ nature of these new technologies, that is, the fact that in many cases, they result from processes of technology fusion. This concept was originally introduced in the technological change literature (Kodama 1986) to unpack how integration of different technology clusters (or domains)—for example, mechanical engineering and electronics—resulted in ‘new’ technology systems—mechatronics. More recently, Martinelli et al. (2020) have investigated the generality, originality and longevity of 4IR technologies, finding heterogeneous results. We argue that widespread fusion of technologies in the 4IR context pose challenges and opportunities for developing countries. Technology fusion poses challenges because it is a demanding process, requiring the development and the cumulation of foundational, as well as more advanced, capabilities in more than one technology domain. It creates opportunities because sector-specific applications of these technologies and their fusion can alter sectoral terrains and boundaries, trigger new processes of diversification, and open new opportunities for value creation and capture (Andreoni 2020).

Given this complexity, we argue that developing countries can better address the new “troubles in the making” and enter new paths of manufacturing development by engaging in the incremental building up of foundational capabilities and production systems, rather than by trying to leapfrog. Understanding the importance of foundational capabilities and incrementalism both as an alternative to and as an input into leapfrogging, as well as the truly revolutionary nature of 4IR, that is, technology fusion, are important pillars for effective industrial policies.

The rest of the paper is structured in three parts. First, we discuss the importance of foundational capabilities and technology fusion in understanding 4IR (section 2). We then present our multi-layered framework and use it to systematise emerging evidence on sectoral and cross-sectoral applications of 4IR technologies (section 3). The framework supported by a detailed evidence matrix is finally used in section 4 to draw a number of policy implications for digital industrialisation in developing countries.

2. Why “natura non facit saltus”? Theoretical perspectives

2.1 Incrementalism within leapfrogging: Foundational capabilities, cross-sectoral technologies, and sector-specificity

The idea of “windows of opportunity” was first developed by Perez and Soete (1988) referring to the fact that the possibilities for catching-up are not homogeneous in time. Given that technologies generally evolve in paradigms (Nelson and Winter, 1982; Perez, 1983; Dosi, 1982), conditions would be particularly favourable for catching-up during technological paradigm shifts.

The first works that associated technological cycle with the diffusion of technology to developing countries were the ones of the “product-cycle” literature (Posner, 1961; Vernon, 1966). The argument of these works was that, as technologies reach maturity, they would shift to less-developed countries, based on the logic of comparative advantage. Perez and Soete (1988), however, argued that mature sectors are exactly the ones that are losing dynamism, thereby presenting a clear risk for the absorbing country to get stuck in a low-wage low-growth development pattern. As such, they argued that: “A real catching-up process can only be achieved through acquiring the capacity for participating in the generation and improvement of technologies as opposed to the simple ‘use’ of them.” (p. 459).

According to Perez and Soete, this could be more easily achieved during technological paradigm shifts. As a new paradigm emerges, at least two entry barriers are lowered (the minimum fixed capital and the minimum experience required). The scientific and technical knowledge required – the other entry barrier – would still be high, but this would be a lesser problem given that, in the initial phases of a paradigm, the appropriability of the required knowledge is weaker (e.g. fewer patents, availability of a lot of non-patented knowledge in universities). Furthermore, incumbents might be entangled with old technologies and become trapped in them, with strong inertia. New entrants, then, would have the advantage of being more flexible in adopting the technologies of the new paradigm. The general idea is that during paradigm shifts the technologies are new to everyone, thus giving developing country firms an opportunity for learning and entering the market faster than the established companies.

Lee (2013) also corroborates this idea, although within his catching-up framework more emphasis is given to the concept of ‘learning cycles’. He states that, to effectively catch up, a “detour” strategy would be required, that is, taking a different route from that of the incumbent, high-income countries. It implies moving first into short-cycle technologies (technologies which are based on recent knowledge) and only later moving to high-value added long-cycle technologies (a moment he calls the “technological turning point”). This would not mean specializing in a fixed list of technologies, but a constant entry into new areas.

Lee and Malerba (2017) further develop this catching-up framework by considering at least two other types of windows of opportunities: demand windows, and institutional/policy windows. Demand windows refer to a new type of demand, a major shake-up in a local market, or a business cycle that enables firms from latecomer countries to enter the market (the major increases in demand in China and in India are good examples of that). Institutional/policy windows are opened through public intervention in industries or through drastic changes in institutional conditions (e.g. high-tech industries in Korea and Taiwan, the telecommunications industry in China, and the pharmaceutical industry in India). However, they point out that the technological window seems to be the most crucial, as the impacts of the other two are realized through the generation, adoption or diffusion of technological innovations. They also highlight that just as important as the opening of windows of opportunity are how latecomer firms respond to them.

Notwithstanding the existence of these windows of opportunity, the literature also recognizes that “leapfrogging” to the more advanced sectors would be available only for countries in the later stage of the catching-up process, such as middle-income countries (Lee, 2013). According to Lee and Malerba (2017), there would be four stages in the catching-up cycle: entry, gradual catch-up, forging ahead and falling behind. Thus, in order to reach the forging ahead stage, several gradual steps must have been previously taken. Although opportunities for leapfrogging exist, countries must have already gone through an early and gradual process of production transformation, if they are going to be able to take advantage of them. In today's developed and middle-income countries, this process was led by the expansion of manufacturing activities and their transformative impacts across sectors, which resulted in the development of collective capabilities in production, technologies and organisations (Andreoni and Chang, 2017).

The rise of the 4IR discourse has re-opened the never-ending debate on the extent to which developing countries need manufacturing industries for developing the productive capabilities that are at the foundation of the prosperity of today's rich countries. While certain type of service industries and high-tech, industrialized agriculture can deliver productivity growth and value addition gains comparable to (and in some cases even higher than) those of manufacturing, manufacturing companies remain the main learning houses of any industrial revolution. This is due to the complex nature of manufacturing processes, the widespread adoption of interdependent set of technologies across different sub-sectors of manufacturing, and the broad range of specialised skills and R&D required in manufacturing production. Indeed, independently of the sector considered – whether it is automotive, mining or farming – companies have been able to engage with 4IR opportunities and, thus, increase productivity and value addition, only because they have introduced the manufacturing principles of production in terms of operational design and technologies (e.g., process automation, use of data for product design, process control).

In the early and the gradual catch-up stages, manufacturing industries are thus central in developing general – as well as sector-specific – collective productive capabilities. We define these *foundational capabilities* as the '*capabilities to learn* new technical and organisational solutions, *integrate* them into production, *organise and commit* resources over time for the effective deployment of these new solutions'. The development of these foundational capabilities is a gradual process, as it requires changes at many levels. The three main levels are: the development of sector-specific production and technological capabilities; the development of organizational capabilities and structures; and institutional changes.

Capability development is a long and difficult process of learning which start from engagement in production – learning in production (Penrose, 1959; Bell and Pavitt, 1992; Lall, 1992; Dosi, 1997; Andreoni, 2014, 2018; Chang and Andreoni, 2020). In order to develop sector-specific production and technological capabilities, firms need a combination of factors and processes that include skills, funding, access to foreign technology, exposure to competition [1] (although not excessive), and government incentives.

Additionally, new technologies often need new organizational structures for them to realise their full economic benefits. This has been the case with the technological innovations of the beginning of the 20th century (electricity, internal combustion engine,

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[1] Exposure to competition does not require trade liberalization. Several successful development experiences (e.g. East Asian countries) have shown that competitive pressure on firms can be generated by a combination of export-push and a high level of domestic competition (see Chang, 1994, ch. 3 on this point).

new processes of producing steel), which only yielded their full benefits with the development of the large-scale vertically integrated multidivisional firm (Chandler, 1977); it has also been the case with the information and communication technologies (ICTs) revolution in the second half of the 20th century, which required, for their full deployment, a parallel development of an organizational paradigm based on flexible networks of firms, also known as “lean production”. In Perez’s (2002) words, every technological revolution leads to a related radical shift in the “techno-economic paradigm”, that is, “a set of all-pervasive generic technological and organizational principles, which represent the most effective way of applying a particular technological revolution and of using it for modernizing and rejuvenating the whole of the economy” (p. 15).

Finally, technological development requires changes at the level of institutions (and political economy). Institutional changes have been emphasized in the literature on National Systems of Innovation (NSI), focusing on the roles of industrial labs, universities, public research institutes, governments (Freeman, 1995; Nelson, 1993; Lundvall, 2010). Institutional change is also a political-economy process involving fundamental reconfigurations of power among organisations and institutions, in primis the state (Chang, 2002; Andreoni and Chang, 2019). This means that, from an institutional perspective, the development of foundational capabilities is not only a process of technological learning but also a political process.

Many of today’s developing countries are still stuck in the second industrial revolution and most of them are still struggling to effectively engage with the technological, organisational and institutional innovations of the third industrial revolution (WEF, 2018; UNIDO, 2020). In such situation, it is impossible for these countries to take advantage of the leapfrogging opportunities opened by the 4IR without the development of selected foundational capabilities.

2.2 What is revolutionary about the Fourth Industrial Revolution?

Continuity within revolutions

The literature on scientific and technological changes has debated extensively contrasting perspectives on the relative importance of incremental changes and disruptive and discontinuous changes.

