Identification of Fourth Industrial Revolution technologies using PATSTAT data

Working Paper Series

#2023-023

Identification of Fourth Industrial Revolution technologies using PATSTAT data

María de las Mercedes Menéndez, Önder Nomaler and Bart Verspagen

Published 2 June 2023

Maastricht Economic and social Research institute on Innovation and Technology (UNU-MERIT)
email: **info@merit.unu.edu** | website: **http://www.merit.unu.edu**

Boschstraat 24, 6211 AX Maastricht, The Netherlands
Tel: (31) (43) 388 44 00

UNU-MERIT Working Papers
ISSN 1871-9872

Maastricht Economic and social Research Institute on Innovation and Technology
UNU-MERIT | Maastricht University

Identification of Fourth Industrial Revolution technologies using PATSTAT data[*]

María de las Mercedes Menéndez[♠]

Önder Nomaler[♠]

Bart Verspagen[♣]

30 May 30, 2023

Abstract

This document provides a methodological procedure to identify the Fourth Industrial Revolution technologies using patent data. Attempts to distinguish these technologies have frequently relied on the European Patent Office (2017, 2020a) methods or have mainly leaned on technical codes and keyword classifications. Frequently, these studies have the limitation of collecting technologies arbitrarily and without a deep justification. Only the latest report from the European Patent Office (EPO, 2020b) attempts to detail the procedure to recognize the Fourth Industrial Revolution technologies. However, it does not offer the possibility of being replicated by scholars outside the organization. This article delivers a procedure to collect Fourth Industrial Revolution patents relying on key concepts from a detailed literature review - focused on whether they make up a new revolution and its conceptualization over time- and the EPO (2020b) report identification method. Subsequently, the evolution of these technologies and the principal trends are exposed. Finally, the search queries and the list of identified patents are available (in the Appendix) to replicate or adapt for other academic purposes.

Keywords: *Fourth Industrial Revolution*, *patents*, identifying patents on Fourth Industrial Revolution technologies
JEL Classification: O14, O30, O31, O33

---

[*] The work for this paper was financially supported by the ADB Institute. The views expressed and any remaining errors remain solely the responsibility of the authors.

[♠] UNU-MERIT, Boschstraat 24, 6211AX, Maastricht, The Netherlands.

[♠] UNU-MERIT, Boschstraat 24, 6211AX, Maastricht, The Netherlands.

[♣] Maastricht University and UNU-MERIT.

1. Introduction

The development of capitalist economies has been driven by "*constellations of innovations*"[2] that gave rise to different technological revolutions. In periods when these constellations start to become visible in the economy, they are labeled as "*revolutionary"* or "*emergent*" or "*disruptive*". This is also the case for the recent group of "*intelligent*" technologies popularly known as the Fourth Industrial Revolution (hereafter 4IR), which are commonly described to comprise, among others, artificial intelligence, robotics, additive manufacturing, and cloud computing.

Although the origin of 4IR technologies dates back to the mid-20th century, it was not until the last two decades that they became a central topic on the agendas of scholars and international organizations. The powerful integration of industrial and societal innovation that characterizes these technologies has already shown a great potential to transform the global economy in the medium and long term. This broad impact of 4IR technologies, in areas such as income distribution, employment and sustainability but also, for example, political decision making, has not only sparked the interest of numerous studies to identify cutting-edge 4IR technologies and their links but has also opened a wide academic debate on whether these innovations constitute a new technological revolution or represent the evolution of the previous ones.

Most of the early studies, as well as more recent research, have defined and identified 4IR technologies by directly linking them to transformations in industrial manufacturing, as a combination of several innovations, mainly in fields such as ICT, manufacturing and computing. This characterization has been closely linked to the possibilities offered by these technologies to promote a new industrial configuration, directly linked to the adoption of cyber-physical systems (hereafter CPS) in factories. However, several academics have highlighted that the transformations caused by these technologies go beyond the manufacturing sector, promoting the emergence of broader conceptualizations that envision the 4IR as a new phase in humankind characterized by the convergence of technological domains or as a new revolution led by the data exchange of millions of interconnected electronic devices across different technological domains. Despite the differences in conceptualizations, scholars agree that defining the 4IR and its technologies poses a set of challenges for several reasons, among which we highlight three. First, the ubiquity of 4IR technologies makes it difficult to associate them with a specific industry or sector. Second, there are various terms to refer to 4IR technologies and they are used interchangeably. Third, but not least, there is a lack of standardized agreement on the definition of 4IR and the technologies linked to this new revolution.

This paper provides a methodological procedure to identify 4IR technologies using patent data as the principal source. The identification collects several key concepts from a detailed literature review on 4IR technologies - focused on whether they constitute a new revolution and its conceptualization over time- and the latest methodological report of the European Patent Office (hereafter EPO) for the identification of 4IR technologies (EPO, 2020b). Data on patented

[2] The term "*constellation of innovations*" was introduced by Keirstead (1948) to refer to those technologies that are "*technically and economically interrelated*" (Freeman & Perez, 1988, pp. 46–47).

inventions stand out for their advantages in terms of their wide availability and, therefore, their potential for comparability between countries. One branch of the literature has identified 4IR technologies relying on the methodology proposed by the European Patent Office (hereafter EPO). EPO (2017, 2020a, 2020b) provide empirical attempts to develop a methodology for a broad identification of the 4IRs. Another branch of the literature has been in charge of developing other methods for their identification and has relied mainly on technical codes and keyword mining to select the technologies. In both branches of studies, we identify that, in several cases, the selection of technologies is arbitrary and only briefly justified, with the EPO (2020b) report standing out for detailing the procedures to recognize 4IR technologies. Specifically, this report includes a methodological annex with detailed information on the identification steps. Nevertheless, only internal EPO software can replicate the EPO methodology. This document fills this gap by proposing a method for identifying 4IR technologies that to an important extent builds on, and therefore closely resembles the EPO (2020b) procedure. However, where the procedure outlined in EPO (2020b) can only be reproduced using the internal EPO query service called EPOQUE, the method that we document here can be reproduced using commonly available SQL systems. Although we start from the EPO (2020b) baseline, we obtain a different set of patents, which to an important extent is caused by the fact that we do not use full-text patant data (which is not available in PATSTAT) and we use SQL instead of EPOQUE. Our identification procedure also leans on a detailed literature review about the conceptualization of the 4IR technologies over time. Finally, the search queries and the list of patents identified are available[3] for replicating or adapting for other academic purposes.

Our methodology for the identification of 4IR is based on two steps. In the first step, we outline our definition of 4IR technologies from a systemic and evolutionary perspective and give details about which are the innovations that comprise this revolution. In the second step, as in previous patent data studies, we identify the technologies mostly relying on technological codes and keyword selection for the period 2000-2019. We use the EPO-PATSTAT database as the main source to report on the outcomes of our proposed identification strategy.

Our identification assumes that 4IR technologies are co-evolving "*technology systems*" that combine innovations in digital data transmission, smart connected devices, computing, communication and connectivity technologies, which goes beyond the manufacturing sector and includes a wide variety of fields such as agriculture, health, home, infrastructure and services. The descriptive analysis of our data is consistent with the evolution of these technologies found in previous works (EPO, 2020a; Foster-McGregor et al., 2019). In this vein, 4IR technologies identified show a growing trend with a high specialization of these technologies mostly in developed countries and emerging economies, such as China. Globally, patent creation is concentrated in sub-fields such as connectivity, (smart) home, consumer goods and IT hardware. Our dataset verifies that only three countries (Korea, China and USA) present a comparative advantage in 4IR technologies creation. Simultaneously, the pattern of specialization of these three countries covers a wide range of subfields.

[3] See Appendix, A.3.

The paper is structured as follows. Section 2 splits into three parts. Section 2.1 briefly describes the challenges of defining and identifying 4IR technologies, whether or not they constitute a new revolution and how the conceptualization of these technologies has evolved, from transformations in the industry to the fusion of different technological domains with repercussions on the development of humankind. Section 2.2 explores the EPO's attempts to identify 4IR technologies through patent data and exposes alternative methods by scholars for technology identification. Section 2.3 drafts our conceptualization of 4IR technologies. Section 3 describes the 4IR patents identification procedure. Section 4 provides a descriptive analysis of the 4IR technologies dataset. Interested readers can perform a similar descriptive analysis on their own using the ADB-ADB Structural Transformation and Innovation dataset[4]. Finally, Section 5 presents the concluding remarks of the paper.

2. Literature review

Defining the 4IR and its technologies poses a set of challenges for several reasons. In the first place, because of their ubiquitous influence, these technologies are not linked to a specific sector or industry, which limits the possibilities of using existing categorization systems. Second, several terms are used interchangeably to refer to them. On the one hand, one finds terminology referring to the historical sequence of technological revolutions ("*4.0 industrial revolution technologies*" or "*Industry 4.0 technologies*"), while on the other hand, these technologies are referred to in reference to their content, e.g., "*smart manufacturing*" or "*cloud manufacturing*" technologies. In addition, some authors consider them simply as "*digital technologies*" or "*digital production technologies*", suggesting a broader definition that also includes important elements from previous technological revolutions. In the third place, there is a lack of standardized agreement on the precise set of technologies that make up 4IR[5], entailing difficulties when identifying them, analyzing their interlinks and considering their technological transfer. These problems may explain why the studies associated with the 4IR are still mostly prospective and therefore, usually denoted by uncertainty and speculation (Fagerberg & Verspagen, 2020). The following subsections aim to briefly survey the debate on the extent to which the 4IR constitutes a new technological revolution and how this new revolution and its technologies have been defined over time. The aim will be to contribute to a working definition of 4IR technologies and thus overcome some challenges mentioned above.

2.1 The 4IR and its technologies

2.1.1 Is the 4IR a new industrial revolution?

Capitalist development has taken place in the form of successive technological revolutions (Schumpeter, 1939). The long wave literature has contributed to the periodization of

[4] https://innovatransformation.adbi.org/innovation/innovation-in-emergent-technologies/

[5] Based on "brainstorm methods" among 11 scholars from several countries, Lee et al. (2018) argue that the 4IR could be defined according to the following key concepts: 1) Second IT revolution, 2) Major technological disruptions with digitalization, 3) Digital age with internet of Things or Industrial Internet, 4) IoT revolution, 5) Innovation based on Combinations, among others.

technological revolutions (Freeman & Louçã, 2002; von Tunzelmann, 1997). The current consensus[6] seems to be to identify three industrial revolutions until the end of the 20th century, each characterized by a "*constellation of interdependent technologies*" (Perez, 2010, p. 189) that transform production systems and foster the emergence of new products and industries (Nuvolari & Russo, 2021). Essentially, the First Industrial Revolution (1IR) was marked by the invention of the steam engine and empowered by mechanization. The Second Industrial Revolution (2IR), which took place from the last decade of the 19th century to the mid-1920s, was empowered by electricity, assembly and mass production. The Third Industrial Revolution (3IR) emerged in the last decades of the 20th century and was empowered by silicon electronic components, computing and the internet. The Fourth Industrial Revolution follows this sequence from the beginning of the 21st century.

The launch of the 4IR idea sparked an extended debate among researchers as to whether these technologies comprise a new industrial revolution or simply represent the evolution of the previous ones. For World Economic Forum (WEF) and its executive chairman, Klaus Schwab, the 4IR constitutes a new technological revolution, with a global scope that implies the transformation of complete systems and is distinguishable from the 3IR in terms of *velocity*, *scope*, and *systems impact* (Schwab, 2017). In terms of *velocity*, for Schwab, the 4IR technological change differs from the 3IR in that it evolves at an exponential and non-linear rate of progress that is linked to the interconnectedness of the world and the capabilities of technological change. Concerning scope, 4IR builds on 3IR technologies, but extends it in ways that are altering the way of what, how and who things are doing. About *systemic impact*, Schwab (2017) argues that 4IR involves deep transformations of entire systems, "across (and within) countries companies, industries and society as a whole" (p.3). Regarding this last characteristic, authors such as Andreoni et al. (2021) point out that the revolutionary character of 4IR seems to build on the combination and interaction of technologies across different fields. Other authors and organizations suggest that 4IR is not either the continuation of the ICT revolution nor its acceleration, and consider it as "a radical step towards a fully data-driven economy" (EPO, 2020a, p. 15). Another branch of studies considers the 4IR as a new trajectory into the Information and Communications Technologies (hereafter ICT) revolution (Fagerberg & Verspagen, 2020; Perez, 2016). Aligned with this approach, Kodama (2018) conceives this new revolution as the "cumulativeness of the innovations" (p.1) from the previous ones only differentiating in terms of the requiring technological learning modes[7] and strategies. Last but not least, Reischauer (2018) argues that 4IR reflects a policy-driven innovation discourse in manufacturing industries to institutionalize a Triple Helix innovation system.

[6] There is a debate in innovation studies about "dating of these 'revolutions', but also over their number and heterogeneity" (von Tunzelmann, 2003, p.370). For example, Freeman and Perez (1988), stick to a periodization based on Kondratieff cycles. This leads to five revolutions since around 1770: 1) Industrial Revolution, 2) Age of Steam and Railways, 3) Age of Steel and Electricity, 4) Age of Oil, Autos and Mass Production and 5) The ICT revolution.

[7] Kodama (2018) argues that the learning mode characteristic of the 4IR is the "learning by porting". The author defines "porting" as "an existing technology used for a different purpose into a new business model which is better than existing business models" (p.14) while "learning by porting" implies that the module is ported to other systems and is able to function in different architectures.

Other areas of studies have recognized "*discontinuities*" among the 4IR and the previous technological revolutions through the identification of General Purpose Technologies (GPTs) (Culot et al., 2020), e.g., the steam engine, electric motor and semiconductor. Each technological revolution has been led by GPTs characterized by their 1) pervasiveness, 2) the inherent potential for technical improvements and 3) 'innovational complementarities' (Bresnahan & Trajtenberg, 1995). Technologies like artificial intelligence (Crafts, 2021; Martinelli et al., 2021) and big data (Martinelli et al., 2021), deep learning (Klinger et al., 2018) present GPT characteristics, however, some works found inconclusive results in this regard (Venturini, 2022). Additionally, Teece (2018) considers that some 4IR technologies – such as artificial intelligence – are "*enabling technologies*" presenting characteristics as GPTs such as their high potential for technical improvements and their potential to generate new opportunities in other application sectors nevertheless, but they still lack of pervasiveness, or in other words, they have no worldwide effects, and may eventually evolve to GPTs.

Among the authors cited in the previous paragraphs, there is some agreement that 4IR technologies comprise innovations whose origin dates back to the 1950s, such as artificial intelligence, robotics, additive manufacturing and the internet of things (IoT) (Brixner et al., 2020; Ciarli et al., 2021; Martinelli et al., 2021). In this vein, a large number of existing studies in the innovation field have emphasized the evolutionary nature of the 4IR conceiving it as an "*evolutionary transition*" rather than a "*revolutionary disruption*" due to the coexistence of technologies that emerged in previous revolutions in it, especially under the 3IR (Andreoni & Anzolin, 2019; Kodama, 2018). Following Brynjolfsson & McAfee's (2014) categorization, the 3IR and 4IR might be catalogued as the "*second machine age*" led by the advances of computer and digital technologies empowered by the human brains marking a watershed with the "*first machine age*" fostered by the steam engine and empowered by mechanical power. In this line, Lee & Lee (2021) argue that some 4IR technologies, including artificial intelligence, might be considered as longer "*technological cycle time*" (TCT) technologies, while changes from 3IR are more "radical" and hence, they rely less on old technologies, showing a shorter TCT. In this vein, it is argued that 4IR technologies "are still evolving into new enabling technologies by convergence or mutual combination" (Culot et al., 2020, p. 5), at different rates and are not established in a specific trajectory yet (Ciarli et al., 2021), hence their development is deep in uncertainties.