In science, the idea of ‘scientific revolution’ has a long history and was initially used to describe the scientific developments that occurred from the sixteenth to the nineteenth century (the works of Copernicus, Kepler, Galileo, Bacon, Descartes, Leibniz, Newton, etc.). Later, the concept of scientific revolutions was further developed by Thomas Kuhn in his 1962 book *The Structure of Scientific Revolutions*. He argued that science evolves through periods of incremental ‘normal science’ within a paradigm and periods of paradigm changes – the ‘Kuhnian revolution’

These ideas, however, were problematized by ‘continuity theorists’ such as Pierre Duhem, Alistair Crombie, and more recently Peter Dear, who argued that, when looking at the history of science, it is hard to point out what was done radically different by the supposed revolutionaries compared to their predecessors. Thomas Kuhn himself, in his later works, modified his initial ideas stating that the scientific process would best be described as an evolutionary process of speciation, in which the new paradigm does not replace the previous one but in which the scientific discipline would split into different branches, leaving the older paradigm intact (SEP, 2017). In other words, there seems to be much more continuity in the scientific 'revolutions' than usually perceived.

In the technology literature, the idea of technological or industrial 'revolutions' is also pervasive. The most widely accepted framework states that so far there have been three industrial revolutions (and that we are on the brink of a fourth one)[2], but other authors propose different periodizations[3]. At a more micro-level, a similar idea is the Schumpeterian concept of radical (as opposed to incremental) innovation. Despite their differences, the definitions of revolution or radicalness generally include two aspects: 1. A high degree of novelty, i.e. being a discontinuity with traditional practices in the field; 2. Profound impacts, be it in the sector itself (opening avenues for future technological development, making old practices obsolete, impacting performance, etc.) or outside the sector (transforming the economy, society, the environment, etc.)[4] (see Kasmire et al, 2012; Perez, 2009).

However, as some authors have argued, many of the 'revolutionary' transformations observed stem from incremental technological advances. As Kasmire et al. (2012) point out: "On closer inspection, several innovations with undoubtedly radical effects comprise several small inventive steps that appear self-evident, even logical, to the developers" (p. 346). Conversely, there are also cases of lone geniuses that developed genuine original thoughts or inventions but were left in obscurity until they represented 'the next logical step' in some incremental path[5]. The widespread neglect of these 'continuities within revolutions' seems to arise from the common-sense assumption that large effects must have large causes. In that sense, it is necessary to distinguish between the *effects* of new technologies and the changes in their *scientific and technical bases*.

Levinthal (1998), akin to Thomas Kuhn's later works, reconciles these perspectives within a punctuated equilibrium framework of evolutionary biology. He argues that what is perceived as a critical technological event is in fact not a transformation of the

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[2] The first industrial revolution being associated with the steam-engine, and the mechanization of the textile industry, the ironmaking industry and various ironworking industries (early 19th century); the second being driven by electrification, the internal-combustion engine, and mass production technologies (late-19th, early-20th century); and the third by the development of electronics, especially ICTs (late 20th century).

[3] Freeman and Louçã (2001) and Pérez (2002), for example, argue that there have been five 'technological revolutions', and that we are still in the middle of the fifth one.

[4] We acknowledge the broad impacts that technologies have on society, institutions, and even culture. This raises question with the very definition of technology itself – should it be limited to the tools used by humans or should it be stretched to include organizational practices, institutions, and broader forms of organization of society? Discussing all these aspects, however, would go well beyond the scope of this paper. Thus, we limit ourselves to discussing the impacts of technologies on production at the firm and the industry levels.

[5] Kasmire et al. (2012) argue that this was the case with Charles Babbage's Analytical Engine and Gregor Mendel's theory of trait inheritance. Both were rediscovered over a century after their initial developments, when incremental developments in relevant areas caught up and provided a context to support them.

technology, but a speciation—the application of existing technology to a new domain. He further clarifies that “the technological change associated with the shift in domain is typically quite minor; indeed, in some instances, there is no change in technology.” However, “it may have significant commercial impact which, in turn, may trigger a substantially new and divergent evolutionary trajectory.” (p. 218) This framework is particularly relevant when we look at some of the so-called 4IR technologies.

Fourth Industrial Revolution: technology fusion and its applications in production

Although they are frequently called ‘revolutionary’ or ‘emergent’, most of the 4IR technologies have been on a long path of incremental development for at least five decades. Neural networks (the basis for AI) have been initially developed in 1943, and renewed interest was given in 1975 with important breakthroughs in algorithms. Initial developments of the internet began in the early 1960s, reaching full commercialization in the USA in 1995. Modern biotechnology has been developed since the 1970s, when gene-splicing and the transfer of genetic material into bacteria were achieved. Despite the dominant 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.

Likewise, a fundamental characteristic of these new technologies which is often pointed out as a major novelty, is the intensive use of large quantities of data and data-processing capacity, even in areas that are not strictly digital, such as genetic engineering and synthetic biology. However, this aspect also seems to be more a continuation of a trajectory of the ICTs than a brand-new revolution. Indeed, data processing has been important at least since the 1950s, although the volume of data used has grown exponentially in the last decades.[6]

Much has been made of the rapid increase in the power of computers in production in the last couple of decades – the dawn of the 4IR, according to some views. And indeed the increase has been impressive From 1993 to 2011, processing power increased by more than three orders of magnitude. In 2016, China launched a supercomputer 40 times more powerful than the fastest computer of 2010. More recently, quantum computing has been shown to be able to take computational power to another level, and image processing has advanced with the development of Graphic Processing Units (GPUs). Moreover, this processing capacity has become increasingly outsourced. Cloud computing platforms have appeared, allowing virtually any firm to access the processing and the storage capacities necessary for advanced data analytics (MGI, 2016).

Although this trend is indeed impressive, with potentially enormous impacts, in terms of its technical base it does not represent a rupture with the past. Since the emergence of digital technologies in the 1950s, the basic trajectory has been a rapid increase in processing power and data usage. The best example of this is the famous Moore’s Law, a prediction made in 1965 by then Intel’s CEO, Gordon E. Moore, that processing power would double about every two years – a promise which has roughly kept its explicative

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[6] Only in the US, it went from 3 exabytes in 1986 to 300 exabytes in 2011, to more than 2,000 exabytes in 2016. Besides the volume, the diversity of data has also grown. Great part of the recently available data is in the form of clicks, images, text, videos, and signs of many types (MGI, 2016).

power until today. The recent developments, in that sense, seem to be a continuation of this trend, instead of a major discontinuity.

4IR technologies, therefore, have a long history, and in many aspects seem to be the result of an 'evolutionary transition' that triggers several processes of speciation within and across sectors, rather than a 'revolutionary disruption'. However, this is not to say that there is nothing new about the 4IR. There is a truly revolutionary character to it which is the *technological fusion*[7]. This concept was originally introduced by Kodama (1986) to define mechatronics as resulting from the technology fusion of electronics and mechanical engineering capabilities. No and Park (2010) have later explored another case of technology fusion by focusing on 'nanobiotechnologies' and providing a measure of the degree of cross-disciplinary technology. Marsh (2012) focused on technological convergence between several fields of knowledge – the nano-bio-info-cogno (NBIC) technologies. Finally, Kodama and Shibata (2017) have more recently looked back at the development trajectory of the Japanese machine tools industry and observed several technological shifts, including new models of open innovation and digital convergence.

Combining different technologies is, of course, not a new phenomenon. Technology has always worked in systems, often with technologies from different origins. However, it seems that in the 4IR context systems are reaching a new level of complexity and interdependency between traditionally separate and specialized fields of knowledge. This increasingly high level of technology fusion requires the interaction between many different actors for their development and application and makes the building of 'ecosystems' of actors working in networks (instead of chains), generally within a unifying digital platform, increasingly important.

Given this continuity in the scientific and the technical bases of even the most seemingly 'radical' or 'revolutionary' technologies, the importance of developing foundational capabilities cannot be over-emphasised. Also, if the truly revolutionary nature of 4IR is not represented by each technology individually, but rather by their fusion and their interaction across the physical, digital and biological domains, then the foundational capability threshold that the developing countries have to reach is particularly high. This is because several processes have to be managed at the same time. First, both general and sector-specific foundational capabilities need to be built up. Second, once a number of sector-specific foundational capabilities have been built, leapfrogging opportunities need to be identified. Finally, emerging technologies and their fusion within and across sectors

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[7] We use the term 'technological fusion' and not 'technological convergence', as the latter has been used to refer to a number of different things, making it very imprecise and confusing. It has been used by authors in the history of technology to refer to a process where several industries start using similar technologies (e.g. metal cutting, welding, measurements and control instruments, computer aided design and manufacture, software applications, etc.) (Rosenberg, 1963; Pavitt, 2003). It has also been used to refer to 'digital convergence', i.e. the trend that different functionalities, such as telecommunications, broadcasting, and computing are merging in a single 'platform' – a computer, or a smartphone (Collins, 1998). A third meaning is used by authors that use patent data to identify the 'merging and overlapping of technologies' involved in innovations (see Geum et al., 2012). This 'merging and overlapping' of technologies is what we mean by 'technological fusion', so we use it, instead of the nebulous concept of 'technological convergence'.

have to be managed. Managing each of these is challenging enough but managing them together is even more so.

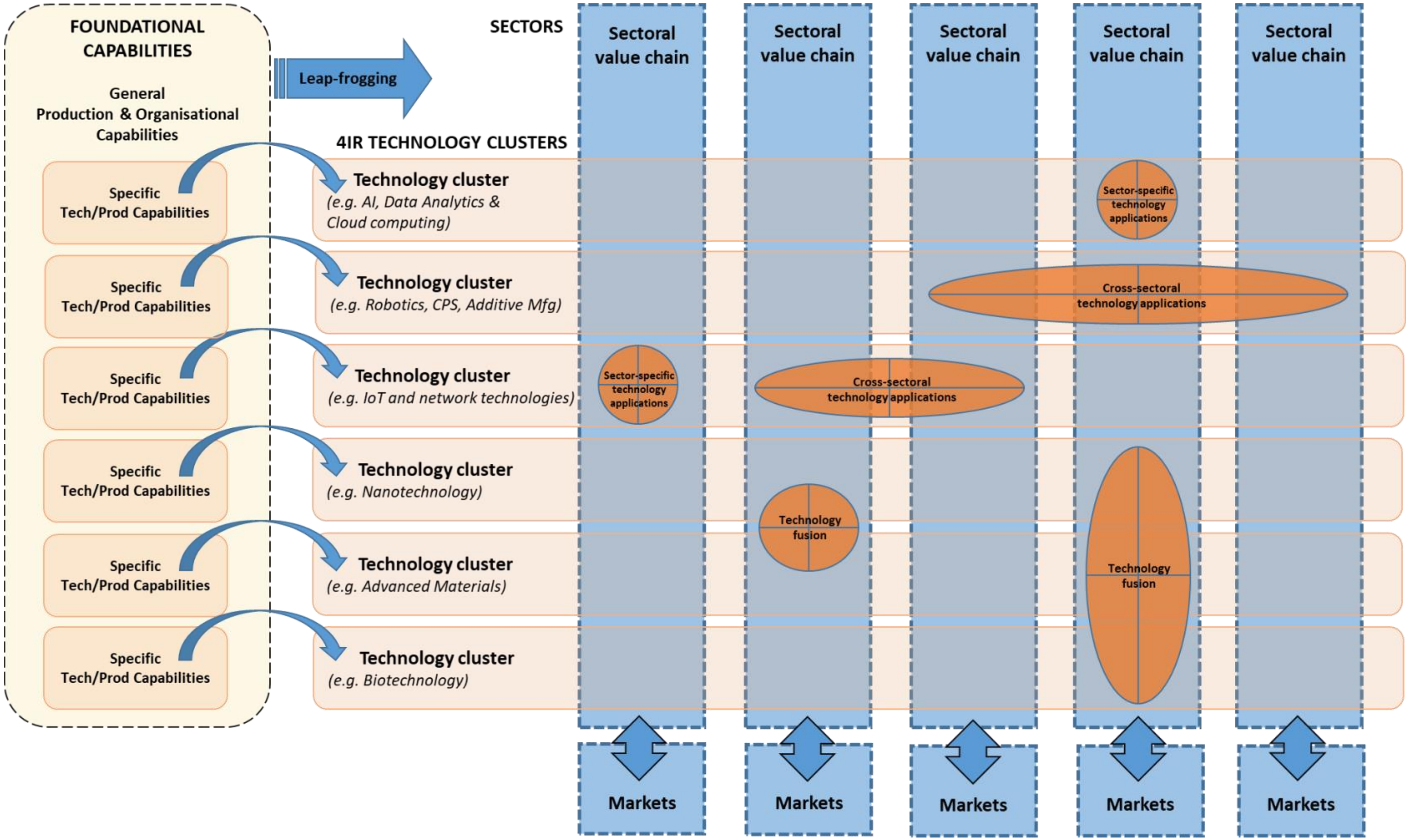
3. Digital industrialisation: A multi-staged multi-layered framework and evidence

3.1 Framework

The concepts of ‘foundational capabilities’ – both general and sector-specific – and ‘technology fusion’ provide two building blocks to assess the new challenges and opportunities of 4IR in the specific context of developing countries. Specifically, we have highlighted how in the early and the gradual catch-up phases, developing countries should focus on building up those foundational capabilities, which can open the way to several evolutionary transition pathways into 4IR (forging ahead phase). Without these foundational capabilities, individual 4IR technologies cannot be effectively absorbed and deployed. The lack of these capabilities also makes it difficult to exploit the opportunities offered by technology fusion, which requires linking different technology clusters and domains by leveraging closely complementary but dissimilar capabilities.

Building on these two concepts – foundational capabilities and technology fusion – Table 1 provides a multi-staged and multi-layered analytical framework to unpack the opportunities and the challenges of digital industrialisation in developing countries. It is multi-staged because there's a first stage of "foundational capability building" and a second stage of "leapfrogging"; and it is multi-layered because there are multiple technological layers that are "fusing". This framework highlights a number of important analytical issues.

Table 1: Digital industrialisation framework



Source: Authors

First, many 4IR technology clusters are ‘platform technologies’, that is, they can be deployed across different sectoral value chains (Sturgeon, 2017; Andreoni, 2018). For example, the use of sensors to collect data or artificial intelligence (AI) for data analytics, find application across many sectors. At the same time, in each sectoral value chain, the same technology platforms will be used according to different parameters and standards, that is, these 4IR technologies will find sector-specific applications. For example, sensors are widely used in aerospace, automotive, machine tools, but in each of these sectors the type of sensors and technology parameters are different. This means that, while 4IR technology are platform technologies, sector-specific applications still matters.

Second, technology fusion operates at the interface of two or more technology clusters and thus can result in both sector-specific and cross-sectoral applications. For example, IoT is based on the combination of sensors and actuators, connectivity devices, network technologies, cloud computing and AI; modern biotechnology often combines genetics with sensors and data analytics, etc.. These technology fusion processes combining new sensors, connectivity devices, cloud computing and complex algorithms of AI are responsible for the real transformation we observe in productive organisations, sectoral value chains and the overall industrial ecosystem. And these transformations are both sector-specific and cross-sectoral. For example, the technology fusion resulting in increasingly autonomous and intelligent machines and systems creates evolutionary transitions in virtually every sector: agriculture (precision agriculture), mining and extraction (autonomous drills and rigs), manufacturing (smart manufacturing, smart factories, smart products), and services (precision medicine, automation of tasks that require image recognition, language understanding, text creation, etc.).

Third, the impacts of new digital technologies in industry goes beyond production in the narrow sense, generating changes also in the way firms are interacting with one another and with their consumers and workers. In other words, big transformations are happening through the digitalization of the market in addition to the shop floor. The main innovation in this sense is the increasing use of online digital platforms as a way of connecting supply and demand (Teece, 2018). These platforms can be used for the connection of consumers with services but can also be used by producers to access resources, services and labour. Examples of the former include Airbnb connecting travellers with hosts and Uber connecting people seeking transport with drivers. Examples of the latter include cloud computing platforms for consumers and digital labour platforms (e.g., Upwork, a platform connecting freelancers with each other and with companies, and Amazon’s Mechanical Turk, a crowdsourcing marketplace for outsourcing processes and jobs to a distributed workforce who can perform these tasks virtually).

This closer interaction with consumers is also intensified by the fact that increasingly products are equipped with sensors and internet connection, giving companies the ability to receive feedback of their use and provide “pay as you go” services, or to update services based on real-time monitoring of the products and specific consumer needs (OECD, 2017). Moreover, the use of increasingly flexible manufacturing processes, such as additive manufacturing, makes the customization of physical products easier. In general, it seems to be a further deepening of the century-long process of division of labour and specialization in industries where the specific needs of the consumers are central. Some authors call this new regime mass-customization (Bianchi and Labory, 2018; Marsh, 2012).

Drawing on several studies on developing countries (IEL, 2017; OECD, 2017; UNIDO, 2020), we populate our multi-staged and multi-layered framework with detailed evidence on a selection of six main technology clusters of 4IR (section 3.2), several instances of technology fusions occurring at the sectoral and cross-sectoral levels (section 3.3) and sector specific applications of 4IR technologies (section 3.4).

3.2 Evidence on Technology clusters

4IR technologies can be grouped in 6 main technology clusters: Artificial Intelligence, data analytics and cloud computing; IoT and network technologies; Robotics, cyber-physical systems and additive manufacturing; Advanced materials; Nanotechnology; and Biotechnology. It is important to note that the boundaries between these clusters are fuzzy, especially given that they are increasingly being fused in technological systems. The descriptions below are based on IEL (2017).

Artificial Intelligence, data analytics and cloud computing

AI is a field of science and a set of computational technologies inspired by the human nervous system aimed at substituting for human cognitive functions, such as learning and problem solving. Its recent advancement is associated with the greater availability of large volumes of data, advancements in mathematical algorithms, and the existence of more powerful computational processing capacity. The main disruptive innovations in the field are machine learning algorithms, natural language processing, image recognition, and big data analytics. Cloud computing offers decentralization of data processing and of storage capacity to external providers, reducing the need to have these capacities internalized to every firm or individual.