2.1.2 Conceptualization of 4IR technologies over time

Despite the early origin of these technologies, it has been barely a decade since the term 4IR has been a prominent part of the research agendas of academia and international organizations. The 4IR and the transformations it entails, mainly in the industrial manufacturing sector, were put into vogue since the presentation of the German industrial strategy plan entitled "*Industrie 4.0*" at the Hanover Fair in 2011 by a group of researchers from the Research Union Economy-Science of the German Ministry of Education and Research. Essentially, the "*Industrie 4.0*" plan proposes a way of industrialization based on the introduction of the CPS into manufacturing production and hence, establishing a watershed with previous technological revolutions empowered by mechanization, electricity and ICT with the main aim to improve German domestic and global manufacturing competitiveness through "*smart factory*" (Kagermann et al., 2013).

Since the German industrial strategy plan, several attempts have been made to define "*Industry 4.0*" and identify its related technologies. Simultaneously, the "*Industry 4.0*" or "*smart factory*" terms have been used in several studies interchangeably with 4IR technologies, presenting limitations as they only acknowledge the technological innovations of manufacturing systems. In this vein, "Industry 4.0" could be understood "as an integrated, adopted, optimized, service-oriented, and interoperable manufacturing process which is correlate with algorithms, big data, and high technologies" (Lu, 2017, p. 3). Furthermore, scholars have made several attempts to determine the Industry 4.0 key concepts or components, among which are highlighted: *smart factory*, *CPS*, *self-organization*, *New systems in distribution and procurement*, *New systems in the development of products and services*, *Adaptation to human needs* and *Corporate Social Responsibility* (Lasi et al., 2014). Among these components, the most distinguishable characteristic of the 4IR is usually considered software development, represented by the CPS. The introduction of software in manufacturing production dates back to the 1970s and 1980s with the implementation of computer-aided design (CAD) and manufacturing (CAM) systems. CPS are formally defined as "transformative technologies for managing interconnected systems between its physical assets and the computational capabilities" (Baheti & Hill, 2011 as cited in Lee et al. 2015, p.18). Monostori et al. (2016) argue that these systems reflect the evolution of the different developments in computer science, ICT technologies and manufacturing science and technology that converge in the interaction between the virtual and physical systems. The synchronization among the physical and virtual spheres accepts novel ways of "control, surveillance, transparency and efficiency in the production process" (Hofmann & Rüsch, 2017, p. 25). The evolution of CPS and the Internet of Things allows not only a new form of decentralized and condensed production in the "*smart factory*" but has also been extended to impact consumption through "*smart products*" and lifestyles through the introduction of the "*smart city*", which implies in the three cases different exchanges between humans, machines and products.

The Industry 4.0 German manufacturing program boosted the development of similar manufacturing strategies linked to the expectation of a "*manufacturing renaissance*" (Culot et al., 2020, p. 1) such as the "*Advanced Manufacturing Partnership*" in the USA, "*European Factories of the Future Program*" in the European Union and "*Made in China 2025*" in China. Additionally, Lund & Vildåsen (2022) point out that global consultancy firms played a significant role in the development of a worldwide portrayal of the 4IR, mainly connected to the opportunities for the manufacturing sector (Blanchet et al., 2014; Rüßmann et al., 2015; Wee et al., 2015). According Wee et al. (2015), Industry 4.0 digitally-enabled disruptive technologies are identified based on their location in the innovation cycle as those that "are at a tipping point today and are ripe to disrupt the manufacturing value chain" (p.11) including novelty technologies (e.g., augmented reality) as well as innovations applied in the manufacturing sector since a long time ago (e.g., big data and advanced analytics). These authors classified these technologies in four main clusters: 1) data and connectivity (e.g., cloud technologies, big data, internet of things), 2) human and machine interaction technologies (e.g., virtual and augmented reality), 3) digital to physical technologies, represented by additive manufacturing (e.g., 3D printing) and advanced robotics and 4) analytics and intelligence technologies (e.g., machine learning and artificial intelligence). Other definitions of Industry 4.0 technologies, not so centered on CPS, conceived them as a *"complex and heterogonous cluster of emergent technologies*" comprised of semi-conductor and internet technologies with the increasing relevance of artificial intelligence (Martinelli et al., 2021). Ultimately, despite various attempts to define a list of "*Industry 4.0*" technologies, there is still no standardized agreement on them (Balland & Boschma, 2021).

Another broad attempt to define 4IR technologies is provided by a recent work from Capello & Lenzi, (2021). The authors conceive of the 4IR as involving various technological changes and do not link them to particular technologies/sectors or specific new transformations. At the same time, they see 4IR as not only encompassing transformations in the manufacturing sector, but also a profound transformation in the services sector, leading to the rise of Industry 4.0, the servitisation of manufacturing, the sharing economy, and digital service intermediation platforms. Ultimately, the authors emphasize that each type is associated with different actors and values of creation, impacting the economy and society with unequal regional patterns.

Several studies acknowledge that the 4IR technologies involve the fusion of digital technologies, biotechnologies, nanotechnologies and new materials across industries (Andreoni et al., 2021; OECD, 2017; Schwab, 2017). The "*technology fusion*" concept is not new in innovation studies since it was introduced by Kodama for explaining previous technological revolutions (2IR and 3IR) and implies a non-linear, complementary and cooperative combination of incremental innovations from different technological fields that aspire to create products that revolutionize markets (Kodama, 2014). In this spirit, the World Economic Forum (WEF) proposed a broader understanding of these technologies and its CEO, Karl Schwab argues that the 4IR technologies make up a new technological revolution, with a global scope that implies the transformation of systems, leaving apart those definitions solely focused on systems machines smart connected (Schwab, 2017). Most popular definitions of 4IR technologies conceive them as new emerging technologies that involve the fusion and interaction between the physical, digital and biological domains. The 4IR technologies "build on the knowledge and systems of prior industrial revolutions, in particular the digital capabilities of the third Industrial Revolution" (Schwab & David, 2018, p.7). However, these technologies are not merely the continuation of the digital revolution, as "Fourth Industrial Revolution technologies promise to disrupt even today´s digital systems and create entirely new sources of value" (p.19). In this sense, the authors propose a concept of technologies that goes beyond the notion of them simply as exogenous forces or tools, but rather requires a deeper understanding of how human values are embedded in these emergent technologies and how them could shape to deliver "common good, environmental stewardship and human dignity" (p.2).

Schwab (2017), based on the WEF work, identifies very broadly the 4IR key technologies within each domain: *physical domain* (such as: autonomous vehicles, 3D printing, advanced robotics, new materials); *digital domain* (such as: internet of things, blockchain, technology enabled-platforms) and *biological* (such as: biotechnologies). Schwab & Davis (2018) "dive more deeply into the substance of specific technologies and governance issues" (p. 1) and identify a list of twelve sets of technologies based on expert consultations[8]. According to the authors, the list of technologies "is by no means exhaustive, as they are so many individual technologies" (p.70) and this selection only reflects those technologies that "are most visible at this early stage" (p.70). The twelve sets of technologies are classified into four sub-sections: a) extending digital technologies: this dimension includes digital, quantum and embedded computers such as, new computing technologies, blockchain and distributed ledger technology, ubiquitous linked sensors, b) reforming the physical world: this sub-section takes into consideration the combination of software and artifacts (artificial intelligence and robotics, advanced materials and nanomaterials, additive manufacturing), c) altering the human being: this category includes technologies that are linked to the biology and how human interact with the world (biotechnologies, neurotechnology, virtual and augmented realities) and finally, d) integrating the environment: this sub-section includes those technologies that have the capabilities to "enable infrastructure development, perform global system maintenance and open up new pathways for the future" **(**energy capture storage and transmissions, space technologies and geoengineering) (Schwab & Davis, 2018, p. 72). The last initiative carried out by WEF to go into the interlinkages between 4IR technologies are the "Transformation maps"[9]. The 4IR technologies map updates with new trends and transformation of a particular topic by top institutions (think tanks and international organizations). Recent work by Andreoni et al. (2021) not only adheres to the idea of the fusion of Industry 4.0 technologies but also classifies these technologies into six main clusters: artificial intelligence, data analytics, and cloud computing; IoT and network technologies; Robotics, cyber-physical systems, and additive manufacturing; Advanced materials; Nanotechnology; and Biotechnology.

In addition to looking at 4IR as a broad sectoral phenomenon, there are also definitions that are limited to the manufacturing sector, e.g., the "*Advanced Digital Production Technologies*" (ADP) (UNIDO, 2019) or "*Digital Production Technologies*" (Andreoni & Anzolin, 2019)[10]. Essentially, these technologies could be conceived as the combination of three evolving components: *hardware*, *software* and *connectivity*. Regarding *hardware*, this component comprises technologies evolved from automated machines to 3D printing, industrial robots and cobots. This type of technological advances do not present substantial differences with the production technologies under 3IR (UNIDO, 2019). Finally, the component of connectivity reflects the evolution from sensors to the internet of things. The Internet of things could interconnect a wide number of dispersed and separate physical devices that could be used to monitor and control physical objects (Xu et al., 2018). As the machines are provided with sensors, they are able to collect data and transmitted through to wireless networks and internet and hence, allowing a transition from a centralized to a decentralized production centered in human-machine and machine-machine interactions. ADP technologies include (IoT), Big Data

[8] World Economic Forum Global Future Councils and Expert Network.

[9] The information of the "Transformation maps" is organized by universities, think tanks and international organizations. The work of these organization focuses on identifying trend and transformation of a particular topic https://intelligence.weforum.org/topics/a1Gb0000001RIhBEAW

[10] According to Chang & Andreoni (2021), the emergence of new technologies is one of the factors that explains why it is necessary to bring the issue of production to development discourses and, therefore, how the fusion of technologies require "foundational productive capacities".

analytics, Advanced robotics and cobots, Machine learning, cloud computing, Artificial intelligence, 3D printing and CAD-CAM. The relevance of digital technologies in the transformation of industrial production are also highlighted by OECD (2017). The report argues that applications of new information and communication technologies, such as big data analytics, cloud computing and IoT, are key technologies enabling additive manufacturing, autonomous machine systems and integration man-machine, which facilitate new forms of production and organization, as well as business models, mainly through industries.

Recently, a report by UNCTAD (2022) adopts the hardware-software-connectivity interaction proposed by UNIDO to define Industry 4IR but highlights two special characteristics of these technologies: a) automation and decentralization of tasks using technologies such as big data and artificial intelligence leaving aside human interaction and b) the interconnection of people and devices to connect and exchange data and communication. Both characteristics do not imply disruptions but rather the evolution of technologies from previous revolutions. Regarding the first one, although the conceptualization of automation technologies dates back to the late 1950s, the beginning of automation technologies in history can be traced back to the 18th century with the introduction of hydropower (Kaplinsky, 1985). Recently, automation technologies have been defined as "automatic guided vehicles, automatic storage and retrieval systems, sensors on machinery, computer-controlled machinery, programmable controllers, and industrial robots" (Acemoglu & Restrepo, 2019, p. 22) and have evolved in full interaction with other technologies such as artificial intelligence, leading to the processes of "*intelligent automation*" (Dosi & Virgillito, 2019). Regarding the second one, it is considered that one novel aspect of the 4IR 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" (Andreoni et al., 2021, p. 337). Even though the volume of information is greater and the processing of the machines has more capacity, this would not mark a break with the ICT paradigm. Moore's Law, introduced by Gordon Moore in the 1960s, states that the number of transistors doubles in about two years and hence, this phenomenon explains the increase in data processing power.

In the same fashion as UNCTAD (2022), data transmission and connected devices are the pillars of the definition of 4IR technologies adopted by the EPO. Ménière (2022) considers that these technologies are "those related to smart and connected devices and which combine features of computing, connectivity and data exchange" (p.104), such as artificial intelligence, 5G and big data enabling the automation of several tasks, and involve a wide range of technological domains beyond the manufacturing sector. These technologies are "paving the way to a data driven economy" (EPO, 2020a, p. 14). EPO (2017, 2020a) agree in pointing out that 4IR entails the "*full integration*" of ICT technologies – 3IR core technologies – in manufacturing but also in areas such as personal, home, vehicles, enterprise and infrastructure.

According to EPO (2017, 2020a), 4IR technologies can be classified under three broad categories: core technologies, enabling technologies and application domains[11]. According to the report and highlighting the evolutionary character of technologies, the core technologies of 4IR

[11] See Appendix, Figure A.1.

consider the same three fields of 3IR, namely: connectivity, software and IT hardware. As it was mentioned previously, also, these three fields are associated as being the core fields of advanced digital manufacturing technologies (Andreoni & Anzolin, 2019; UNIDO, 2019). The enabling technologies build upon and complement the core technologies such as those linked to data management, user interfaces, artificial intelligence, geo-positioning, power supply, data security and 3D support systems. EPO (2020a) includes a technology field connected with safety. Finally, the application domains include the final applications of the 4IR technologies. EPO (2017) includes six technology fields in application domains, namely: Personal, Home, Vehicles, Enterprise, Manufacture and Infrastructure, while EPO (2020a) includes eight technology fields in applications domains: Consumer goods, Home, Vehicles, Services, Industrial, Infrastructure, Healthcare and Agriculture.

In line with this last conceptualization and the classification of 4IR technologies, the next section focuses on their identification using patent data, with a special emphasis not only on EPO methods but also on alternatives using technical codes and keyword mining.

2.2 Identification of Fourth Industrial Revolution technologies using patent data

Although defining and identifying 4IR technologies presents several obstacles, as we have mentioned in the previous section, several efforts have been made to identify and analyze the evolution of these technologies using various data sources such as patents, scientific publications, open-source software (Baruffaldi et al., 2020) and hyperlinks (Chiarello et al., 2018). Some of the flaws related to patents as indicators are that not all patents lead to innovations that are introduced in the market, patenting propensities differ among industries (Foster-McGregor et al., 2022) and their value is skewed (Gambardella et al, 2008). Additionally, using patents for identifying new technologies entails limitations such as the inexperience of patent examiners with these innovations, problems for determining patentable subjects and lack of previous studies on them (Webb et al., 2018). On the other hand, patents stand out as one of the main sources for identifying innovations because of their availability, for a wide range of countries, of technological, industrial and organization data (Griliches, 1998). Taking these advantages into account, the EPO's attempts to broadly identify 4IR technologies through patent data are important milestones. We will discuss these attempts as well as examples of how the EPO work was adapted by various academic studies in the following sub sections. We will also discuss alternative methods for 4IR technologies identification.

2.2.1 EPO method

EPO (2017, 2020a) made two attempts for a broad identification of 4IR technologies. In first instance, EPO (2017) aims to identify and map these inventions into different technological fields through a three-step methodology: 1) patents cartography, 2) identification of the applications and 3) classification. The report focuses on EPO patents application for the period 1978-2016.

In the first step, cartography, the EPO experts are asked to identify in which field ranges of the Cooperative Patent Classification (hereafter CPC) scheme they would assign 4IR inventions and to which technological areas of the mapping these ranges should be attributed.[12] Around 320 CPC field ranges are identified with their respective technological fields. In the second step, a full text search query in patents based on keywords is applied to identify the 4IR technologies. As a general constraint, all the documents must contain the concept of "*data exchange*". Once this limitation is applied, more sub-queries are defined including concepts such as communication, computing and devices. The last step consists of classifying the patent applications to the cartography fields. This report identifies almost 50,000 published and non-published patent applications linked to 4IR technologies filed at EPO during the period 1978-2016.