IoT and network technologies

IoT is a development of the concept of machine-to-machine connectivity (M2M), expanding it to many types of objects – from industrial machinery, to consumer goods such as accessories and household appliances, to infrastructural equipment such as lampposts and traffic lights - that communicate and interact among themselves. These communications and interactions are done through systems of sensors, actuators (components of machines responsible for moving and controlling a mechanism or system, e.g. opening a valve), controllers, and software embedded in machines, equipment, packages, etc.. These systems generate and analyse data, producing autonomous (without human interference) actions.. Network technologies are the infrastructure that sew all these technologies together, enabling the stable, reliable and low-latency (minimal delay) transmission of data – a key aspect for the adequate operation of these autonomous systems.

Advanced Robotics, Cyber-Physical Systems (CPS), and additive manufacturing

Although these technologies are fundamentally different from each other, we group them together as they are the main enablers of what is commonly being called Smart and

Connected Production, or the Smart Factory. This refers to a new architecture of production based on machines with connectivity and cognitive functions, enabling a higher level of interaction between the physical and the virtual worlds. Advanced robotics refers to a new trend in robotics to develop increasingly autonomous and collaborative robots, that is, robots that can work with one another and even learn from one another (given that they are equipped with machine learning functions). CPS is an evolution of flexible automation, characterized by machines and robots that can be programmed (or reprogrammed) to process different products or product designs in a short timeframe. The main feature of CPS is that all constituent elements of the production chain (machines, suppliers, clients, etc.) are digitally connected and remotely accessible, through what is sometimes known as their "digital twins", giving rise to a highly integrated value chain. Additive manufacturing, also known as 3D printing, is an emerging paradigm substituting traditional subtractive processes in industry (cutting, smelting, welding, etc.) by additive layer-by-layer processes, enabled by the development of high-precision 3D printers. These processes have the advantage of being faster as it requires fewer and easier steps, done entirely by the printer and with less material – although the production of the starting materials can be a complicated process and may require advanced materials.

Advanced materials

Advanced materials are new or modified materials that show superior performance in one or more characteristics critical for its application. The main innovations in materials are: (i) Nanomaterials: 2D Materials (graphene, molybdenum disulphide, tungsten dissulfide, montmorillonite), carbon nanotubes, and polymeric nanocomposites; (ii) Self recovering and/or functional materials: carbon-glass self-recovering composites (materials with the capacity of stopping the spread of cracks), thermo-reversible polymers, materials for controlled release (of drugs, cosmetics, defensives and nutrients), thermo-sensors, radiation and contamination sensors, materials for printed electronics (conducive polymers), bio-inspired textiles, and bio-glasses; iii) High-resistance materials: vitreous metals, light alloys of high mechanical and thermal resistance, monolithic thermal isolating ceramics (aerogels), light materials for ballistic protection, 3D printing materials (metals, polymers, ceramics, composites), advanced structural materials (composites, rigid expanded materials), materials for the coating of buildings (photovoltaic, polymers, fibre cement), and high-resistance glasses; (iv) Materials from renewable sources and biorefinery[8] products: polymeric blends with biopolymers, nanocellulose, furan, glycerol, oil-chemicals, lignin, pectin, fusel oil, silica, waxes, , green carbon fibre, biopolymers (tissue regeneration, biodegradables, scaffolds, etc.); (v) Rare earths: compounds and alloys with rare earths for application in permanent magnets of elevated energetical product (applications in batteries, electrical and hybrid vehicles).

Nanotechnology

Nanotechnology deals with matter at the nanoscopic scale (less than 100 nano-meters). The recent disruptive innovations in this area relate to flexible and wearable devices, sensoring for IoT, nanotechnology for energy (e.g. energy storage), nanotechnology for

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[8] Biorefinery refers to the production of energy and materials from biomass

food, nanomedicine and nanocosmetics, nanoelectronics, and new advanced materials (treated separately above).

Biotechnology

Modern biotechnology emerged with genetic engineering and the sequencing of the human genome in 2001. Simultaneous developments in bioinformatics (combination of biology, computer science, information engineering, mathematics, and statistics to analyse and interpret biological data), microchemistry (the branch of chemistry dealing with minute quantities of substances), and new materials have permitted the evaluation of the genome responses to the environment and the changes in these responses in sick organisms. Also, the convergence between biology and engineering has been enabling the building of artificial biological systems for research, engineering and medical applications – known as synthetic biology. Advances are also being made in bioprocesses, that is, reactions involving living organisms, such as bacteria or yeast.

3.3 Evidence on Technology fusion and its applications

Although the applications of technologies are sector- (and sometimes firm-) specific, there are some technology fusion processes resulting in combinations of 4IR technologies that have general applications for a wide array of sectors. These general applications of 4IR technologies can be divided into four categories: R&D/design/pre-manufacturing innovations; process innovations; product innovations; and supply chain management/business model innovations.

Applications in the R&D, design and pre-manufacturing stage refer to the virtualization of the product development stage by using virtual/augmented reality technologies, or by enhanced modelling and experimentation processes using AI and big data analytics. By producing complex parts and components in a short time, 3D printing also enables much faster prototyping, which accelerates product development and time-to-market. 4IR technologies can also enhance prospecting activities in extractive industries by enhanced image recognition and data treatment. They can also speed up certification systems of new drugs and chemicals, and also of new vehicle components and embedded systems (e.g. new aircraft autonomous piloting systems). This is enabled by enhancing test-conditions and test reliability – e.g. by improved screening of volunteers in clinical trials for new drugs, or by improved simulation and modelling of vehicles.

The impact of the technological fusion in industrial processes can be summarized in one expression: Smart and Connected Production. This refers to the widespread use of sensors and actuators (IoT), AI, cloud computing, advanced and collaborative robotics, CPS, additive manufacturing, and network technologies that sew all these together. This enables predictive maintenance of equipment and systems, lower energy and materials uses, enhanced tracking and monitoring of processes, improved processes control (temperature, vibrations, deformations, etc.), improved quality control, higher yields in chemical processes, and many other applications.

Regarding product innovations, these inevitably involve very sector-specific applications. However, a generalization that can be made concerns the development of smart and connected products, that is, products with embedded connectivity and analytics functions, from smart wearables (clothes, watches, glasses), to smart household appliances, and smart and connected vehicles (cars, aircrafts, drones, tractors, etc.). These require not only digital technologies but often also nanotechnology solutions and advanced materials. Another general trend in 4IR-enabled products is the possibility of highly customized products. These range from 3D printed clothes to the highly customized drugs of the "precision medicine" model, based on advanced biotechnology. New bioprocesses, which are intensive in computing and data analytics, are also creating new products in the chemical, pharmaceutical, food, and basic-inputs industries.

Finally, there are several applications of 4IR technologies in supply-chain management and new business models. A key point here is the enhanced capacity of tracking and monitoring products both upstream (requested raw materials or components) and downstream (final product delivery to the consumer, and product disposal). This can lead to better stock management, and to the next step in the just-in-time paradigm, as 4IR technologies enable real-time demand monitoring. Product monitoring continues after sale, creating opportunities for complementary services, and intensifying the process of blending between manufacturing and services, where companies increasingly sell a combination of both (a process also known as servitization of manufacturing). 4IR technologies also enable processes of disintermediation, especially with the rise of electronic platforms of commercialization, where customers are able to access multiple suppliers (and suppliers to access multiple buyers) and find the best combination of cost, quality, and delivery speed. Finally, decision-making can be significantly improved in most sectors with the use of insights originating from business-related data analytics.

3.4 Evidence on Sector-specific applications

The applications discussed above are very general and could be applied to almost all sectors. There are, however, important sectoral differences in terms both of individual 4IR clusters and of combinations of them. Let us now have a brief look at the main applications of 4IR technologies in 10 sectors, which will be further described in Table 2 at the end of this section.

Agroindustry

Regarding the agroindustry sector, large impacts are occurring in agriculture, with the development of autonomous agricultural machines and of the "precision agriculture" concept - the calibration of inputs to the specific conditions of each location, enabled by sensors, drones, and climate information systems. Precision agriculture still faces lots of barriers, including the low infrastructural development in rural areas and the low digital literacy of farmers (especially older ones), but it is already giving rise to collaborations between input developers and information system controllers (e.g. Monsanto acquiring farm information system providers and agricultural machinery producers John Deere, CNH and AGCO acquiring drone companies).

Another important sectoral application of 4IR technologies is the electronic traceability of products, improving supply chain management and reducing waste, especially in the perishable foods segment. This is especially challenging for large traders, for which integrated digitalization strategies are more complex.

Yet another important area is the application of bioprocesses and synthetic biology (combining CRISPR/Cas9 techniques with big data analytics) for producing either agronomic inputs (seeds, fertilizers) or food.

The packaging segment is also under transformation with nanotechnology applications to create packages that seal the entry of oxygen (extending the shelf-life of products), or with nano-sensors that detect the presence of bacteria and alert when the food is beginning to rot.

Finally, an IoT-enabled application that may create some business model transformations is the development of the Smart Home and Smart Kitchen concepts – keeping track of the food inventory at home, identification of rotten food, diet control measures, remote meal preparation, etc.. The use of digital platforms for commercialization of food products (e.g. Amazon's acquisition of Whole Foods in 2017) is a growing trend and might open opportunities for new entrants in this sector.

Aerospace and Defence (A&D)

The A&D industry seems to be lagging behind other sectors, such as automotive and electronics, in terms of automation. This relates to the nature of the sector, which operates with much smaller scale of production, with components and processes of extremely high complexity, and with very rigorous safety regulations. However, exactly because of these characteristics, 3D printing of complex parts and components has been playing an important role in the sector. In the aircraft segment, specific applications include AI applied to autonomous piloting, advanced pilot assistance systems, enhanced aircraft monitoring, electrical aircrafts (in the light aircrafts sub-segment), and new, lighter and more resistant materials. A developing concept that fuses all technological clusters is the "hybrid aircraft" (see Table 3.1 below). The drone segment is probably one of the most affected by the fusion of 4IR technologies and may, in the medium to long term, lead to a new segment of Urban Autonomous Aerial Vehicles. In the military weapons segment, enhanced navigation systems and advanced image recognition and treatment are further developing smart weapons (e.g. smart missiles). In the space segment, enhanced embedded systems for satellites can lead to the enhanced image treatment and recognition of earth-monitoring systems. Also, the trend for miniaturized satellites can open opportunities in the small-sized launching vehicles (carrier rockets used to carry spacecrafts to space) segment. Impacts are also expected in improving systems of systems, such as air traffic control, or the command, control, communication and information systems (C3IS) of the military.

Automotive

The automotive industry, given its tradition of using advanced robotics and automation systems, is the leading the use of 4IR technologies. In addition to the general applications described above, the sector is also in turmoil, with three major new trends: electric vehicles, the “connected car”, and the autonomous car. Regarding electrical vehicles, the main issues are the uncertainties related to batteries (its cost, performance, and safety), market demand, infrastructure (e.g., energy supply, charging stations), and the dominant design that will emerge (pure electric, hybrid, etc.). These, however, are being mitigated by the emerging strong consensus that the future is in electrification. The “connected car” is also being developed, creating many opportunities for new businesses. This concept refers to a vehicle with multiple internet connections – whether for leisure (music, entertainment, internet browsers), for navigation and driving support (GPS and others), or for services (maintenance, parts ordering). The autonomous vehicle, in turn, is surrounded by several uncertainties, technological, regulatory and market-related, and the prospect for its diffusion seems very limited in the short to medium term. In addition, some new 4IR-technology-enabled business models, such as car-sharing, may redefine the use of cars in the future.

Basic inputs

The basic inputs sector, which includes metallurgy, cement, ceramics, glass, and pulp and paper, is a technologically mature sector, with high barriers to entry and exit, due to scale requirements. Its industrial structures are homogeneous oligopolies of often very old companies. For this reason, there is a low diffusion of 4IR technologies in this sector. However, the diffusion is expected to grow considerably in the next decade, especially because the investment requirements for digitalization are relatively small when compared to the standard investments required in this sector. Specific applications include enhanced quality control of processes and products, and possibly new products, such as new metallic alloys and nanostructured materials. In general, however, 4IR trends are not strong enough to change significantly the existing technological trajectories within the sector. The only exceptions might be the disintermediation trends in supply chain management, which might disrupt some current business models, and the development of new bioprocesses in the pulp and paper segment. Also, the increasing demand for batteries might have upstream impacts on this sector, especially in the demand for lithium and cobalt.

Capital goods

This sector is of particular interest, as it is both a large user of 4IR technologies and also its central developer, especially in the Robotics, CPS and additive manufacturing clusters. Expectations are very positive in this sector, driven not only by the new technological possibilities but also by the perception that there is a wide market to be explored, as Smart Production can be introduced in any productive activity with gains in efficiency, quality, and flexibility. The strongest trend in this sector is its fusion with the ICT sector (with many capital goods companies acquiring assets from this sector through mergers, acquisitions and international investments), such as in the development of smart machine-tools, smart vehicles (autonomous tractors, harvesters, sowers, drilling machines, underwater vehicles, etc.), and equipment for energy generation, transmission and distribution adapted to the smart-grid concept.

Consumer goods

This sector encompasses the segments of household appliances (large: ovens, air conditioners, refrigerators, washing machines, microwave ovens, etc.; and portable: vacuum cleaners, blenders, mixers, coffee machines, electric irons, etc.) – or the durable segment – and textile, apparel and footwear – or the non-durable segment.

In the durables segment, the specific trends in this sector are the developments of smart household appliances (smart washing machine, smart refrigerator, smart coffee machine, etc.) and household robots.

In the non-durables segment, the strongest trend is in the developments of smart wearables (clothes, watches, glasses, etc.) and smart textiles (e-textiles, smart fabrics, functional fabrics). These not only require advanced digital technologies but also the use of nanotechnology and advanced materials. 3D printing has also been having a strong (and possibly disruptive) impact on the production process and business models of many companies in this segment. Experimental projects depart completely from traditional production processes by doing without threads, needles or sewing, and reducing the traditional textile production to a single step through 3D printing (e.g. Electroloom, Continuum, Materialise). Another growing trend is the development of digital platforms where consumers can customize and create their own tailored clothes from digital files (e.g. Open Knit).

Chemicals

In the chemical industry, by its own nature, digital technologies are less prominent, in comparison with the other 4IR technological clusters (advanced materials, nanotechnology, biotechnology). This, however, has been changing, and many companies, especially in the developed countries, are now under a digital transformation process, where production is being transformed by the use of large amounts of data that used to be discarded. The exploration of these data can increase reaction yields, reduce energy consumption, enhance the health, security and environmental (HSE) management, etc.. Data can also be used in R&D, where advanced analytics and machine learning enable simulating experiments and optimizing choices on which research paths to follow. The main gains come from reduced time for R&D because many ‘experiments’ can be done mathematically, which means that the research can be focused on a fewer alternatives, including some new alternatives that could not be picked up without ‘virtual experiments’. There are also opportunities for new business models, especially in the provision of complementary services jointly with traditional products, in which producers keep connected to the product after the sale. This would enable, for example, selling a service based on performance parameters and not products (e.g. Ecolab/Nalco offers a water treatment solution in the real-time connected format, instead of just selling a product). This change in business models can be disruptive, as companies need to be able to gather and integrate a vast amount of data and to extract valuable information from them. Also, within the chemical industry, there is a new segment, the bioeconomy segment, which includes a set of innovating activities regarding the production and the utilization of renewable biological resources. This segment is still being structured, with the prevalence of innovation-oriented competition. As a result, it is characterised by a high level of uncertainty, creating opportunities for new entrants, especially those that have bio-resources available, which is the case of many developing countries.

Information and Communication Technologies (ICTs)

This sector, like the Capital Goods sector, has a two-fold importance in the 4IR, as a dynamic user of various technologies and as the heart of the generation of new technologies that have general applications. In the microelectronic components segment, there are two main trends, one driven by IoT and the other driven by advanced technologies of data storage, treatment and analysis.

The big innovations driven by IoT are in the projects of electronic products as a whole. As IoT is the integration of electronic components to traditionally unconnected objects, innovations are required in the design and packaging of the components, and in the adaptation of their physical interface to the object in question. These innovations enable a unique synergy between companies that possess design and electronics packaging know-how and new companies of ICT services enabled by IoT. It is interesting to note that these innovations in IoT do not depend on the cutting-edge processing technologies. Their focus is on solving design and adaptation problems, and not on pushing the frontier of processing power.

The innovations driven by technologies of data storage, treatment and analysis are of the “more-Moore” type, that is, they require increases in processing capacity (following the Moore’s law – see above). They are the ones to benefit from advances in microprocessors, such as the evolution to 5nm to 6nm CMOS (complementary metal-oxide-semiconductor – a class of integrated circuits).

In the telecommunication equipment segment, the new trends are in the growing importance of data centres and new network technologies, such as: (i) software-defined networks (SDN) – a technology that allows the administrator to control, personalize, alter, and manage a network without having to physically interconnect and organize it (ii) network function virtualization (NFV) – a network architecture concept that uses IT virtualization techniques to virtualize various network nodes, connecting them and creating communication services; and (iii) the continuing trend of substituting metallic cables for optic fibres. The increasing demand for data connectivity will also result in a strong demand for solutions of energy generation and storage.

In the software segment, there are many trajectories, the main ones being the increasing development of open software, due to the need to integrate different systems and platforms and the increasing focus on cybersecurity.

In the computer segment, a strong trend is on high-performance computers (HPC) for big data analytics, of which the most disruptive innovation is quantum computing, although it is still in a relatively early phase of development.

Oil and Gas

The activity of exploration and production (E&P) of oil and gas has been oriented towards non-conventional resources – shale gas, shale oil, and tight oil – especially in North America, and towards the exploration in deep and ultradeep waters, especially the pre-salt reserves in Brazil. In this context, especially in the deep-water exploration sub-segment, the specific impacts of 4IR are in the improvement of the prospection (better modelling and image recognition and image treatment of potential oil reserves), robotics for IMR (inspection, maintenance and repair), modular and hybrid systems, and autonomous underwater vehicles (AUV). The trend that stands out the most in this segment, however, is the growing expansion of equipment installed in the seabed (subsea equipment), which augments and multiplies units called "subsea factories". These solutions, initially aimed at the improvement of the interconnection of oil wells to the production systems, aim to reduce the weight and the space restriction of offshore platforms. The refining segment is also undergoing several structural transformations, with the application of smart manufacturing solutions for the optimization of processes, monitoring and management.