The concordance table between CPC field ranges and 4IR technology fields carried out by EPO (2017) was adopted for 4IR technologies identification by several academic studies concentrated on developed countries to make a descriptive analysis about 4IR technological trends and characteristics of firms. Benassi et al. (2020) combine 4IR technologies identified by EPO (2017) and ORBIS-IP data at the firm-level to examine the 4IR technological trends and characteristics of firms in Europe for the period 1985-2014. The same combination of datasets is used by Li et al. (2020) to study the impact of 4IR technologies on firm wages levels for 27 OECD countries. Also at the firm level, Peters & Trunschke (2021) study the benefits of German firms engaging into the development of 4IR-related technologies considering patents as related to 4IR if at least one of them is linked to one of the 320 CPC field ranges. Venturini (2022) adopted the EPO (2017) classification to determine the stock of knowledge in 4IR technological fields and their impact on productivity in 32 industrialized economies from 1990-2014.

Simultaneously, EPO (2017) technology fields and CPC codes were applied to study the technological differences between 3IR and 4IR. Laffi & Boschma (2021) analyze the diversification of technological knowledge between 3IR and 4IR among European regions during 1991-2015 by designing combinations of EPO 4IR categories (core, enabling and application). The authors find that the relationship between 3IR and 4IR technologies is characterized by heterogeneity, with some technologies being closer than others, thus highlighting the relevance of the evolution of cumulative knowledge. At the regional level, authors identify that the European regions are more likely to develop 4IR innovations if they are specialized on 3IR technologies. Moved by a similar objective as Laffi & Boschma (2021), Laffi & Lenzi (2021) analyze the continuities or novelties of the 4IR technologies concerning the 3IR in European countries for the period 2000-2015. To achieve a more widely agreed definition of the 4IR technologies, the authors carry out a Delphi survey to collect keywords based and the most relevant technologies that describe them for each of the 16 EPO (2017) technology fields relying on expert consultation. Under the study, a patent is tagged as 4IR if at least one of the 522 keywords retrieved is present in the text of the patent (title, abstract, claims, and description). Contrary to other studies mentioned in previous sections, the authors find that "3.0 and 4.0 inventions are inherently different and continuity and cumulation characterize only a minority

[12] EPO (2017) Annex contains the concordance table between CPC field ranges and 4IR technology fields.

fraction of 4.0 patents" (p.15). Furthermore, the authors find that 4IR technologies are more radical and original, combining different types of heterogeneous technologies in a very novel way, providing more evidence for those positions that highlight the revolutionary nature of these technologies.

EPO (2020) constitutes the second extensive attempt to identify 4IR technologies and, unlike the previous report of the office, focuses on international patent families (IPFs)[13] for a shorter period (2000-2018). The methodology proposed in this new report follows the same three steps as (EPO, 2017): 1) cartography, 2) identification of applications and 3) classification. Regarding the first step, cartography is also based on the expertise of EPO patents examiners who are asked to identify in which field ranges of the CPC scheme they would assign 4IR inventions and to which technological field(s) of the mapping these ranges should be attributed. 368 CPC field ranges are identified with their respective technological fields. In the second step, full-text data search queries are applied in the patents to identify the documents related to the 4IR definition. As in EPO (2017), all the documents must contain the concept of "*data exchange*" to emphasize the importance of data as the main source of value creation in the 4IR, and specifically, its exchange emphasizes the idea that "*bringing together data from different sources and the systems that create and exploit that data*" (p.16). Additionally, EPO (2020a) explains that once this constraint is applied, more sub-queries are defined, including concepts in three areas:

a) **Communication** (e.g., internet, mobile, wireless).
b) **Computing** (e.g. big data, cloud, artificial intelligence).
c) **Intelligent devices** (e.g. sensor networks, Internet of Things, Smart homes).

Distinct from the former report, the EPO (2020a) report offers more detailed information on the keyword queries applied to the full-text patent database for English, German and French languages. Two different full-text queries are run depending on CPC code ranges. One query is applied for the following CPC groups: **G06** (Computing; calculating; counting), **H04** (Electric communication technique) and, **G16** (ICT technology specially adapted for specific application fields). Another query is applied to all **other CPC range codes**.

The keywords used in both queries (general and subqueries) are detailed in the report but are expressed in an internal EPO query service called EPOQUE, which is not easily available outside the EPO, and which is not well documented in publicly available documents. The third step consists of classifying the patents applications to the cartography fields. Following this methodology, 264565 IPFs are identified for the period 2000-2018. As far as our knowledge reaches, Meindl et al. (2021) is the only study that implements the CPC ranges codes from EPO (2020a) classification to identify 4IR technologies and then, study the exposure of occupations to these type of technologies.

2.2.2 Other methods

[13] International patent families "represents a unique invention and includes patent applications filed and published in at least two countries" (EPO, 2020a, p. 22).

Simultaneously, several studies have tried to identify constellations of 4IR technologies using other methodologies apart from the EPO (2017, 2020a) reports. Most of them rely on the identification of CPC codes and keyword analysis.

Trappey et al. (2016) identified the 4IR technologies through focusing on the cyber physical systems (CPS) or smart manufacturing. For the authors, CPS plays a key role in the transition from the 3.0IR to the 4IR. Briefly, the authors identify the CPS patents based on the construction of a CPC ontology[14] based on five layers: smart connection, cyber computation, data to information conversion, cognition and configuration. The patent data is extracted from Thompson Innovation database for the period 2006-2015. The authors made a search string query based on the CPS ontology terms using text mining techniques. Through applying this methodology, the authors identify 1401 patents[15]. Trappey et al. (2016) CPC classification is used by Corrocher et al. (2018) to identify the 4IR technologies in Chinese and German companies.

Foster-McGregor et al. (2019) offered a different method to identify 4IR patents. For the identification, the authors recur to the patent classification system from Derwent, specifically in those patents classified under the code T06: Process and Machine control. The search is refined by excluding those codes not connected with smart manufacturing. Once patent families containing manufacturing-related inventions on process and machine control are defined, four new subqueries are carried out to select those patents that are related either to data transmission or machine learning or artificial intelligence. Firstly, as EPO (2017, 2020a) but not as a general restriction, the authors impose a data exchange criterium by considering digital information transmission (from Derwent) and 4IR digit IPC codes H04L "*transmission of digital information*" and H04W "*wireless communication network*". Secondly, the authors impose the machine learning criteria by considering the CPC codes that capture machine learning concepts selected through using the J-tagging system. Third, based on WIPO technology trends report on Artificial Intelligence, a machine learning keyword analysis on patents titles and abstracts was carried out. Fourth, an artificial intelligence criterion by selecting those patents classified under the Derwent manual code T01-J16 "Artificial Intelligence" is applied. The final dataset contains 18.285 patent families for the period 2000-2018. Finally, the patents are classified in four main categories: robots (are identified according to the IPC code and keywords related to "robot"), 3D (patents corresponding to filtering B33 IPC code), machine learning (identified by the criterium explained above) and Total factory control (identified based on Derwent sub-codes).

Martinelli et al. (2021) examine to what extent the six 4IR technologies emerged as the combination of semiconductors and internet paradigm, such as internet of things, artificial intelligence, big data, cloud manufacturing, robotics and additive manufacturing, might be considered together or individually as GPTs technologies. The authors recur to EPO-PATSTAT database but concentrate only on USPTO granted patents for the period 1990-2014. Martinelli

[14] The map of the CPS ontology is available in Figure 8 in Trappey et al. (2016), p. 7366
[15] See Appendix, Figure A.2.

et al. (2021) expose the search strategy by giving the main literature references, the CPC codes classes and keywords (including wild cards) for each 4IR technology.[16]

Balland & Boschma (2021) try to identify the Industry 4.0 technological centers of knowledge in European regions adopting the relatedness framework for the period 2002-2016. The authors focus on 10 Industry 4.0 technologies arguing that their selection is based on an extensive review of the literature on the subject. According to the authors, this selection of technologies is reflecting a broad understanding of Industry 4.0, "*that includes but also goes beyond the digitalization of industries and value chains*" (p.1663) and comprises the following technologies: 1) additive manufacturing, 2) artificial intelligence, 3) augmented reality, 4) autonomous robots, 5) autonomous vehicles, 6) cloud computing, 7) cyber-security, 8) machine tools, 9) quantum computers and 10) system integration. Patents are extracted from OECD's REGPAT database and the 10 Industry 4.0 technologies are directly and indirectly linked with the CPC codes. The direct method means that the patents from a particular technology are straightforwardly associated with a CPC class (e.g., cloud computing with the code G06F 9/5072- Grid computing). The indirect method implies that the identification of the technologies implies combining CPC codes (e.g., autonomous vehicles implies combining B60W30/14- Cruise control and G01S17- Lidar system).[17] Therefore, their methodology is limited to the possibility of isolating the CPC codes. In a nutshell, the authors conclude that the Industry 4.0 technologies tend to locate in the periphery of the knowledge space that means that "*they build on capabilities that are not generic, and not easy to find in other technologies*" (p.1657), and hence, supporting the position in favour of the "novelty" nature of these technologies. In terms of relatedness, the authors identified two different knowledge clusters, namely: a) computer related, including ("*quantum computers, AI, cloud computing, cybersecurity and system integration*" (p.1657) and b) manufacturing technologies, including (″*machine tools, autonomous robots and autonomous vehicles*" (p.1657)). Furthermore, the authors find that those European regions with a more developed Industry 4.0 knowledge base have more potential for diversifying these technologies. Finally, Balland & Boschma (2021) identify significant geographical differences in Industry 4.0 technologies, which ultimately reflect regional technological capabilities.

Lee & Lee (2021) compared the technological regimes of 4IR and the 3IR technologies. The authors recur patent data from a special USPTO[18] search engine to identify 4IR patents for the period 1976-2018. Through this engine, the authors search for keywords in patents titles and abstracts following the steps provided by Leydesdorff & Bornmann (2012). Relying on the literature about 4IR technologies and their interdependence, the authors focus on five technologies, namely: 3D printing, big data, IoT, AI, and cloud computing. Following this method, the authors identified 4269 patents linked to 4IR.

---

[16] More information about the sources, the CPC classes and the keywords, see Table 1, p.168 (Martinelli et al., 2021).

[17] It is worthily mentioning that (Balland & Boschma, 2021) do not expose in their study which are the CPC codes combined in each technology in order to replicate this method for academic purposes.

[18] https://patft.uspto.gov/netahtml/PTO/

A recent study of Confraria et al. (2021) is not directly focused on the identification of specific 4IR technologies but on the identification of emerging technologies. By recurring to Rotolo et al. (2015) attributes of emerging technologies, and using patent data, the authors estimate three indicators for: a) relatively fast growth by calculating the growth rate of IPC total share of grants in each patent office for different periods of time, 2) coherence, estimating the growth rate of absolute IPC grants in each patent office for different periods and 3) prominent impact by estimating the total share of patents grants from an IPC in an office for a certain period.

Finally, as far as our knowledge is concerned, the study of Benassi et al. (2021) constitutes the first attempt to develop a novel method using the latest EPO (2020b) methodology as the main source to study the profitability of the 4IR stock of technological knowledge on the performance of German companies in the period 2009-2014. Following EPO (2020b) procedure, the authors follow two steps. In the first step, they collect the list of CPC codes potentially related to 4IR technologies and provided by EPO (2020b). In the second step, the keywords provided in the EPO (2020b) queries were searched in the patent´s full text[19]. Then, the authors classified the 4IR technologies in six different classes: 1) Cyber-Physical Systems (CPS); 2) Industrial Internet of Things (IoT); 3) AI, cognitive computing, and big data analytics; 4) cloud computing/ manufacturing; 5) Augmented Reality (AR); and 6) wireless technology. In essence, the authors verify that there is a positive and significant relationship between the stock of 4IR patents and the productivity in terms of labor productivity and total factor productivity. Additionally, firms with a long history of patenting 4IR technologies present benefit more than those firms that started later. Finally, the relationship between productivity and 4IR is higher for technologies such as wireless technology, artificial intelligence, cognitive computing and big data analytics.

2.3 Towards a conceptualization of 4IR technologies

In this part, based on sections 2.1 and 2.2, we propose to draft our conceptualization of 4IR technologies. This definition will guide the identification procedure of these technologies using patent data explained in section 3. Our conceptualization brings together some of the key aspects mentioned in the literature review section, such as the **systemic** and **co-evolving** nature of the 4IR technologies and the fact that they involve a wide range of technological fields. This last key aspect is linked to the concept of **technological fusion**. The scope of technological fields included in our definition lean on "*data-centered*" methodology provided by EPO (2020a) report.

Regarding the **systemic nature of technologies**, we conceive that the 4IR technologies do not operate in isolation. Contrarily, and in concordance with Brixner et al (2020), we consider them as "*technological systems*". Chris Freeman coined this term to refer to those "constellations of innovations" which are technically and economically interrelated". According to Freeman & Perez (1988), "*technological systems*" impact on the different sectors of the economy as well as could be giving rise to new sectors. Additionally, these systems combine the radical and incremental innovations, "*together with organizational and managerial innovations affecting*

[19] Benassi et al. (2021) mentioned that the patent full text could be retrieved at https://www.epo.org/searching-for-patents/data/bulk-data-sets/data.html

more than one or a few firms" (p.46). Aligned with other authors, we conceived that the changes of many clusters of 4IR technologies comprised by radical as well as incremental do not necessarily imply a change in the entire economy and hence, do not suppose a change in the techno-economic paradigm. Therefore, in this paper, we assume that the 4IR technologies constitute the evolution of the ICT revolution. It is in this way that it can be pointed out that the 4IR are several technological trajectories conformed by combinations of "technological systems" within the paradigm led by ICTs. At the same time, the systemic character of the 4IR might be supported by the theoretical framework of national systems of innovations that assumes that innovations and learning capacities are directly linked with the social and institutional structure of each country.

Concerning the **co-evolving** nature of technologies, as many other authors, we conceive that the 4IR technologies are the result of the **evolution** of technologies that emerged in previous technological revolutions, specially under the 3IR (Andreoni & Anzolin, 2019; Kodama, 2018). As we have highlighted in previous sections, several of the technologies that are considered as "revolutionary" and "disruptive" of 4IR are the result of tacit, accumulative and incremental process of technological change. Simultaneously, it is highlighted the "*co-evolutionary nature"* (Fagerberg & Verspagen, 2020, p. 4) of these technologies that means that their potential for influencing each other in the evolution process.

Finally, the 4IR broad scope of the technological field is strongly linked with technological fusion notion. We assume that the 4IR implies the **fusion**[20] of technologies across different technological domains. From a theoretical point of view, this characteristic can be studied under the "*fusion of technologies*" approach developed by Fumio Kodama and recently adopted by Andreoni et al (2021). The "*technology fusion*" was a concept introduced to explain the emergence of technologies such as "*mechatronics*" and "*optoelectronics*". According to Kodama (2014), the "*technology fusion*" implies a non-linear, complementary and cooperative combination of incremental innovations from different technological domains that aspire to create products that transform markets. For the author, technology fusion involves the existence of long-term R&D ties among diverse companies in all industries under reciprocal and substantial relationships. Regarding the former, it implies that companies bet on the integration of the R&D project from the first stages to the most advanced. For reciprocity, it means that companies should share mutual respect, mutual responsibility and mutual benefit. Kodama argues that it is possible to identify an evolution of technological change and not a technological

[20] Convergence, merger, and overlap are interchangeable terms to refer to the reduction of boundaries between different technologies (Zhu & Motohashi, 2022). Nathan Rosenberg introduced the technological convergence concept in 1963. The author considers the diffusion of knowledge in technological convergence to be a central factor. In this sense, the spread of innovations in the machinery industry, such as firearms, sewing machines and bicycles, to other products was central to the convergence of technology across industries. As we explained in Section 2.1.2, Fumio Kodama introduced the technological fusion concept. Curran & Leker (2011) identified differences between the two terms. Technology convergence occurs when technologies merge in a new field. Fusion of technologies implies for the authors that new technologies substitute parts of the prior technologies. Finally, (Andreoni et al., 2021) stick to the idea of referring to the 4IR as a fusion rather than convergence because this last term is "nebulous" as it is associated with different meanings, for example: to refer to industries that start using similar technologies, 2) to refer to digital convergence and 3) to refer to the merging and overlapping technologies involved innovations using patent data.

revolution since the mid-1970s from "technology fusion" to "technology-service convergence" through a process of modularization. For Kodama (2014), the "technology-service convergence" implies that "*two systems which had been evolving by following quite different trajectories, and which had reached quite different architectures, are now integrated with each other.*" (p.510).

Regarding the scope of technological fields included in our definition, relying on the "*data-centered*" methodology provided by (EPO (2020a) report, our 4IR technologies dataset comprises technologies in four main areas: **1) digital data transmission innovations**, **2) intelligent devices/smart devices and connectivity innovations**, **3) computer science technologies** and **4) communication technologies**. The classification of technologies by areas makes more sense for the reader's understanding rather than for technical aspects, since these technologies are closely interrelated and are spread through a wide range of technological domains and productive sectors. The following paragraphs explain what is meant by these groups of technologies, which ones are included, and their interrelationships.

Concerning **data-transmission innovations**, what it is relevant to highlight is that our conceptualization of 4IR technologies is aligned with those approaches that consider data as a "*source of growth*" (OECD, 2013) and "*value creation*" (EPO, 2020a) of the economies. Following OECD (2013), it is worth mentioning that the use of data for economic and social activities is not a distinctive feature of 4IR. Nevertheless, what turns to be novel are the technological developments within each component of the data value chain[21] and their combination, namely: the extension of the broadband access, the sensorization of devices and applications, a large decrease in the cost of the internet, the proliferation of data collecting devices such as mobile telephones and decreasing cost of storage -linked to the technological advances in cloud computing- as well as in the processing and the analysis data. Similarly, authors such as López-Gómez et al. (2017) expose a framework to study the interaction between data and technologies to analyze the digitalization on the manufacturing sector. Digital technologies are categorized regarding four data functions: 1) data application (e.g., advanced manufacturing capabilities), 2) data conditioning, storage and processing (e.g., big data and cloud computing), 3) data transmission (e.g., network infrastructure as internet, wireless protocols) and 4) data generation and capture (e.g., cyber physical systems).

We capture data-transmission patents by including in our data set all the patents of the CPC groups H04L (Digital Information Transmission) and HO4W (Wireless Communication Network). As it will be explained in the next section, we also include **two keywords queries** linked to the topics "*wireless*" and "*data transfer*".

With regard to **intelligent devices/Smart products and connectivity innovations**, our definition considers that 4IR technologies' scope is beyond the manufacturing and industrial sector. In this vein, smart devices or smart products blurred the lines between the conventional conceptualization of products and services as well as industries, involving the interaction between connectivity, hardware and software technologies. Smart products/intelligent devices

[21] According (OECD, 2013) data value chain comprises the following components: Generation, Collection, Storage, Processing, Distribution and Analytics

relied on the connectivity evolution advances, from sensors to IoT. To capture **intelligent devices** and **smart products** queries linked to IoT and sensor-linked keyword searches are carried out. To include the relevance of smart product/intelligent devices in our 4IR dataset, a keyword query linked to "smart home" is used. It is verified in the next section that we include among our keywords examples of CPS, such as "smart home", "smart city", and "smart building" but also consider the keyword "cyber-physical systems" as a way to include the interaction of hardware-software-connectivity more extensively.

As for **computer technologies**, their identification implies a challenge due to their vast field of study. Briefly, computer science could be understood as "*the study of computers and computing as well as their theoretical and practical applications. Computer science applies the principles of mathematics, engineering, and logic to a plethora of functions, including algorithm formulation, software and hardware development, and artificial intelligence.*" (López-Gómez et al., 2017). When considering the relevance of data on innovations, the technologies in this group are closer to data science technologies, conceived as a sub-field of computer science and statistics. In this vein, this category includes artificial intelligence, conceived by several authors as the core technology of 4IR, and which might be defined as "*the knowledge and techniques developed to make machines "intelligent," that is to say able to function appropriately also through foresight in their environment of the application*." (Martinelli et al., 2021, p. 163). At the same time, this category includes machine learning, a subfield of artificial intelligence, in which machines use data and algorithms to predict patterns. Deep learning, which is a sub-dimension in machine learning, comprises algorithms in which neural networks are trained based on the structure of the human brain. It also includes fuzzy logic algorithms that constitute an attempt to handle uncertainty and varying degrees of human decision-making. Other technology included in this category is cloud computing. This technology is considered to support the storage and processing of data from multiple servers located in different data centers (EPO, 2020a). In next section, we capture these innovations including a keyword query with concepts linked to artificial intelligence such as: machine learning, neural networks, fuzzy logic, deep learning, neuronal intelligence. Regarding cloud computing, we capture these technologies including a keyword query with the core concepts such as: cloud computing, cloud data, cloud server. Also, we add queries regarding the three types of cloud services models such as: "infrastructure as service", "platform as service" and "software as service".

Regarding **communication technologies**, they capture the evolution of ICT technologies, linked to the previous technological revolution (3IR). In contrast to the 4IR technologies, for the 3IR technologies, linked to ICT, authors agree in pointing out the existence of a general agreement about their definition, linking those technological fields related to computer and automated business equipment" and "communication technology". Similarly, Nuvolari (2019) identified that 3IR might be under four development blocks of technologies, namely: semiconductors, computers, software, and networking equipment. J. Lee & Lee (2021) identify five keywords involving these blocks: ASIC and memory chips (electronics), PC (computers), internet (software), and mobile phones (network equipment).We capture these technologies in our query through including keywords linked to internet and mobile devices.

Considering all these key factors, we draft the following definition:

In this paper, we understand 4IR technologies as co-evolving "technological systems" that combine innovations in the fields of digital data transmission, smart connected devices, computing, communication and connectivity technologies, the scope of which goes beyond the manufacturing sector and includes a broad variety of technological domains, such as agriculture, health, home, infrastructure and services.

3. Methodology

3.1 Procedure for the identification of 4IR patents

In this part, based on the definition of 4IR technologies drawn up in the previous section and the latest report from the European Patent Office (EPO, 2020b), we detailed our strategy for identifying 4IR innovations using PATSTAT as a data source. Like the academic studies detailed in previous sections, our strategy relies on the identification of CPC codes, for which we use the EPO (2020b) proposal, and text keywords in the titles and abstracts of patents in English. The final 4IR database assumes the combination of both strategies. The fact that we use only titles and abstract for keywords is an important difference to EPO (2020b), which uses the full text of the patents. The use of only titles and abstracts also enables us to use PATSTAT, which does not have full text.

A) Keywords identification[22]

First, keywords related to a set of 10 technologies (see Table 1) linked to the 4IR core concepts by EPO (2020) are identified in English-language patent titles and abstracts. For each of the technologies, a keyword search was carried out following the EPO (2020b) methodology but approximating the truncation and proximity operators in the EPOQUE language to standard SQL syntax[23].

Key concepts	Keyword queries
Data driven innovations	Search 1 (S1)- Data transfer
Intelligent devices/smart products and connectivity innovations	Search 2 (S2)- IoT Search 3 (S3)- Sensor Search 4 (S4)- Smart home Search 5 (S5)- Augmented reality
Computer science technologies	Search 6 (S6)- Artificial intelligence Search 7 (S7)- Cloud
Communication technologies	Search 8 (S8)- Internet Search 9 (S9)- Mobile device Search 10 (S10)- Wireless

[22] See the list of keywords selected in the queries are detailed in the Appendix, A.3.
[23] More information about the operators are detailed in the Appendix, A.3.

B) CPC codes identification

Second, three main queries are executed:
- Search 11 (S11)) Identification of all patents which have at least a CPC code beginning with H04L or H04W**.**
- Search 12 (S12)) Identification of all patents which has at least a CPC code beginning with G06 or G16 or H04
- Search 13 (S13)) Identification of all the patents which have at least one CPC code indicated in the list of "other CPC ranges" provided by EPO (2020).

The dataset of 4IR technologies patent applications constitutes the union/intersection of the search queries define above:

$$4IR\ patent\ applications = (S1 \cup S11) \cap \big((S1 \cap S12) \cup (S2 \cup S3 \cup S4 \cup S5 \cup S6 \cup S7 \cup S8 \cup S9 \cup S10)\big) \cap S13$$

Once the 4IR patent applications are identified, patent families are selected considering the EPO (2020) quality control scheme which only takes into account patent families that are applied for at an international patent office (such as EPO), or at least for national patent offices and whose priority date is after 1999. A patent family "*is defined as a set of related patent documents (applications and grants) that originate from different patent offices around the world, but cover a single invention. Each of the different documents, or family members, protect a specific geographical jurisdiction, which is often an economy, but can also be multiple economies*." (Foster-McGregor et al., 2022, p. 30). In addition, each family patent can be associated (not exclusively) with the CPC ranges of the EPO (captured in S13) that correspond to 19 application fields distributed in three different main technologies[24].

4. Evolution of 4IR patenting: main trends and regional disparities

This section performs a descriptive analysis using our 4IR technologies database. Based on our methodology, we identified 106,640 patent families (hereafter PFs) between 2000 and 2019. Although EPO (2020b) does not reveal the detailed list of PFs that it constructs, it is clear that our list is different. Although we do not document this here, a detailed comparison of the descriptive results in this section with similar results in EPO (2020) reveals such differences.

In some cases, we express some of our results using 10-year cumulative numbers due to the few identified 4IR patents for the 1990s. Therefore, for these cases, the values for year T express the number of patent families from years T-9 to T. The analysis is divided in three sections. The first

[24] See Appendix, Figure A.1.

part examines the 4IR technologies global trends. The second part examines the patenting of the top-10 countries innovators based on the analysis of Revealed Technological Advantage (RTA). Finally, the third part describes some results regarding to what extent the 4IR technologies are fostering greener innovation paths.

4.1 World main trends: patenting evolution

Figure 1 shows the global trend of 4IR technologies patents as well as the share of these technologies in all technologies. The blue line denotes cumulative numbers, hence, is showing global patents families up to 2019. The number of 4IR rises sharply from 2010 up to the last two years (which are affected by delays in the data). This growing trend is consistent with other works mentioned in section 2.2. Simultaneously, the share of 4IR technologies in all tech goes from representing 0.9% in 2000 to 2.5% in 2019.

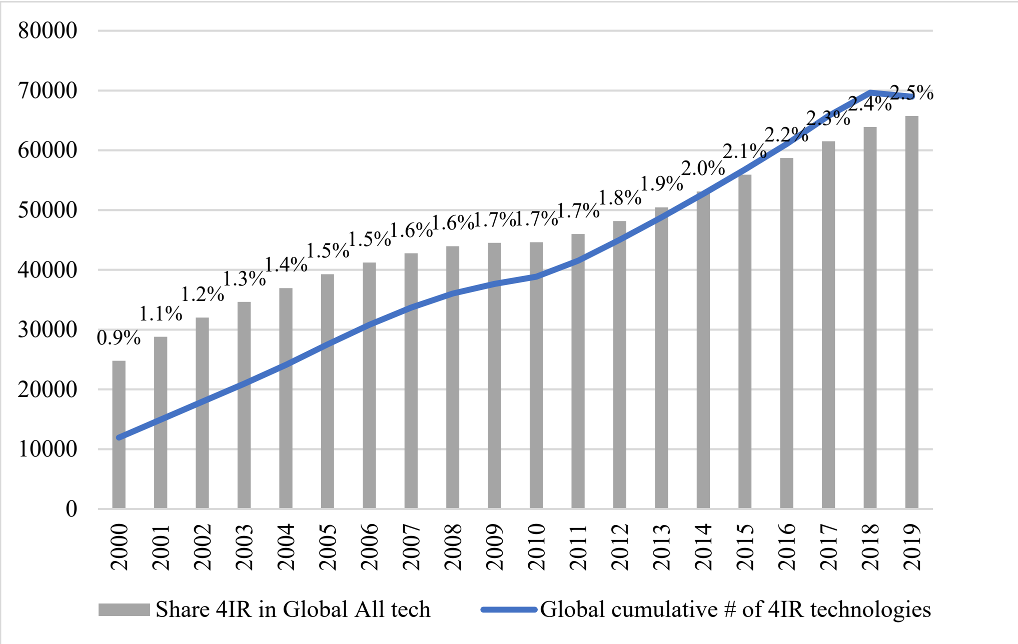


Figure 1. Global cumulative # of 4IR technologies and share in all tech 10 year cumulative

Table 2 shows that this increasing trend is accompanied by a concentration of patents in a small group of countries (patents are assigned to countries on the basis of the location of inventors). Only four countries (1st United States, 2nd Japan, 3rd China and 4th Korea) are in responsible for patenting 73% of all the 4IR technologies while this percentage increases to almost 90% when considering the top-10 countries (5th Germany, 6th Taiwan, 7th Sweden, 8th Canada, 9th France, 10th United Kingdom). Like many other studies, our data confirm that the 4IR technologies creation is concentrated in a very small group of developed countries and emerging economies, such as China. Among the top 10, Finland and Sweden are the countries that show the "highest innovation intensity" (EPO, 2020a) measured in patents per million inhabitants. Furthermore, Table 2 shows that despite China's patent leadership position, innovation intensity is still below the world average.

	Number of IPFs	Share of IPFs	Number of PFs per million inhabitants
World	**106.640**	**100%**	**15**
United States	36.347	34,1%	118
Japan	15.163	14,2%	119
China	14.373	13,5%	11
Korea	12.235	11,5%	249
Germany	3.715	3,5%	45
Taiwan	3.126	2,9%	135
Sweden	2.968	2,8%	315
Canada	2.940	2,8%	87
France	2.780	2,6%	45
United Kingdom	2.684	2,5%	43

Authors own estimation based on 4IR dataset and Population Data from UN

Table 2. Geographic distribution of patent family, by inventor location, 2000-2019

Focusing our attention on European Union[25] (hereafter EU) patent families, Table 3 confirms that 91% of 4IR patenting creation in the European Union is concentrated in seven countries. Germany is the leader of the region accounting the 25% of all the patent families generated in the EU (3,5% of world PFs). Sweden follows Germany with 20% of EU family patents (2,8% of the world PFs). In the third place is France with 19% of EU family patents (2,6% of world PFs). Regarding innovation intensity, Table 3 checks the existence of regional differences within the EU. Northern Europe seems to carry the banner of leadership in the creation of innovations linked to 4.0 technologies for millions of inhabitants: the Nordic countries lead the path followed by Ireland, reaching almost the same values in terms of innovation intensity as USA and Japan.

	Number of PFs	Share of PFs	Number of PFs per million inhabitants
EU	**14.692**	**14%**	**34**
Germany	3.715	25,3%	45
Sweden	2.968	20,2%	315
France	2.780	18,9%	45
Finland	1.839	12,5%	344
Netherlands	1.187	8,1%	71
Ireland	483	3,3%	110
Italy	434	3,0%	7

Authors own estimation based on 4IR dataset and Population Data from UN

Table 3. Geographic distribution of patent families by inventor location in EU countries, 2000-2019

Figure 2 shows the evolution of 4IR technologies in several countries. The increasing trend of appreciation in Figure 1. Is observed in the case of the United States, UK, Taiwan, Sweden and Korea. Simultaneously, the graph shows the Chinese advance in technologies 4.0 the advance during the period of China as a key player in creating these types of technologies. Several of the works reviewed in the literature review highlight the importance of this country in the

[25] EU countries: Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

technological race. According to Foster-McGregor et al., (2019), "is a relative latecomer". Japan's evolution shows that, together with the USA, it turns out to be one of the countries with the highest accumulation of patents of this type since the beginning of the period, but maintains its accumulation throughout the period.