Pharmaceuticals

Demand-side changes, such as population ageing, improvements of standards of living in developing countries, the explosion of health expenditures in developed countries (and the ensuing budget constraints of national health systems) are increasing the pressure on technologies for improving the cost/effectiveness ratio of new drugs. On the supply side, advances in genomics, proteomics (large-scale study of proteomes – set of proteins in a particular organism, tissue or organ), bioinformatics, and biomarkers are close to enabling the concept of "precision" or "personalized" medicine as a general practice. With the development of biomarkers, the diagnostics, the biotechnology and the pharmaceutical industries are already converging with each other (a segment also known as Pharmacogenomics). Advances in the study of cellular systems should develop regenerative therapies. Akin to the chemicals industry, new bioprocesses are creating new pathways to producing drugs that might substitute old chemical processes or produce compounds that were not technically or economically viable before – opening opportunities for new entrants. Also, this is a highly R&D-intensive sector, dominated by large companies in each of its segments, with the average company investing 15% of its revenue in innovation. In this context, AI techniques, combined with the steep increase in computational power, can bring pharmaceutical R&D to a new level, accelerating drug discovery and reducing certification time by improving clinical trials.

Table 2 below describes the technology fusions and sectoral applications described above in greater detail. For every sector, examples of applications of each 4IR technology clusters are described, as well as the technology fusion potentials. What can be observed is that 4IR technologies have very specific applications in each sector, with impacts ranging from marginal to potentially disruptive. Also, the importance of the different clusters varies for each sector. This is particularly pronounced in the Biotechnology cluster, whose applications are focused mainly on the Agro, Chemical and Pharmaceutical industries. Another observation is that there are some technology fusions that can be applied to all sectors, such as virtualization of R&D processes, predictive maintenance, smart production and smart products. This allows us to think of 4IR technologies as general purpose technologies.

Table 2 – Sectoral applications based on the technological fusion potential of 4IR technology clusters

Aerospace and defence	Agroindustry	Automotive	Basic inputs	Capital goods	Chemical industry	Consumer goods	ICTs	Oil and Gas	Pharmaceuticals
Process innovations: Digitalization of machines and processes for monitoring, tracing parts and components, identification of trends and anomalies, predictive maintenance and optimization of aircraft production, and logistics enabled by IoT, AI and network technologies **Product innovations:** New aircraft projects such as the 'hybrid aircraft': combination of advanced materials (new metallic alloys, nanostructured composites), high complexity components produced with 3D printing, hybrid propulsion systems combining conventional or gas propulsion and electric propulsion, embedded digital technologies enabling detailed monitoring and optimal control of aircraft performance, and optimized operation and services (aircraft health management, automation and optimization of take-off, single pilot operation, etc.) Drones (UAVs): increasingly autonomous and collaborative, drones have a potential of application in several markets, such as defence (security and monitoring), civil (transport and delivery of cargo) or recreational. Developments within this sector can lead to a new segment of Urban Autonomous Aerial Vehicles, used for transportation within big cities. New miniaturized satellites that can operate in formation. Relatedly, new launching vehicles for miniaturized satellites	**Process innovations:** Precision agriculture Sensors for monitoring of various conditions: water levels, soil, weather, plant and herd health, aerial images from drones and satellites, and capital goods performance Automatic responses, such as intelligent irrigation systems and adaptations to meteorological conditions Predictive maintenance of tractors and equipment **Supply-chain management/ Business model innovations:** Traceability of products with electronic tags, real-time control of operations, and optimization of logistics of the supply chain, storage, and distribution. Increasing use of online commercialization platforms enabling demand monitoring in real time	**Process innovations:** Digitalization of machines and processes for monitoring, tracing parts and components, identification of trends and anomalies, predictive maintenance and optimization of automobile production and logistics with connected sensors, AI algorithms and network technologies **R&D process innovations:** Product development through virtualization technologies **Product innovations:** Connected car (short-term) and autonomous cars (long-term): convergence of advanced sensors (produced with nanotechnology), new battery technologies, AI algorithms and communication networks, with parts produced with 3D printing Electric (or hybrid) car	**Process innovations:** Identification of anomalies in equipment and predictive maintenance Traceability of products and components Improved quality control (e.g. detecting surface defects), reducing waste Reducing ramp-up time **Supply chain management/ Business model Innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Enhanced stock management Commercialization platforms with real time monitoring of requests Virtualization of business management systems	**Process innovations:** Identification of anomalies and predictive maintenance Improved quality and process control **R&D process innovations:** Product development through virtualization technologies **Product innovations:** Connected devices and machines with own processing and analytics capacity (agricultural machinery, machine tools, engines, etc.) Key machinery to enable Smart and Connected Production **Supply-chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Virtualization of business management systems Traceability of products and components	**Process innovations:** Identification of anomalies and predictive maintenance Increase reaction yields Reduce energy consumption Enhance health, security and environmental (HSE) management **Supply chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Improving processes of decision-making with data Electronic sales platforms Continued connection to the product after sale - trend of servitization (e.g. instead of selling products, selling services of water treatment, soil fertilizing, crop defence, catalysing, etc.)	**Process innovations:** Identification of anomalies and predictive maintenance Virtualization of business management systems Traceability of products and components **Product innovations:** Consumer robots (e.g. for the elderly and for deliveries) Smart and connected household appliances Smart wearables (smart textiles, smart fabrics, smart accessories) **R&D process innovations:** Product development through virtualization technologies **Supply-chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution)	**Process innovations:** Identification of anomalies and predictive maintenance **R&D process innovations:** Product development through virtualization technologies **Supply-chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Virtualization of business management systems Traceability of products and Components	**Process innovations:** Identification of anomalies and predictive maintenance of wells and drills In refining, optimization and control of flux in real time under uncertainty Green molecular design for high value-added products **R&D process innovations:** Innovations in prospection: sensors and AI for characterization of reservoirs (transformation of data in 3D images), enabling the reduction in dry oil well drilling (a large source of costs in the sector) **Supply-chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Virtualization of business management systems Traceability of products and components	**Process innovations:** Bioprocesses using genetically modified organisms Identification of anomalies and predictive maintenance **R&D process innovations:** Applications to early stage drug discovery, including speeding-up certification processes **Product innovations:** Precision (or personalized) medicine: Combination of genetic engineering, synthetic biology, AI, and pharmacogenomics to produce drugs adapted to the genotype of the individual Biosensors (and biomarkers), new materials for controlled release of drugs are also necessary **Supply-chain management/ Business model innovations:** Intelligent interconnection of the business chain (logistics, stock, supplies, distribution) Virtualization of business management systems Traceability of products and components

Source: Authors, based on IEL (2017)

4. Policy implications and relevance of 4IR technologies for different groups of developing countries

Since the first industrial revolution, industrial policies have always shaped and driven the transformation of the economy, particularly when the engagement with new technologies have required coordination and commitment of resources under uncertainty (Chang and Andreoni, 2020). Our paper has looked at the key technologies associated with 4IR, focusing on digital industrialisation, and looked at the available evidence regarding their developments and impacts. It has shown that the opportunities associated with 4IR technologies are very heterogenous, in some cases sector- and even process-specific. Therefore, countries will need very targeted industrial policies to capture these opportunities. On top of this, for countries at early stages of catching-up, foundational capabilities building is a pre-condition to enter the incremental and evolutionary transition process needed to join the 4IR.

Exactly because they don't understand the true nature of 4IR, most economists and policy pundits recommend to developing countries policies that are either vague – such as the development of 'digital skills' policy – or downright unrealistic – such as investments in futuristic technologies that are detached from the country's production structure. Our paper shows that, above all, developing countries must identify and incrementally develop those foundational capabilities, if they want to be part of 4IR. These capabilities will allow them to learn how to exploit newly-emerging technical and organisational solutions, integrate them into their production system (including retrofitting legacy systems), and mobilise and organise complementary capabilities needed to exploit the opportunities for technological fusion. But how to build these foundational capabilities? To a great extent, this has already been unravelled by the 'technological capabilities' literature in the 1990s (Lall, 1992; Bell and Pavitt, 1992). It is beyond the scope of this article to revise it here, but, as we have discussed in section 2.1, it involves a great deal of 'learning in production' and changes in individual skills, organizational structures, and institutions. A point we stress is that, despite a lot of recent rhetoric that the 4IR would require completely new and different policies, the 'old' recommendations of the capability building literature remain valid. The difference now is that because of technological fusion, the complexity of such capabilities is higher, thus the effort needed by countries is also higher. Once the foundational capabilities are in place, many policy options open for leapfrogging strategies.

As shown in Table 2, as the potential benefits of 4IR technologies differ significantly across industries, a number of industries could be the targets of industrial policy. It must be highlighted that opportunities exist not only in high-tech 'frontier' sectors typical of developed countries, but also in sectors that are typical of the production structure of developing countries, such as farming and agroindustry, extractive industries, and labour-intensive industries such as textiles and apparel.