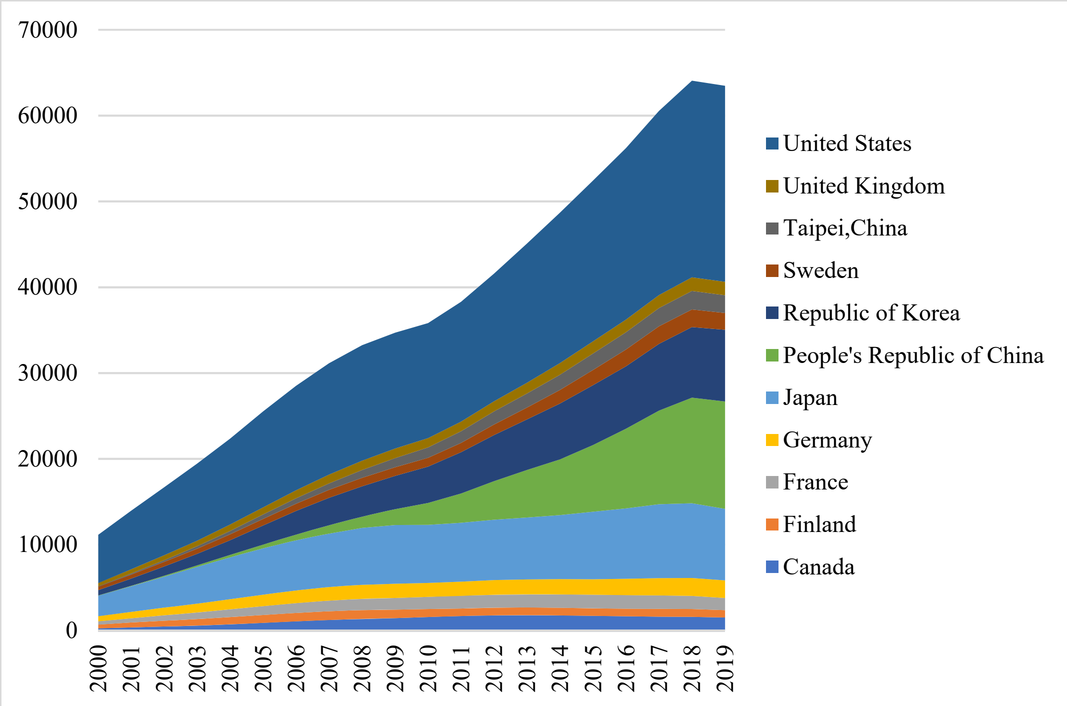


Figure 2. Main countries accumulative # of 4IR technologies

Figure 3 shows the cumulative number of 4IR patent families in 2019. The map confirms the dominant position of China and the USA in 4IR technologies creation. Simultaneously, the map confirms that the less developed regions are the ones that are completely excluded from the technological process of the creation of these technologies. It is interesting to note that if we compare this map with the one from 2010[26], we can see that the coloured territories remain the same, which sheds some light on the existence of a certain "technological path dependence".

[26] See Appendix, Figure A.4.

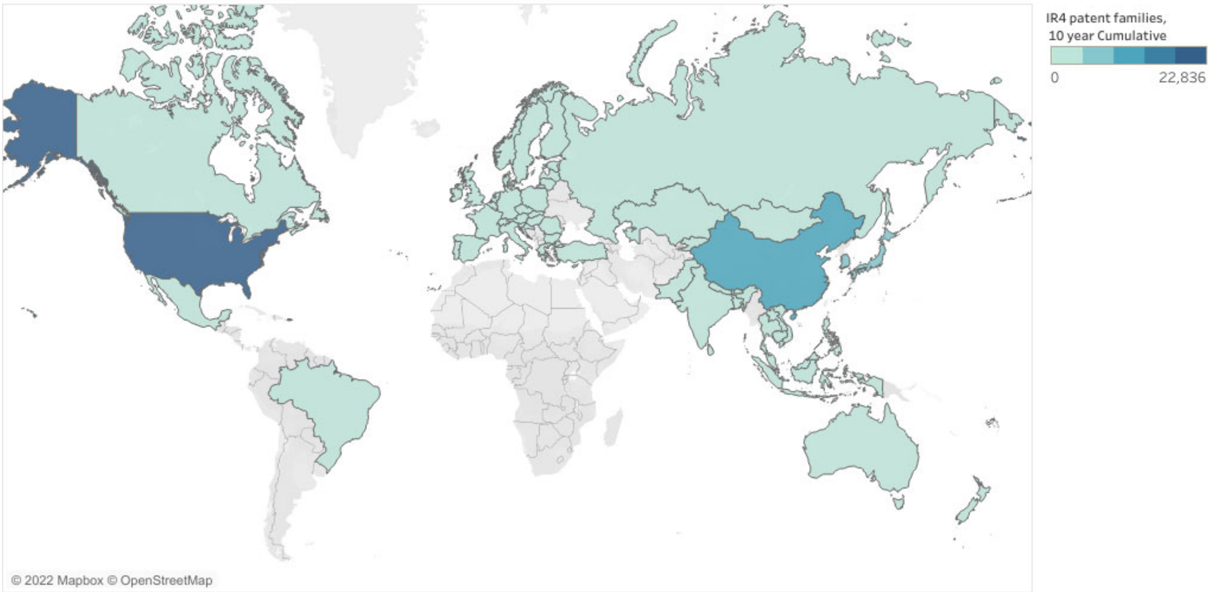


Figure 3. Cumulative # of IR4 Patents Families, All economies, 2019

4.2 World main trends: Patenting sub-fields

Figure 4 shows the global number of patents in 4IR, split by subfield. Connectivity, (smart) home, consumer goods and IT hardware constitute the predominant fields for patenting 4IR technologies over the period of analysis.

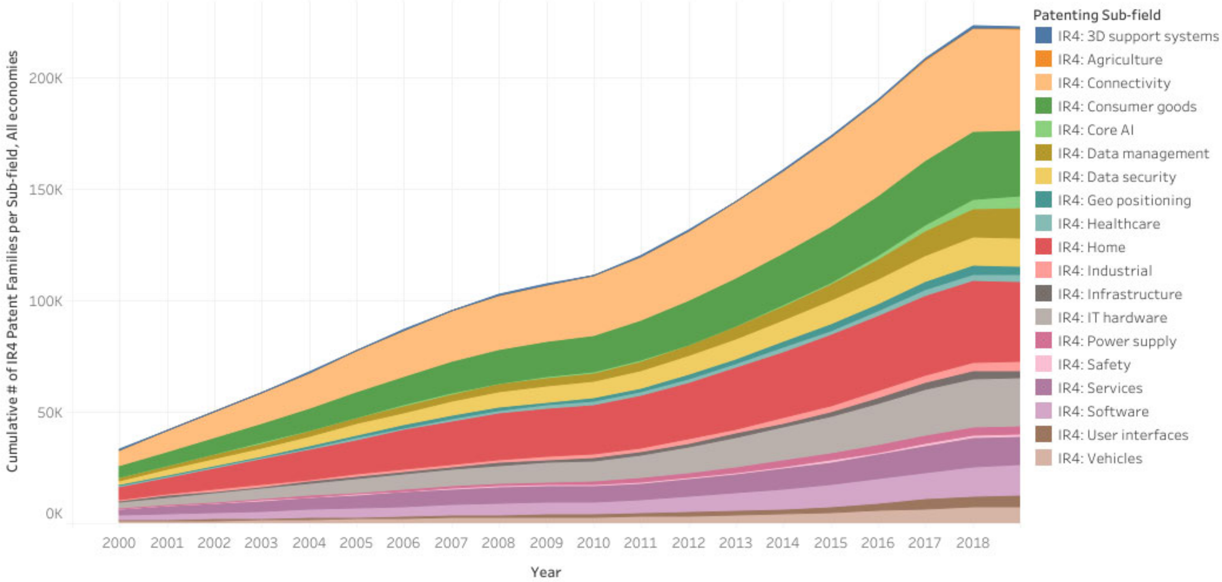


Figure 4. Cumulative # of IR4 Patents Families per sub-field, All economies

4.3. Patenting trends and specialization profiles in comparative perspective: Asia, EU and the USA

4.3.1 Patenting trends

In this section we analyze the different patterns of specialization in Asia (China, Korea and Japan), the USA and the EU. These regions concentrate more than the 90% of the 4IR patent families of our dataset.

Relative technological positions are often analyzed using the concept of so-called Revealed Technological Advantage (RTA). RTA is conceived "*as the ratio of the share of a technology in the country's total patents to the same ratio at the world level*" (Foster-McGregor et al., 2019, p. 14). In other words, RTA is equal to the **Share of 4IR in a country's total patents** divided by the **Share of IR4 in global patenting in all technologies**. Figure 5 explores this concept by showing shows the 4IR patenting share in the entire portfolio of patents for China, the EU, the USA, Korea and Japan and the share of 4IR for the global economy (dashed orange line). The figure confirms the abrupt increasing trend of 4IR patenting in China since the first years of the 21st century, surpassing the values of the USA and Korea. Korea begins the period presenting a percentage of 4IR technologies above the USA and China, but lags behind these two countries later on. Additionally, it is appreciated that the 4IR patenting share of China, USA and Korea is higher than the global share. This suggests that (only) these three economies have a revealed technology advantage in 4IR technologies.

A different pattern is observed for the case of Japan and the EU. Throughout the entire period of analysis, the 4IR patenting of EU and Japan was below the global share. Therefore, they do not present a revealed technology advantage in 4IR technologies (see also European Investment Bank, 2021). Furthermore, the differences between Japanese and global patenting seem to widen over the years.

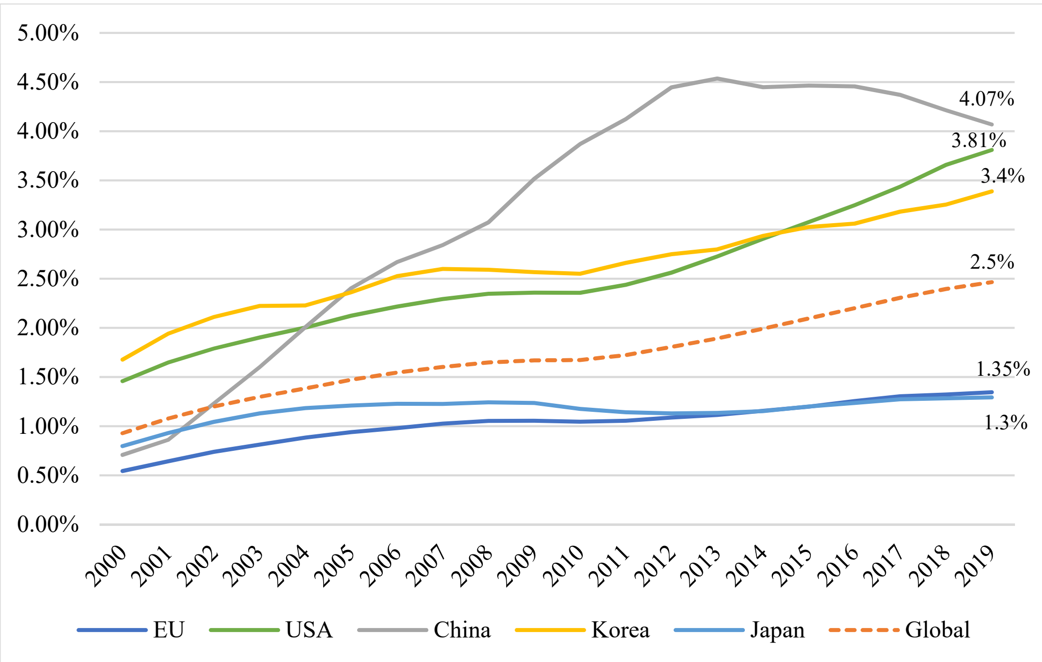


Figure 5. 4IR Share in all technologies

4.3.2 Specialization profiles

Table 4 shows the specialization by 4IR subfields of the main 4IR countries. In this table, the RTA was calculated as the share of the 4IR subfield in the country in all techs divided by the Share of 4IR subfield in global patenting in all technologies, i.e., it measures specialization relative to the entire set of technologies including non-4IR. An RTA higher than 1 is expressing that the country is specialized in the 4IR subfield.

Regarding USA, our results are aligned with the results obtained by EPO (2020a)[27]. The specialization pattern is spread across many subfields, and strongest in areas such as 3D support systems, healthcare, and software. China also has many subfields in which it is specialized, with only a few subfields are below 1. However, the RTA values in the "top" subfields for China (home, connectivity and, to a lesser extent, software) are lower than for the USA. For the case of Korea, it is appreciated that the RTA value is highest for user interfaces and power supply, but above 1 in a large range of subfields.

The other columns, for Japan and Europe, show values lower than 1 in all subfields. The performance of Japan is concentrated in industrial areas, user interfaces and vehicles. The EU performance is highest in areas such as vehicles (reflecting the relevance of automotive industry in this region), healthcare, geo-positioning and 3D support systems. The RTA values are higher if we consider Central Europe (with the exception of agriculture and services). It is worth noting that if we compare Table 4 with the one covering the period 2000-2009[28], Chinese technological specialization has become less skewed over time, that Japan and Korea lost to some extent their position of leadership between the periods and Europe maintains and, even in some cases, deteriorates its technological advantage in different subfields.

	China	**USA**	**Korea**	**Japan**	**EU**	**Central Europe**
3D support systems	0,86	1,99	0,97	0,36	0,67	0,68
Agriculture	0,90	1,73	0,94	0,50	0,65	0,58
Connectivity	1,72	1,58	1,32	0,46	0,58	0,62
Consumer goods	1,47	1,55	1,59	0,50	0,56	0,58
Core AI	1,46	1,82	1,62	0,38	0,46	0,50
Data management	1,34	1,55	1,49	0,57	0,56	0,57
Data security	1,51	1,78	0,93	0,38	0,60	0,62
Geo positioning	0,96	1,81	1,09	0,51	0,71	0,76
Healthcare	0,76	1,91	1,15	0,39	0,72	0,72

[27] See Table 5.2, p.54.
[28] See Appendix, Figure A.5.

Home	1,80	1,65	1,23	0,41	0,56	0,60
Industrial	1,27	1,56	1,13	0,70	0,59	0,60
Infrastructure	1,14	1,74	1,31	0,52	0,53	0,50
IT hardware	1,27	1,68	1,30	0,64	0,48	0,51
Power supply	1,27	1,63	1,79	0,55	0,53	0,58
Safety	1,00	1,59	1,52	0,69	0,60	0,62
Services	1,09	1,81	1,31	0,51	0,41	0,40
Software	1,57	1,91	1,00	0,46	0,42	0,44
User interfaces	0,95	1,55	1,95	0,81	0,39	0,41
Vehicles	1,03	1,54	1,29	0,76	0,68	0,72

Authors own estimation based on 4IR dataset

Table 4. Specialization of global innovation centers by 4IR technologies subfields, 2010-2019

4.4 A brief comment on 4IR technologies in the green transition

The term "*Twin transition*" refers to the combination of digitization – mostly linked to the emergence of 4IR technologies – and a green transition, associated to the adoption of circular economy strategies and decarbonization schemes. Although digitization and sustainability have been widely studied separately, their interrelation has recently attracted the attention of academics and international organizations as a post-pandemic development strategy. Both mega-trends are entailing changes in the way countries produce and distribute goods and services and people's jobs and lifestyles all around the world.

It is widely recognized in the literature that 4IR technologies enhance energy saving and reducing emissions by "*enabling*" the efficient allocation of resources such as materials, energy and water by recurring to digitalization, Internet of Things and Artificial intelligence that optimize supply considering the different priorities and resources. For example, 4IR and green technologies research has provided evidence for demonstrating that 4IR technologies are more likely to integrate in green technologies (*green patents citing digital technologies*), especially in Europe (European Investment Bank, 2021), they have above-average green content, mainly robots, total factory control, machine learning and other (Foster-McGregor et al., 2019) and firms in low productivity industries are more likely to innovate in Green ICT (Cecere et al., 2019).

Following a similar procedure as (Foster McGregor et al, 2019), patents tagged with the Y02 CPC code (technologies or applications for mitigation or adaptation against climate change) can be identified as "green". In the 4IR dataset, only **8,7%** of the total patents families (docdb_family_id) are **Y02 tagged**. Within this group, **61%** of the patents correspond to those mitigation technologies in information and communication technologies aiming at the reduction of their own energy use (Y02D). Next in importance are climate change mitigation technologies related to transportation **14%** (Y02T).

5. Summary and conclusions

This paper provides a methodological procedure to identify 4IR technologies using patent data. This started by formulating a more comprehensive definition of these technologies. After examining the literature regarding how 4IR and its technologies have been conceived through the time and exposing the different methods used for identifying these technologies using patent data, the following definition of 4IR technologies was adopted:

"4IR technologies are understood in this paper as co-evolving "technological systems" that combine innovations in the fields of digital data transmission, smart connected devices, computing, communication and connectivity technologies, the scope of which goes beyond the manufacturing sector and includes a broad variety of technological domains such as agriculture, health, home, infrastructure and services."

We then propose a method to identify 4IR patents. It is based on EPO (2020b) but has the advantage that it can be reproduced using generally available software (SQL) and the PATSTAT database. Although our method resembles the procedures used by EPO (2020b), and uses important elements of the EPO(2020b) procedure, our list of patents is different from the EPO list. Using the set of 4IR patents identified by our proposed method, the descriptive analysis of our data is consistent with the evolution of these technologies found in previous works (EPO, 2020a; Foster-McGregor et al., 2019). We found that the 4IR technologies show a growing trend during the period of analysis. The number of 4IR rises sharply from 2010 up to the last two years, representing 2,5% of all tech patents by 2019. In the second place, our dataset verifies that the creation of these technologies is highly concentrated in developed countries and emerging economies, such as China. Only four countries (1st United States, 2nd Japan, 3rd China and 4th Korea) are in charge of patenting 73% of all the 4IR technologies while this percentage increases to 90% when considering the top-10 countries. Focusing our attention on the European Union, we find that 91% of the creation of 4IR patents in the European Union is concentrated in seven countries, with Finland and Sweden being the countries with the highest innovative intensity. Our results confirm the total exclusion of developing countries from the creation of these technologies. With regard to global patenting by subfields, it concentrates on subfields such as connectivity, (smart) home, consumer goods, and IT hardware.

Our dataset verifies that the percentage of 4IR patents from China, the US, and Korea is higher than the global percentage, meaning that all three countries have a comparative advantage in creating 4IR technologies. Although the share of the European Union and Japan in global patenting, the percentage of 4IR technologies is still below the global share. Japan's relative technological advantage appears to be widening over time. The only countries whose share shows an increase in total global patenting are China and Korea. The rest of the countries analyzed show a drop in participation that turns out to be more pronounced in the case of Japan. Regarding the pattern of productive specialization, we find that the pattern of specialization by technological fields is more diversified in the case of the US The technological advantages of China and Korea seem to be more concentrated in certain sectors. The RTA for Japan and the

US is less than one even though some traditional subfields, such as vehicles, rank with higher values than the rest.

Finally, and regarding the combination of green digital technologies, we find that less than 10% of the identified patents are labelled with Y02 and, therefore, are linked to technologies or applications for mitigation or adaptation against climate change. Simultaneously, more than half of the 4IR patents labelled with Y02 are related to information and communication technologies, which could be explained because these technologies are the core of our definition of 4IR technologies.

References

Acemoglu, D., & Restrepo, P. (2019). Automation and new tasks: How technology displaces and reinstates labor. *Journal of Economic Perspectives*, *33*(2), 3–30.

Andreoni, A., & Anzolin, G. (2019). A revolution in the making? Challenges and opportunities of digital production technologies for developing countries. *Inclusive and Sustainable Industrial Development Working Paper Series*, *7*, 2019.

Andreoni, A., Chang, H.-J., & Labrunie, M. (2021). Natura non facit saltus: Challenges and opportunities for digital industrialisation across developing countries. *The European Journal of Development Research*, *33*(2), 330–370. https://doi.org/10.1057/s41287-020-00355-z

Baheti, R., & Hill, H. (2011). *Cyber-Physical Systems. The Impact of Control Technology*. 161–166.

Balland, P.-A., & Boschma, R. (2021). Mapping the potentials of regions in Europe to contribute to new knowledge production in Industry 4.0 technologies. *Regional Studies*, *55*(10–11), 1652–1666. https://doi.org/10.1080/00343404.2021.1900557

Baruffaldi, S., Beuzekom, B. van, Dernis, H., Harhoff, D., Rao, N., Rosenfeld, D., & Squicciarini, M. (2020). *Identifying and measuring developments in artificial intelligence: Making the impossible possible*. OECD. https://doi.org/10.1787/5f65ff7e-en

Benassi, M., Grinza, E., & Rentocchini, F. (2020). The rush for patents in the Fourth Industrial Revolution. *Journal of Industrial and Business Economics*, *47*(4), 559–588. https://doi.org/10.1007/s40812-020-00159-6

Benassi, M., Grinza, E., Rentocchini, F., & Rondi, L. (2021). Patenting in 4IR technologies and firm performance. *Industrial and Corporate Change*, 1–25. https://academic.oup.com/icc/advance-article/doi/10.1093/icc/dtab041/6330953

Blanchet, M., Rinn, T., von Thaden, G., de Thieulloy, G., Dujin, A., Geissler, C., & Horstkötter, D. (Eds.). (2014). *Industry 4.0*. file:///Users/Marialadelbarrio/Downloads/roland_berger_tab_industry_4_0_20140403.pdf

Bresnahan, T. F., & Trajtenberg, M. (1995). General purpose technologies "Engines of growth"? *Journal of Econometrics*, *65*(1), 83–108. https://doi.org/10.1016/0304-4076(94)01598-T

Brixner, C., Isaak, P., Mochi, S., Ozono, M., Suárez, D., & Yoguel, G. (2020). Back to the future. Is industry 4.0 a new tecno-organizational paradigm? Implications for Latin American countries. *Economics of Innovation and New Technology*, *29*(7), 705–719. https://doi.org/10.1080/10438599.2020.1719642

Brynjolfsson, E., & McAfee, A. (2014). *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*. W. W. Norton & Company.

Capello, R., & Lenzi, C. (2021). 4.0 Technologies and the rise of new islands of innovation in European regions. *Regional Studies*, *55*(10–11), 1724–1737. https://doi.org/10.1080/00343404.2021.1964698

Cecere, G., Rexhäuser, S., & Schulte, P. (2019). From less promising to green? Technological opportunities and their role in (green) ICT innovation. *Economics of Innovation and New Technology*, *28*(1), 45–63. https://doi.org/10.1080/10438599.2018.1423766

Chang, H.-J., & Andreoni, A. (2021). Bringing Production Back into Development: An introduction. *The*

European Journal of Development Research, *33*(2), 165–178. https://doi.org/10.1057/s41287-021-00359-3

Chiarello, F., Trivelli, L., Bonaccorsi, A., & Fantoni, G. (2018). Extracting and mapping industry 4.0 technologies using wikipedia. *Computers in Industry*, *100*(February), 244–257. https://doi.org/10.1016/j.compind.2018.04.006

Ciarli, T., Kenney, M., Massini, S., & Piscitello, L. (2021). Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy*, *50*(7), 104289. https://doi.org/10.1016/j.respol.2021.104289

Confraria, H., Ferreira, V. H., & Godinho, M. M. (2021). Emerging 21st Century technologies: Is Europe still falling behind? In *Working Papers REM* (No. 2021/0188; Working Papers REM). ISEG - Lisbon School of Economics and Management, REM, Universidade de Lisboa. https://ideas.repec.org/p/ise/remwps/wp01882021.html

Corrocher, N., Mavilia, R., & Giorgio, M. (2018). The Sino-German alliance for the fourth industrial revolution: Dynamics and policy implications. *Journal of Economic Policy Reform*. https://doi.org/10.1080/17487870.2018.1547639

Crafts, N. (2021). Artificial intelligence as a general-purpose technology: An historical perspective. *Oxford Review of Economic Policy*, *37*(3), 521–536. https://doi.org/10.1093/oxrep/grab012

Culot, G., Nassimbeni, G., Orzes, G., & Sartor, M. (2020). Behind the definition of Industry 4.0: Analysis and open questions. *International Journal of Production Economics*, *226*, 107617. https://doi.org/10.1016/j.ijpe.2020.107617

Curran, C.-S., & Leker, J. (2011). Patent indicators for monitoring convergence – examples from NFF and ICT. *Technological Forecasting and Social Change*, *78*(2), 256–273. https://doi.org/10.1016/j.techfore.2010.06.021

Dosi, G., & Virgillito, M. E. (2019). Whither the evolution of the contemporary social fabric? New technologies and old socio-economic trends. *International Labour Review*, *158*(4), 593–625. https://doi.org/10.1111/ilr.12145

EPO. (2017). *Patents and the Fourth Industrial Revolution: The Inventions Behind Digital Transformation*.

EPO. (2020a). *Patents and the Fourth Industrial Revolution Fourth Industrial Revolution. The global technology trends enabling the data-driven economy*. https://www.epo.org/service-support/publications.html?pubid=222#tab3

EPO. (2020b). *Methodology for identifying 4IR technologies in patent data. Annex to the report "Patents and the Fourth Industrial Revolution Fourth Industrial Revolution. The global technology trends enabling the data-driven economy."* https://www.epo.org/service-support/publications.html?pubid=222#tab3

European Investment Bank. (2021). *EIB Investment Report 2020/2021: Building a smart and green Europe in the COVID-19 era*. European Investment Bank. https://doi.org/10.2867/904099

European Patent Office. (2020). Patents and the Fourth Industrial Revolution (EPO). *European Patent Office, Handelsblatt Research Institute*, *December*, 100.

Fagerberg, J., & Verspagen, B. (2020). Innovation–diffusion, the economy and contemporary challenges: A comment. *Industrial and Corporate Change*, *29*(4), 1067–1073. https://doi.org/10.1093/icc/dtaa019

Foster-McGregor, N., Nomaler, Ö., & Verspagen, B. (2019). Measuring the Creation and Adoption of New Technologies using Trade and Patent Data. In *UNU-MERIT Working Paper Series* (Vol. 053). UNU-MERIT. https://doi.org/10.20955/r.85.67

Foster-McGregor, N., Nomaler, Ö., & Verspagen, B. (2022). *The ADB-ADBI Innovation and Structural Transformation Database: A Guide*. https://innovatransformation.adbi.org/wp-content/uploads/2022/02/All_Indicators_Guide_V1.1.pdf

Foster-McGregor, N., Nomaler, Ö., & Verspagen, B. (2022). *The ADB-ADBI Innovation and Structural Transformation Database: A Guide*. ADB-ADBI Innovation and Structural Transformation Database.

Freeman, C., & Louçã, F. (2002). *As Time Goes By: From the Industrial Revolutions to the Information Revolution*. Oxford University Press. https://doi.org/10.1093/0199251053.001.0001

Freeman, C., & Perez, C. (1988). Structural crises of adjustment, business cycles. In *Technical change and economic theory* (pp. 38–66). Pinter Publishers.

Griliches, Z. (1998). *Patent statistics as economic indicators: A survey. In R&D and productivity: The econometric evidence* (pp. 287–343). University of Chicago Press.

Hofmann, E., & Rüsch, M. (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in Industry*, *89*, 23–34. https://doi.org/10.1016/j.compind.2017.04.002

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for Implementing the Strategic Initiative Industrie 4.0: Final Report of the Industrie 4.0 Working Group." Acatech-National Academy of Science and Engineering, Germany*. Acatech-National Academy of Science and Engineering.

Kaplinsky, R. (1985). Electronics-based automation technologies and the onset of systemofacture: Implications for Third World industrialization. *World Development*, *13*(3), 423–439. https://doi.org/10.1016/0305-750X(85)90139-1

Keirstead, B. S. (1948). *The Theory of Economic Change*. Macmillan.

Klinger, J., Mateos-Garcia, J., & Stathoulopoulos, K. (2018). Deep learning, deep change? Mapping the development of the Artificial Intelligence General Purpose Technology. *ArXiv:1808.06355 [Cs, Econ]*. http://arxiv.org/abs/1808.06355

Kodama, F. (2014). MOT in transition: From technology fusion to technology-service convergence. *Technovation*, *34*(9), 505–512. https://doi.org/10.1016/j.technovation.2013.04.001

Kodama, F. (2018). Learning Mode and Strategic Concept for the 4th Industrial Revolution. *Journal of Open Innovation: Technology, Market, and Complexity*, *4*(3), Article 3. https://doi.org/10.3390/joitmc4030032

Laffi, M., & Boschma, R. (2021). Does a local knowledge base in Industry 3.0 foster diversification in Industry 4.0 technologies? Evidence from European regions. *Papers in Regional Science*, *September*, 1–31. https://doi.org/10.1111/pirs.12643

Laffi, M., & Lenzi, C. (2021). The antecedents of 4.0 technologies: An analysis of European patent data. *Economics of Innovation and New Technology*, *0*(0), 1–18. https://doi.org/10.1080/10438599.2021.1937617

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T., & Hoffmann, M. (2014). Industry 4.0. *Business & Information Systems Engineering*, *6*(4), 239–242. https://doi.org/10.1007/s12599-014-0334-4

Lee, J., & Lee, K. (2021). Is the fourth industrial revolution a continuation of the third industrial revolution or something new under the sun? Analyzing technological regimes using US patent data. *Industrial and Corporate Change*, *30*(1), 137–159. https://doi.org/10.1093/icc/dtaa059

Lee, M., Yun, J. J., Pyka, A., Won, D., Kodama, F., Schiuma, G., Park, H., Jeon, J., Park, K., Jung, K., Yan, M.-R., Lee, S., & Zhao, X. (2018). How to Respond to the Fourth Industrial Revolution, or the Second Information Technology Revolution? Dynamic New Combinations between Technology, Market, and Society through Open Innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, *4*(3), Article 3. https://doi.org/10.3390/joitmc4030021

Li, S., Shi, L., & Fu, X. (2020). The fourth industrial revolution, technology innovation and firm wages: Empirical evidence from OECD economies. *Revue d'Economie Industrielle*, *169*(2020).

López-Gómez, C., Leal-Ayala, D., Palladino, M., & O'Sullivan, E. (2017). *Emerging trends in global advanced manufacturing: Challenges, opportunities and policy responses.* nited Nations Industrial Development Organization and University of Cambridge's Institute for Manufacturing.