Our analysis shows that different industries will play different roles in the unfolding of 4IR and therefore industrial policy towards different industries needs to be designed accordingly. It is widely recognised that some of them – machine tool industry, for example – will play a key role in 'technology push'. Less well recognised is the 'demand pull' role that some other industries can play. For example, the application of manufacturing principles to agricultural production could deliver dramatic productivity gains and better international market access, while creating the demand for a modern agricultural equipment industry. The enormous potential of digitalisation of mining could provide another significant demand-pull factor towards development of global leading mining equipment industries in countries like South Africa and several others in the Latin America continent.

The complexity that arises with technological fusion, and the different 'push' and 'pull' roles played by different sectors calls our attention to the different types of policies needed. For 'push' sectors (such as ICT and Capital Goods), policies aimed at facilitating the creation of ecosystems, bringing together traditionally separated actors, are needed for the adequate absorption and development of the knowledge bases of 4IR technologies. For 'pull' sectors, policies of technological diffusion are needed, aimed at reducing the costs associated with adopting 4IR technologies and reducing the uncertainty associated with new technological investments. The widespread adoption of these technologies is what will guarantee the demand for the 'push' sectors, and the interaction between the 'push' and 'pull' sectors can bring about sector-specific incremental innovations which, if properly incentivized, can lead to the emergence of specialized players adapted to the local needs. By making targeted investments at the intersection of these demand pull and technology push dynamics, developing countries can also manage to reduce their reliance (and related trade burden) on capital goods from advanced industrial economies. Investing in these intersections of emerging industrial ecosystems can be also a way of laterally entering those manufacturing industries where the capability threshold might be too high for many developing countries. The penetration by developing countries into the 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 are found and the right companies are supported.

Indeed, the capability challenges that developing countries face in their quest for industrialisation in the forthcoming age of 4IR are daunting, and much of productivity growth and value addition gains from 4IR technologies can only be achieved by engaging in specific processes and activities. Consequently, industrial policy in the 21st century will have to be more grounded in the reality of digital production technologies, smarter in climbing the technology ladder, and more agile in picking opportunities than it has typically been in developing countries.

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Annex

Table 3 – Sectoral applications of 4IR technology clusters

	Aerospace and defence	Agroindustry	Automotive
AI, data analytics and cloud computing	Data-analytics of aircrafts and embedded systems Enhanced image recognition and treatment for navigation, target recognition for smart weapons, earth-monitoring satellites and biometric systems used as security keys. Man-machine interface for pilots and passengers Autonomous piloting (for weapons, drones and aircrafts) AI for Command, control, communication and information systems (C3IS). Ex: Air traffic control In the space segment, incremental advances amply the capacity of current platforms and satellites especially the volume of data transmission using existing communication satellites	Deep learning for precision agriculture Machine learning in production Facial and body recognition of animals, allowing for health monitoring of cattle Machine learning in retail: Creating personalized products and diets	Advanced driving assistance systems (ADAS) Improved man-machine interface (e.g. voice commands) Support of information entertainment (“infotainment”)
Robotics, CPS and additive manufacturing	3D printing for complex aircraft components 3D printing for prototyping (e.g. Airbus THOR mini aircraft) Robotics for larger-scale productive units, specially in the Robots in military (robots for security and defence missions) and civilian applications (co-pilot bots)	Robots for classification of plant seedlings according to its growth potential Business intelligence tools applied to agriculture Autonomous platforms for precision agriculture Robots and drones for use in agriculture and for obtaining data of the farm	Advances in smart robotics in the assembly line
IoT and network technologies	Use of IoT in civilian aviation: Fuel, engine and system monitoring, aircraft tracing, baggage smart tagging, passenger identification token Use of IoT in military aviation: Integration of C3IS systems with intelligent weapons and air platforms Optic fibres in aircraft command systems Systems of civilian and military C3IS systems: higher capacity and security (advances in cryptography)	Stock optimization, with adjustment of production to demand (including changing crops in response to changes in consumption trends) Optimization of the use of inputs, defensives and seeds Optimization of environmental management and use of resources (energy, water, soil) Blockchain and QR technology for relationship with clients Data collecting, integration and coordination through wireless networks Mesh networking and Hop networking systems with the use of digital stations that function with repeaters	Protocol of wireless communication between vehicles (V2V) aimed at avoiding collisions
Nanotechnology	Satellites and launching vehicles: reducing size, weight and energy consumption, and embedded systems capable of processing and transmitting large volumes of information. 2D materials, such as graphene and other carbon-based ones, such as structural materials of high stiffness and resistance, for aircrafts and equipment (long-run changes) New batteries may allow conventional engines to be substituted by electrical ones in some segments. Nanoelectronics, especially for the drone segment.	Sensoring and control for precision agriculture Sensoring for quality control and compliance with international standards Nanomaterials and processes for improving food and packaging Food enhanced with nutrients and medicine, and nanofoods Smart packaging (including eatable ones), with better oxygen seal and nano-sensors that alert when the food is about to rot Improved electric batteries for tools and equipment	Hardware parts (including electronics) for autonomous cars High-performance composites and plastics Batteries, fuel cells for electrical propulsion, energy capture Omnipresent sensors Electrochromic windows and displays Painting Components and devices produced with 3D printing Rechargeable batteries and fuel cells for light vehicles Rechargeable high-density batteries for passenger vehicles Hydrogen fuel cells for passenger vehicles
Advanced materials	Light alloys reinforced with carbon nanotubes or high entropy materials Advanced structural materials Materials for ballistic protection with special attention for glass ceramics Systems with rare earths	Nanomaterials and functional materials for new smart packages High-performance functional materials for biodegradable packages, vegetable maturation retarders, transparent packages impermeable to gas and humidity	Electrical engines depend on advanced materials formed by metallic alloys that contain rare earths to achieve low weight and high-performance. New light and resistant materials like reinforced composites with carbon fibres New lighter metallic alloys
Biotechnology	Non applicable	Making plantations more resistant to pests and meteorological conditions	

		Adapting plants to specific soil and climate conditions Making plants resistant to pesticides Genetic manipulation of cattle (e.g. reducing age for slaughter) Increasing productivity of dairy herds Improving immunology of herds (especially important in poultry and swine farming) New food products and ingredients (non-GMO, healthier products)	

Table 3 – Sectoral applications of 4IR technology clusters (cont.)

	Basic inputs	Capital goods	Chemical industry	Consumer goods
AI, data analytics and cloud computing		AI for autonomous machine-tools, robots, vehicles, electric equipment of the smart-grid, etc.	Chemical product (inputs) personalization through big data analytics Deep learning for new product development (also GAN algorithms) to accelerate development and reduce costs of R&D Patent and publications analysis in the chemical field through PLN and deep learning GAN and neural networks to test new chemical molecular entities Virtual models of synthetic elements	Incorporation of AI solutions in traditional household equipment, such as physical exercise equipment, interactive games, smart kitchen apparel with voice recognition and natural language processing (NLP). Retail market: virtual search, personalized purchase recommendations, electronic wearables, chatbots (virtual shops) Many applications of machine learning in productive processes of consumer goods
Robotics, CPS and additive manufacturing	Supercomputers and drones with sensors capable of elaborating 3D maps of natural resources in real time Robotics for enhancing work safety. For example, metal baths can be carried out by robots.	More precise, faster, smaller scale, more energy efficient 3D printers that can operate with different materials Autonomous and collaborative robots	Use of 3D printing in the transformation of plastics Impacts upstream of the productive chain, with increases in demand for specific inputs Demand for development of specific intermediary products Robots for inspection in petrochemicals Robots for detection of leaks (improving safety in chemical and petrochemical industries)	Use of 3D printing for personalized consumer goods (e.g. Electroloom, Open Knit) Entirely 3D printed clothes (e.g. Bikini N12, Materialise)
IoT and network technologies		New demand of energy from external sources (energy harvesting) coming from IoT implies the development of specific generation, transmission and distribution (GTD) equipment. Generalization of the use of wireless communication protocols in machines and equipment Equipment compatible with the means and protocols of the “smart grid”	Information derived from clients helping understand the performance of the product in use	Networks used for monitoring of the product lifecycle, especially in durable household appliances, enabling new attributes to products and complementary services. Product traceability can also be important in non-durable goods (e.g. when there is a regulation in which the producer is liable for the disposal of the product) Incorporation of assistive technologies (e.g. assisting elderly people to take medication at the correct time), or washing machines with connected services of hygiene and cleaning products
Nanotechnology	Addition of nanoparticles to improve properties of steels and alloys Anticorrosion coating Composites	Sensors and components for smart tractors and machinery Miniature energy storage, autonomous functioning of portable electronic devices and networks of wireless sensors Micro-supercapacitors and nanobatteries for medical implants High density data storage	Green chemistry: Production of materials from less toxic, safer, biodegradable and profitable sources Nanoparticles synthetized from plants, microbes or other natural resources – applications in nanomedicine and cosmetics	Fabrics that repel water, oil and are resistant to crease Anti-flame fabrics Fabrics with bactericide, anti-odour, with UV protection Textile fabrics with more thermal stability, anti-statics, with microwave and electromagnetic attenuation