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, *6*, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

Lund, H. B., & Vildåsen, S. S. (2022). The influence of Industry 4.0 narratives on regional path development. *Regional Studies, Regional Science*, *9*(1), 82–92. https://doi.org/10.1080/21681376.2022.2029552

Martinelli, A., Mina, A., & Moggi, M. (2021). The enabling technologies of industry 4.0: Examining the seeds of the fourth industrial revolution. *Industrial and Corporate Change*, *30*(1), 161–188. https://doi.org/10.1093/icc/dtaa060

Meindl, B., Frank, M. R., & Mendonça, J. (2021). *Exposure of occupations to technologies of the fourth industrial revolution*. http://arxiv.org/abs/2110.13317

Ménière, Y. (2022). Patents and the Fourth Industrial Revolution: The Global Technology Trends Enabling the Data Economy. In A. Bounfour (Ed.), *Platforms and Artificial Intelligence: The Next Generation of Competences* (pp. 103–109). Springer International Publishing. https://doi.org/10.1007/978-3-030-90192-9_5

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals*, *65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005

Nuvolari, A. (2019). Understanding successive industrial revolutions: A "development block" approach. *Environmental Innovation and Societal Transitions*, *32*, 33–44. https://doi.org/10.1016/j.eist.2018.11.002

Nuvolari, A., & Russo, E. (2021). Technical Progress and Structural Change: A Long-term View. In *New Perspectives on Structural Change*. Oxford University Press. https://doi.org/10.1093/oso/9780198850113.003.0016

OECD. (2013). *Exploring Data-Driven Innovation as a New Source of Growth*. https://www.oecd-ilibrary.org/content/paper/5k47zw3fcp43-en

OECD. (2017). *Benefits and challenges of digitalising production*. https://www.oecd-ilibrary.org/content/component/9789264271036-6-en

Perez, C. (2010). Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics*, *34*(1), 185–202. https://www.jstor.org/stable/24232030

Perez, C. (2016). Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future. In *Rethinking Capitalism: Economics and Policy for Sustainable and Inclusive Growth* (Vol. 1, pp. 191–217).

Perez, C. (2020). *Digital and green_ a very convenient marriage*.

Peters, B., & Trunschke, M. (2021). Benefits of Investing into the Development of 4IR-Related Technologies working paper. *GROWINPRO*. https://www.zew.de/publikationen/benefits-of-investing-into-the-development-of-4ir-related-technologies

Reischauer, G. (2018). Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing. *Technological Forecasting and Social Change*, *132*, 26–33. https://doi.org/10.1016/j.techfore.2018.02.012

Rotolo, D., Hicks, D., & Martin, B. R. (2015). What is an emerging technology? *Research Policy*, *44*(10), 1827–1843. https://doi.org/10.1016/j.respol.2015.06.006

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group*, *9*(1), 54–89.

Schumpeter, J. A. (1939). *Business Cycles. A Theoretical, Historical and Statistical Analysis of the Capitalist Process*. McGraw-Hill Book Company.

Schwab, K. (2017). *The Fourth Industrial Revolution*. Crown.

Schwab, K., & Davis, N. (2018). *Shaping the Future of the Fourth Industrial Revolution: A guide to building a better world*. Penguin UK.

Teece, D. J. (2018). Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy*, *47*(8), 1367–1387. https://doi.org/10.1016/j.respol.2017.01.015

Trappey, A. J. C., Trappey, C. V., Govindarajan, U. H., Sun, J. J., & Chuang, A. C. (2016). A Review of Technology Standards and Patent Portfolios for Enabling Cyber-Physical Systems in Advanced Manufacturing. *IEEE Access*, *4*, 7356–7382. https://doi.org/10.1109/ACCESS.2016.2619360

Tucker, A., & Belford, G. G. (2021). *Computer science*. Encyclopedia Britannica. https://www.britannica.com/science/computer-science

UNCTAD. (2022). *Industry 4.0 for Inclusive Development* (Science Technology Innovation) [Current Studies]. https://unctad.org/system/files/official-document/dtlstict2022d4_en.pdf

UNEP. (2012). *Application of the sustainability assesment of technologies methodology: Guidance Manual*.

UNIDO. (2019). *Industrial Development Report 2020*.

Venturini, F. (2022). Intelligent technologies and productivity spillovers: Evidence from the Fourth Industrial Revolution. *Journal of Economic Behavior & Organization*, *194*, 220–243. https://doi.org/10.1016/j.jebo.2021.12.018

von Tunzelmann, G. N. (1997). Innovation and industrialization: A long-term comparison. *Technological Forecasting and Social Change*, *56*(1), 1–23. https://doi.org/10.1016/S0040-1625(97)00027-9

Webb, M., Short, N., Bloom, N., & Lerner, J. (2018). Some facts of high-tech patenting. *NBER Working Paper*, *24793*.

Wee, D., Kelly, R., Cattel, J., & Breunig, M. (2015). Industry 4.0-how to navigate digitization of the manufacturing sector. *McKinsey & Company*, *58*, 7–11.

Xu, H., Yu, W., Griffith, D., & Golmie, N. (2018). A Survey on Industrial Internet of Things: A Cyber-

Physical Systems Perspective. *IEEE Access*, *6*, 78238–78259. https://doi.org/10.1109/ACCESS.2018.2884906

Zhu, C., & Motohashi, K. (2022). Identifying the technology convergence using patent text information: A graph convolutional networks (GCN)-based approach. *Technological Forecasting and Social Change*, *176*, 121477. https://doi.org/10.1016/j.techfore.2022.121477

A. Appendix

A.1.

Figure A.1- Core, enabling and application technologies

	Definition	EPO (2017) Fields	(EPO, 2020a) Fields
Core technologies	Inventions that directly contribute to the three established ICT fields inherited from the previous industrial revolution	Hardware*, Software and Connectivity	IT hardware, Software, Connectivity
Enabling technologies	These technologies build upon and complement the core technologies.	Analytics, User interfaces, Three dimensional support systems, AI, Position determination, Power supply, Security	Data management, User interfaces, Core AI, Geo-positioning, Power supply, Data security, Safety, Three-dimensional support system
Application domains	Encompasses the final applications of 4IR technologies in various parts of the economy.	Personal, Home, Vehicles, Enterprise, Manufacture, Infrastructure	Consumer goods, Home, Vehicles, Services, Industrial, Infrastructure, Healthcare, Agriculture

Source: (EPO, 2017, 2020a)

A.2.

Figure A.2- Top 10 leading classes

	CPC CODE	Short description
1	G05B 19/418	Total Factory Control
2	G05B 19/42	Using digital processors
3	G05B 19/00	Program control systems
4	G05B 19/18	Numerical control
5	G06F 19/00	Digital computing or data processing equipment or methods, especially adapted for specific applications
6	G05B 19/05	Programmable logic controllers
7	G05B 23/02	Electric testing or monitoring
8	G05B 11/01	Automatic controllers (Electric)
9	H04L 29/0	Characterized by a protocol
10	G05B 19/02	Program control systems (Electric)

Source: Trappey et al. (2016)

A.3. Keywords queries used to construct the 4IR patent database

The main source of information for retrieving 4IR keywords is EPO's (2020b) methodological report where rather complicated queries are reported in the language of EPO's proprietary database (search) engine (EPOQUE). Our effort was to 'translate' these queries into the 'standard' SQL language (we use Transact-SQL dialect of Microsoft© SQL Server).

Our translation uses a combinations of two different search functionalities of Transact-SQL: 1) Full-text search (with the CONTAINS function) where multi-term search can be restricted to word proximity and the order of appearance (this functionality requires the titles and abstracts to be fully-indexed for textual searches) 2) Single term search with the standard LIKE operator. The obvious reason for this mixed approach is the fact that each operator has their own limitations (see below).

Note that both functionalities are provided also by other database engines (e.g., MySQL). Although the syntax of the latter functionality (by the LIKE operator) is identical across different database engines, that of the former (i.e., indexed full-text search) can be different.

Here are some partial examples on the (Transact-SQL) syntax:

WHERE tls203_appln_abstr.appln_abstract LIKE '%iot%' will search in all patent abstracts in the PATSTAT table tls203_appln_abstr, and retrieve all where the term "iot" shows up anywhere in the text. Obviously, a query like this is not a good idea in terms of precision, since abstract that include terms like "iota" or "antibiotics" will also be selected. Thus, one should rather search for variants such as ***'% iot %'*** or ***'%iot,%'*** or ***'%iot.%'***

Note that the LIKE operator also allows a number of wildcards other than '%' (which implies anything, including nothing). For example, a phrase such as ***LIKE '%4.0_industry%'*** (with the wildcard '_' accepts all variants such as "4.0-industry" or "4.0 industry" or "4.0_industry"

WHERE CONTAINS (tls202_appln_title.appln_title, 'NEAR((ambient, intelligence),3, TRUE)') will search in all patent titles in the PATSTAT table tls202_appln_title, and retrieve all where the terms "ambient" and "intelligence" both appear, but only if the latter follows the former in the text, as not separated by more than 3 other words in between. A similar query omitting the flag 'TRUE' would relax the condition on the order of appearance.

Also note that the CONTAINS function also allows wildcards but only at the end of search terms. For example, the phrase ***NEAR((machine, type, "commun*"),1, TRUE)*** accepts variants such as "machine type communicating", "machine type communication", "machine-type communicate" or "machine-type communication"

These basic elements can be further combined with the AND or OR operators with appropriate parentheses to indicate the priority in the order of execution to unionize or intersect, such as:

WHERE
CONTAINS (tls202_appln_title.appln_title, 'NEAR((ambient, intelligence),3, TRUE) OR NEAR((ubiquitous, computing),3, TRUE)') OR (tls202_appln_title.appln_title LIKE '% iot % OR tls202_appln_title.appln_title LIKE '% iot,% OR tls202_appln_title.appln_title LIKE '% iot.%)
OR
CONTAINS (tls203_appln_abstr.appln_abstract, 'NEAR((ambient, intelligence),3, TRUE) OR NEAR((ubiquitous, computing),3, TRUE)') OR (tls203_appln_abstr.appln_abstract LIKE '% iot % OR tls203_appln_abstr.appln_abstract LIKE '% iot,% OR tls203_appln_abstr.appln_abstract LIKE '% iot.%)

We provide all queries below as organized thematically into technology-based blocks. However, in order to save space (especially considering the redundancy of reporting the same queries for titles and abstracts separately) we use a particular reporting convention. In this convention, where we group queries under each thematic block further into the two search functionalities (i.e., the CONTAINS function and the LIKE operator), the exemplar query above would appear as:

CONTAINS (tittle or abstract, 'NEAR((ambient, intelligence),3,TRUE) OR NEAR((ubiquitous, computing),3, TRUE)')
OR (title or abstract) LIKE
('% iot % OR '% iot,% OR '% iot.%)

The 4IR patents dataset resulting from these set of SQL queries run on the 2021 Spring edition of PATSTAT can be downloaded at:
https://dataverse.nl/dataverse/4IR_Patents_Database

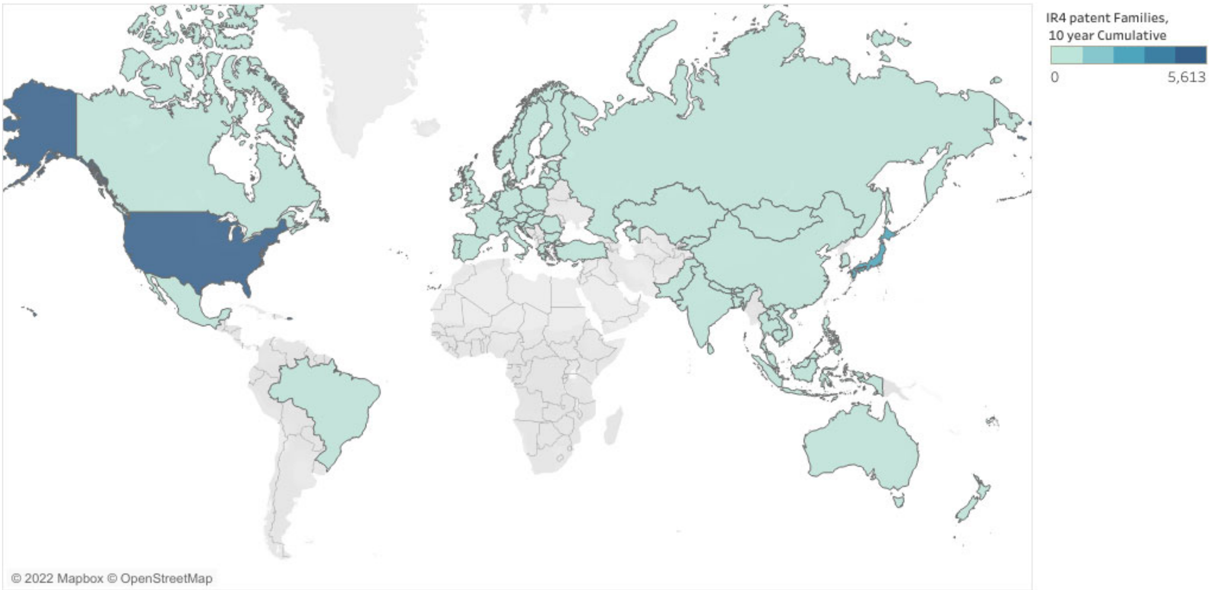
Subject	Keywords queries
Data transfer	**(title or abstract) LIKE** (('%content%' OR '%data%' OR '%file%' OR '%frame% OR '%image%' OR '%information% OR '%message%' OR '%packet%' OR '%record%') **AND** ('%broadcast%' OR '%communicat%' OR '%deliver%' OR '%distribut%' OR '%download%' OR '%exchang%' OR '%forward%' OR '%multicast%' OR '%notif%' OR '%report%' OR '%request%' OR '%send%' OR '%sent%' OR '%stream%' OR '%subscrib%' OR '%traffic%' OR '%transf%' OR '%transmi%' OR '%transport%' OR '%upload%'))
Internet of Things	**CONTAINS** (tittle or abstract, 'NEAR((machine, type, "commun*"),1, TRUE) OR NEAR((inter, vehicle),1) OR NEAR((inter, car),1) OR NEAR((ambient, intelligence),3, TRUE) OR NEAR((ubiquitous, computing),3, TRUE) OR NEAR((internet, things),3, TRUE) OR NEAR((internet, everything),3, TRUE) OR NEAR((web, things),3, TRUE) OR d2d OR iot OR m2m OR mtc OR mtm OR p2p') **OR (title or abstract) LIKE** ('%industry_4.0%' OR '%4.0_industry%' OR '%c_2_c%' OR ' %c_2_car%' OR '%c_2_infrastructure%' OR '%c_2_server%' OR '%c_2_v%' OR '%c_2_vehicle%' OR '%c_2_x%' OR '%c_to_c%' OR '%c_to_car%' OR '%c_to_infrastructure%' OR '%c_to_server%' OR '%c_to_v%' OR '%c_to_vehicle%' OR '%c_to_x%' OR '%car_2_c%' OR '%car_2_car%' OR '%car_2_infrastructure%' OR '%car_2_server%' OR '%car_2_v%' OR '%car_2_vehicle%' OR '%car_2_x%' OR '%car_to_c%' OR '%car_to_car%' OR '%car_to_infrastructure%' OR '%car_to_server%' OR '%car_to_v%' OR '%car_to_vehicle%' OR '%car_to_x%' OR '%device_2_device%' OR '%device_to_device%' OR '%inter%vehic%communic%' OR '%machine_to_machine%' OR '%peer_to_peer%' OR '%v_2_c%' OR '%v_2_car%' OR '%v_2_infrastructure%' OR '%v_2_server%' OR '%v_2_v%' OR '%v_2_vehicle%' OR '%v_2_x%' OR '%v_to_c%' OR '%v_to_car%' OR '%v_to_infrastructure%' OR '%v_to_server%' OR '%v_to_v%' OR '%v_to_vehicle%' OR '%v_to_x%' OR '%vehicle_2_anything%' OR '%vehicle_2_c%' OR '%vehicle_2_car%' OR '%vehicle_2_infrastructure%' OR '%vehicle_2_server%' OR '%vehicle_2_something%' OR '%vehicle_2_v%' OR '%vehicle_2_vehicle%' OR '%vehicle_2_x%' OR '%vehicle_to_anything%' OR '%vehicle_to_c%' OR '%vehicle_to_car%' OR '%vehicle_to_infrastructure%'OR '%vehicle_to_server%' OR '%vehicle_to_something%'OR '%vehicle_to_v%' OR '%vehicle_to_vehicle%'OR '%vehicle_to_x%' OR '% iot %' OR '% iot,%' OR '% iot,%' OR '%machine_type_communication%' OR '%inter_vehicle%' OR '%inter_car%' OR '%internet_of_things%' OR '%web_of_things%' OR '%internet_of_everything%' OR '%ubiquitous_comput%' OR '%ambient_intelligen%')
Augmented reality	**CONTAINS** (tittle or abstract, 'NEAR(("aug*", reality),3, TRUE) OR NEAR((mixed, reality),3, TRUE) OR NEAR((virtual, reality),3, TRUE) OR NEAR((enhanced, reality),3, TRUE) OR NEAR((mediated, reality),3, TRUE) OR NEAR((head, display),5, TRUE) OR NEAR((wearable, display),5, TRUE) OR NEAR((helmet, display),4) OR NEAR((environment, virtual),3) OR NEAR((world, virtual),3) OR HMD OR HUD') **OR (title or abstract) LIKE** (%data_eyeglass%' OR '%data_spectacle%' OR '%google_glass%') OR '%head_mounted_display%' OR '%head_up_display%' OR '%hmd%' OR '%hud%' OR '%wearable_display%' OR

	'%environment_virtual%' OR '%virtual_environment%' OR '%display_helmet%' OR '%helmet_display%' OR '%mixed_reality%' OR '%virtual_reality%' OR '%enhanced_reality%' OR '%augmented_reality%' OR '%augmented_environment%' OR '%mediated_reality%' OR '%mixed_environment%' OR '%virtual_world%')
Sensor	**CONTAINS** (tittle or abstract, 'NEAR((sensor, node),1, TRUE) OR NEAR((detector, network),1, TRUE) OR NEAR((meter, network),1, TRUE) OR NEAR((sensor, cluster),3, TRUE) OR NEAR((sensor, network),3, TRUE) OR NEAR((network, transducer),5) OR NEAR((network, probe),5) OR mwsn OR wsn') **OR (title or abstract) LIKE** ('%sensor_cluster%' OR '%sensor_network%' OR '%network_transducer%' OR '%transducer_network%' OR '%network_probe%' OR '%sensor_node%' OR '%detector_network%' OR '%meter_network%')
Smart Home	**CONTAINS** (tittle or abstract, 'NEAR((smart, city),1, TRUE) OR NEAR((smart, home),1, TRUE) OR NEAR((smart, house),1, TRUE) OR NEAR((intelligent, city),5, TRUE) OR NEAR((home, automation),1, TRUE) OR NEAR((office, smart),5) OR NEAR((intelligent, office),5) OR NEAR((building, intelligent),5) OR NEAR((cyber, "physic*", system),5, TRUE)') **OR (title or abstract) LIKE** ('%smart_city%' OR '%smart_house%' OR '%smart_home%' OR '%intelligent_building%' OR '%smart_office%' OR '%intelligent_office%' OR '%intelligent_city%' OR '%home_automation%' OR '%cyber%physi%system%')
Internet	**CONTAINS** (tittle or abstract, 'NEAR((internet, page),1,TRUE) OR NEAR((web, page),1,TRUE) OR NEAR((web, interface),3) OR NEAR((web, server),3) OR NEAR((web, application),3, TRUE) OR NEAR((web, service),3, TRUE) OR NEAR((web, application),3, TRUE) OR NEAR((representational, state, transfer),3, TRUE) OR NEAR((remote, function, call),3, TRUE) OR NEAR((remote, procedure, call),3, TRUE) OR NEAR((remote, method, call),3, TRUE) OR NEAR((remote, procedure, invocation),3, TRUE) OR NEAR((remote, method, invocation),3, TRUE) OR "BROWSER*" OR IP4 OR IP6 OR IPV4 OR IPV6 OR JSON OR SSL OR TLS OR VOIP OR VPN OR WEBSITE OR RFC OR HTML OR HTTP OR HTTPS OR INTERNET') **OR (title or abstract) LIKE** ('%e_mail%' OR '%voice_over_ip%' OR '%rest_api%' OR '%restful_api%' OR'%soap%´ AND '%protocol%´) OR '%browser%´ OR '%html%´ OR '%http%´ OR '%https%´ OR '%internet%´ OR '%ip4%´ OR '%ip6%´, '%ipv4%´ OR '%ipv6%´ OR '%json%´ OR '%ssl%´ OR '%tls%´ OR '%voip%´ OR '%vpn%´ OR '%website%´ OR '%web_site%´ OR '%interface_web%´ OR '%web_interface%´ OR '%server_web%´ OR '%web_server%´ OR '%web_application%´ OR '%application_web%´ OR '%web_service%´ OR '%representational_state_transfer%´ OR '%transfer_representational_state%´ OR '%remote_function_call%´ OR '%remote_procedure_call%´ OR '%remote_method_call%´ OR '%call_remote_function%´ OR '%call_remote_procedure%´ OR '%call_remote_method%´ OR '%remote_procedure_invocation%´ OR '%remote_method_invocation%´ OR '%invocation_remote_procedure%´ OR '%invocation_remote_method%´)
Wireless	**CONTAINS** (tittle or abstract, 'NEAR((wireless, lan),2) OR gprs OR gsm OR lpwan OR lte OR sms OR umts OR wifi OR wwan') **OR (title or abstract) LIKE** ('%3g%' OR '%4g%' OR '%5g%' OR '%802_11%' OR '%wi_fi%' OR '%w_lan%' OR ' '% lte%´ OR 'lte %´ OR '% sms%´ OR 'sms %´ OR '%umts%´ OR '%wifi%´ OR '%wireless_lan%´ OR '%wlan%´ OR '%wwan%')
Mobile device	**CONTAINS** (tittle or abstract, 'NEAR((mobile, "phone*"),1, TRUE) OR NEAR((cell, "phone*"),1, TRUE) OR NEAR((cellular, "phone*"),1, TRUE) OR NEAR((mobile, "phone*"),1, TRUE) OR NEAR((personal, digital, assistant),1, TRUE) OR NEAR((wireless, "device*"),1, TRUE) OR NEAR((cellular, "device*"),1, TRUE) OR NEAR((note, "book*"),2, TRUE) OR NEAR((net, "book*"),1, TRUE) OR NEAR((smart, "phone*"),1, TRUE) OR NEAR((hand, held),1, TRUE) OR NEAR((tablet, "computer*"),1, TRUE) OR blackberry OR "laptop*" OR "pager*" OR pda OR "notebook*" OR "netbook*" ') **OR (title or abstract) LIKE** ('%I_phone%' OR '%I_pad' OR '%I_pod%' OR '%blackberry%' OR ('%cellular%' AND ('%phone%' OR '%network%')) OR '%cellular_device%' OR '%hand_held%' OR '%iphone%' OR '%i_pad%' OR '%laptop%' OR '%net_book%' OR '%pager%' OR '%pda%' OR '%smart_phone%' OR ('%tablet %' AND '%computer%') OR '%mobile_phone%' OR '%mobile_device%' OR '%cell_phone%' OR '%personal_digital_assistant%' OR '%wireless_device%')

Cloud	**CONTAINS** (tittle or abstract, 'NEAR((cloud, "comput*"),3) OR NEAR((cloud, data),3) OR NEAR((cloud, "distribut*"),3) OR NEAR((cloud, "grid*"),3) OR NEAR((cloud, point),3) OR NEAR((cloud, "serv*"),3) OR NEAR((cloud, "stor*"),3) OR NEAR((grid, "comput*"),2) OR NEAR((software, "service*"),2) OR NEAR((platform, "service*"),2) OR NEAR((infrastructure, "service*"),2) OR NEAR((cluster, "server*"),2, TRUE) OR NEAR((server, "cluster*"),2, TRUE) OR NEAR((data, "center*"),2, TRUE) OR NEAR((server, "farm*"),2, TRUE) OR iaas OR paas OR saas') **OR (title or abstract) LIKE** ('%software_service%´ OR '%platform_service%´ OR '%infrastructure_service%´ OR '%cluster_server%´ OR '%cloud_comput%´ OR '%cloud_data%´ OR '%data_cloud%´ OR '%cloud_distribut%´ OR '%cloud_grid%´ OR '%cloud_point%´ OR '%cloud_server%´ OR '%cloud_stor%´ OR '%comput%grid%´ OR '%grid_comput%´ OR '%data_center%´ OR '%server_farm%´)
Artificial intelligence	**CONTAINS** (tittle or abstract 'NEAR((neuronal, "network*"),2) OR NEAR((neural, "network*"),2) OR NEAR((knowledge, based),2, TRUE) OR NEAR((inductive, logic),1, TRUE) OR NEAR((genetic, "algorithm*"),1, TRUE) OR NEAR((support, vector, "machine*"),2, TRUE) OR NEAR(("artifi*", logic),1) OR NEAR((neural, "reason*"),1) OR NEAR(("intellig*", "neuron*"),1) OR NEAR((fuzzy, "network*"),1) OR NEAR((fuzzy, logic),1) OR NEAR(("artifi*", "intelli*"),1) OR NEAR(("auto*", "learn*"),1) OR NEAR((data, mining),1) OR NEAR((deep, "learn*"),1, TRUE) OR NEAR((machine, "learn*"),1, TRUE)) **OR (title or abstract) LIKE** ('%artificial_intelligen%´ OR '%autonomous_learning%´ OR '%bayesian%´ OR '%data_mining%´ OR '%deep_learning%´ OR '%machine_learn%´, '%artificial_logic%´ OR '%intellig_neuronal%´ OR '%neural_reason%´ OR '%fuzzy_network%´ OR '%inductive_logic%´ OR '%knowledge_based%´ OR '%genetic_algorithm%´ OR '%support_vector_machine%´ OR '%neuronal_network%´ OR '%neuronal_intelligen%´ OR '%neural_network%´ OR '%fuzzy_logic%’)

A.4

Figure A.4- Cumulative # of IR4 Patents Families, All economies, 2000



A.5

Table A.5 - Specialization of global innovation centers by 4IR technologies subfields, 2000-2009

	China	USA	Korea	Japan	EU
IR4: 3D support systems	0,53	2,02	1,05	0,44	0,48
IR4: Agriculture	0,00	1,97	0,50	0,27	0,74
IR4: Connectivity	2,59	1,38	1,53	0,67	0,68
IR4: Consumer goods	1,89	1,34	1,81	0,73	0,63
IR4: Core AI	0,28	1,82	0,71	0,50	0,66
IR4: Data management	0,65	1,57	1,36	0,77	0,62
IR4: Data security	2,61	1,53	1,15	0,63	0,66
IR4: Geo positioning	0,56	1,46	1,09	0,89	0,65
IR4: Healthcare	0,28	2,16	0,73	0,37	0,62
IR4: Home	2,61	1,46	1,54	0,60	0,68
IR4: Industrial	0,60	1,63	1,06	0,67	0,70
IR4: Infrastructure	0,63	1,73	1,42	0,64	0,54
IR4: IT hardware	1,61	1,41	1,32	0,98	0,52
IR4: Power supply	1,48	1,35	1,94	0,84	0,48
IR4: Safety	0,22	1,15	1,59	0,92	0,82
IR4: Services	0,75	1,78	1,30	0,70	0,46
IR4: Software	1,06	1,78	1,18	0,74	0,46
IR4: User interfaces	0,73	1,60	1,35	0,87	0,45
IR4: Vehicles	0,55	1,31	1,18	0,93	0,77

The UNU-MERIT WORKING Paper Series

2023-01 *Can international mobility shape students' attitudes toward inequality? The Brazilian case* by Cintia Denise Granja, Fabiana Visentin and Ana Maria Carneiro

2023-02 *Demand-led industrialisation policy in a dual-sector small open economy* by Önder Nomaler, Danilo Spinola and Bart Verspagen

2023-03 *Reshoring, nearshoring and developing countries: Readiness and implications for Latin America* by Carlo Pietrobelli and Cecilia Seri

2023-04 *The role of product digitization for productivity: Evidence from web-scraping European high-tech company websites* by Torben Schubert, Sajad Ashouri, Matthias Deschryvere, Angela Jäger, Fabiana Visentin, Scott Cunningham, Arash Hajikhani, Lukas Pukelis and Arho Suominen

2023-05 *More than a feeling: A global economic valuation of subjective wellbeing damages resulting from rising temperatures* by Stephan Dietrich and Stafford Nichols

2023-06 *Was Robert Gibrat right? A test based on the graphical model methodology* by Marco Guerzoni, Luigi Riso and Marco Vivarelli

2023-07 *Predicting social assistance beneficiaries: On the social welfare damage of data biases* by Stephan Dietrich, Daniele Malerba and Franziska Gassmann

2023-08 *Related or unrelated diversification: What is smart specialization?* By Önder Nomaler and Bart Verspagen

2023-09 *Breach of academic values and digital deviant behaviour: The case of Sci-Hub* by Giulia Rossello and Arianna Martinelli

2023-10 *The effect of lobbies' narratives on academics' perceptions of scientific publishing: An information provision experiment* by Giulia Rossello and Arianna Martinelli

2023-11 *Making impact with agricultural development projects: The use of innovative machine learning methodology to understand the development aid field* by Lindsey Moore, Mindel van de Laar, Pui Hang Wong and Cathal O'Donoghue

2023-12 *Green windows of opportunity in the Global South* by Rasmus Lema and Roberta Rabellotti

2023-13 *The green and digital transition in manufacturing global value chains in latecomer countries* by Rasmus Lema and Roberta Rabellotti

2023-14 *Impact of prestigious-STEM Education of corporate board members on innovation effort: Evidence from India* by Rituparna Kaushik, Sourabh Bikas Paul and Danilo Spinola

2023-15 *Reducing environmental impact through shared ownership: A model of consumer behaviour* by Francesco Pasimeni and Tommaso Ciarli

2023-16 *Welfare losses, preferences for redistribution, and political participation: Evidence from the United Kingdom's age of austerity* by Patricia Justino, Bruno Martorano and Laura Metzger

2023-17 *Inequality, social mobility and redistributive preferences* by Isabel Günther and Bruno Martorano

2023-18 *Automation-induced reshoring and potential implications for developing economies* by Hubert Nii-Aponsah, Bart Verspagen and Pierre Mohnen

2023-19 *Ethnic spatial dispersion and immigrant identity* by Amelie F. Constant, Simone Schüller and Klaus F. Zimmermann

2023-20 *Public R&D and Growth: A dynamic Panel VECM Data Analysis for 14 OECD Countries* by Thomas H.W. Zieseme by r

2023-21 *Innovation and the labor market: Theory, evidence and challenges* by Nicoletta Corrocher, Daniele Moschella, Jacopo Staccioli and Marco Vivarelli

2023-22 *Revisiting Schumpeter in Europe: Place-based innovation and transformative industrial policy* by Luc Soete and Johan Stierna

2023-23 *Identification of Fourth Industrial Revolution technologies using PATSTAT data* by María de las Mercedes Menéndez, Önder Nomaler and Bart Verspagen