	Electrification and robotization of mining will increase the demand for new and more efficient batteries Batteries for mining in remote places Increasing production of batteries will increase the demand for lithium, cobalt, and other basic inputs	Fuel cells or nanostructured solids for efficient storage of hydrogen Nanophotonics for communications Production of vehicles and equipment with carbon-based ultra-hard nanomaterials Electric batteries for intelligent electric networks and for machinery	Energy-efficient reactions Processes that use water as a solvent Chemical industry can contribute for the development of solutions that potentialize electrochemical storage of energy (batteries)	Sensors of temperature, humidity and pressure incorporated in textile matrices New fashion with colours and textures obtained from nanomaterials Reduction of pollution caused by dyes Nanotechnology solutions for smart apparel With the diffusion of domestic robots, new portable devices, and IoT products, batteries of different sizes will be demanded
Advanced materials	New alloys for specific niches, such as high-performance light alloys with the addition of rare earths Durable goods industry may increase demand for polymers, composite materials and light alloys (substituting ferrous metals) Additive manufacturing will demand development of polymeric, ceramic, vitreous and metallic filaments of high-performance	Biorefinery capital goods: Equipment for biorefinery processes Equipment for the production and processing of the carbon nanotubes Systems for the fabrication of fibre textiles from new inputs like nanocellulose Equipment to produce carbon fibres and for the processing of rare earths and permanent magnets fabrication Equipment for processing materials with supercritical fluid (oil extraction, processing and biomass) High-power electrical motors that require rare earths GTD equipment: electrical motors will be increasingly employed in agricultural machinery and implements	Chemical inputs derived from renewable sources and products of the integrated biorefinery, like furan, oils, alcohols, pectin, etc. Other relevant technologies include biochemicals, bioplastics and other biopolymers Polymer materials for 3D printing	In durable goods, advanced materials should substitute metallic and plastic components, resulting in lighter and more resistant household appliances. In textiles and apparel, materials with nanoparticles for functional properties such as blocking UV radiation, fungicide and bactericide properties, insect repellent properties, etc.: Fabrics with special properties obtained through morphology and addition of nanoparticles Fabrics produced with nanocellulose, and synthetic functional fabrics combined with biopolymers (nanocellulose, chitosan)
Biotechnology	New bioprocesses in the Pulp and Paper segment	Non applicable	Advanced biology and synthetic biology Advanced bioprocesses can make fermentation, catalysis, and others, more efficient, and enable synthesis of new bioproducts from simple sugars. Biofuels and other bioproducts	There are potential applications of biotechnology, especially in the textile and apparel segment, but they are still in the scientific experiment phase: bio-fabrics, bio-fibres and bio-clothes.

Table 3 – Sectoral applications of 4IR technology clusters (cont.)

	ICTs	Oil and gas	Pharmaceuticals
AI, data analytics and cloud computing	Development (prototyping) of software of applications of machine learning and deep learning Development of applications for cybersecurity, for example, in anticipating cyber attacks Data analytics for personalization and customization of products Machine learning for auto-updating of software and correction of bugs New algorithms in a language that is compatible with sensors and actuators	Big data analytics for prospection geological models – improved characterization of reservoirs	Deep learning in the development of new drugs including GAN algorithms for accelerating development and reducing costs Analysis of patents, genomic data and publications in the life-sciences field though PLN and deep learning GAN and neural networks for testing new molecular entities that are candidates for new drugs Substitution of tradition in vitro HTS (high throughput screening) methods by totally in silico screenings. Advancing in this direction, AI systems could contribute in the selection of leading compounds that create the desired genetic expression. AI applications to image diagnosis Big data analytics of enormous amount of multimodal data generated by research and diagnostic platforms, health professionals and mobile systems worldwide. This includes image, phenotypical and clinical data.

Robotics, CPS and additive manufacturing	Advances in smart robotics in assembly lines	Autonomous underwater vehicles (AUV) to assist oceanographic research and E&P of oil and gas Increasing use of robots for inspection, maintenance and repair (IMR) and painting procedures Lighter and more compact equipment, with embedded electronics and intensive use of advanced materials will enable low cost production methods Subsea machinery / subsea factories, whose main goal is to reduce the weight over offshore plaftorms	
IoT and network technologies	Micro-controllers, sensors and actuators; microchips for embedded use; distributed processing capacity (cloud and fog computing) Among sensors, sensors based on semiconductors MEMS (Micro-Electro-Mechanical Systems) which require techniques and materials of nanotechnology Network technology for local processing, as well as for data transmission System on chips (SoCs) containing communication modules (generally wireless) and embedded sensors Increasing role of software in communication systems (Software defined networks – SDN; Network function virtualization – NFV)	Offshore production uses networks of optic fibres to connect platforms to the shore (submarine optic cables). Long distance communication networks compete with optic fibres in this application A new interesting is optic fibre sensors, which can detect alterations in the optic signal due to external conditions (pressure, temperature, seismic-acoustic vibrations, etc.) Use of optic fibres in the inspection of pipelines and E&P wells	Connected devices for medical/hospital use (e.g. diagnostics and monitoring) and patient use (continuous monitoring with preventive diagnostic) Traceability of products similar to the food industry Change in business models of pharmaceutical companies that would become "healthcare firms" Use of sensors and digital services in continued treatment Offering online orientations to patients in association with the medical class Possibility of collecting data from the field for clinical tests, monitoring of the performance of medicines, as well as new forms of managing the product cycle
Nanotechnology	Relevant contributions in all hardware sector of ICTs, such as: Electronic devices with components with 25nm or smaller Electronic circuits printed in different substrates and flexible electronics Printed photovoltaic cells generating electricity from solar light in windows or building walls Nano-electronic systems of medical diagnosis Electronic tattoos: monitoring of vital signs LEDs of large areas for illumination and nano-lasers (potentially disruptive) Omnipresent sensors for IoT (potentially disruptive) Batteries are fundamental for IoT and micro-electro-mechanical systems (MEMs), and to guarantee reliability and energetic security for large servers, including network back-ups	Sensors for monitoring the functioning of equipment and safety of extraction wells Increase in the oil exploring capacity with prospection studies of porous matter with magnetic resonance and other nanotechnology methods Nano-catalysers for oil refining Monitoring in real-time of emulsion characteristics Reduction in energy losses during production with intelligent systems Creation of new materials derived from oil (e.g. plastic industry) Use of new batteries for the electrification of large equipment Use of new batteries in remote areas	Bio-drugs: genetically modified microorganisms or cells Fitomedicines Drugs extracted from marine organisms Genic therapy: use of normal genes to substitute defective genes Photodynamic therapy, thermotherapy, immunotherapy Fighting super-resistant bacteria Controlled release of drugs Artificial organs, skin and tissue engineering The increasing use of nanorobots, prosthetics and autonomous organs (and other solutions based on microelectronic) will demand new batteries, often in nanoscopic scale
Advanced materials	Advanced materials compose parts of components of ICTs such as batteries and electronic circuits ICTs are necessary for the management and control of sophisticated productive systems of advanced materials. Graphene and carbon nanotubes have exceptional properties that will enable the fabrication of new devices Organic electronics involves conductive polymers, substrates and processes for fabrication of organic electronic circuits, such as the printed electronics – a technique that can enable the production of electronic circuits in large scale, with reduced costs, miniaturized and personalized, with application such as sensors, intelligent packages, screens, etc.	In deep waters, production is more dependent on flexible and stress-resistant materials, giving importance to: High-performance materials (metals, polymers and its nanocomposites and composites), with focus on the reduction of the cost of prospection. Flexible polymeric materials with high resistance to temperature and to chemical agents Drilling auxiliary materials – materials for completion of wells and other additives (biodegradables/green)	Sensoring systems and medical dosing, controlled release of drugs, preventive systems, tissues and films for therapies, etc.: Polymeric films and gels for controlled release of drugs Sensors, systems of ICT and materials for controlled dosage of medicine Active implants containing growth factors, anti-inflammatory, and others (bio-glass, bio-glass-ceramics and biopolymers) Active tissues and films (e.g. bactericide) for burns and long-term hospitalizations (bio-glass, bio-glass-ceramics, biopolymers) In the case of bio-drugs, some materials are considered strategic: Materials for controlled and/or localized release (blends, nanocomposites, fibres) Active materials: bio-glass and biopolymers
Biotechnology	Mainly upstream impacts: modern biotechnology is dependent of bioinformatics/e-Science (big data enabled medicine), including the use of IoT and sensors to monitor medical parameters and drug application	Non applicable	Diagnostics (through genomic markers) and specific prognostics to every patient type.

	Development of methods of bioinformatics and cost-performance of data processing (the biggest cost is not sequencing, but analysis of genomic data) Improving of algorithms for genomic analysis and its adaptation to clinical use Development of bio-databases		Specific drugs (new molecules) for each disease (e.g. subtypes of tumours, cardiovascular diseases) Cellular therapies: regenerative medicine, stem-cells and biomaterials Clinical trials, focused in the individual response and not on the average response to the therapy

Source: Authors, based on IEL (2017)