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COVID-19 and R&D Trends: Evidence from Patent Data.

TESI DI LAUREA MAGISTRALE IN
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Abstract

The advent of COVID-19 has reshaped consumption behaviors in the daily life of businesses and citizens, generating consequences in innovation activity. In this thesis, I will analyze patent trends in the most innovative technological fields, focusing especially on evidences of changes in their trajectories that have emerged during the two-year period marked by the COVID-19 pandemic (2020 – 2022). The aim of the work is to find out and observe the main R&D trends in the last decade (2012 – 2022) and look at preliminary evidence of changes in innovation activity through patent data analysis. During this process, I reflect on hypotheses concerning the role that COVID-19 pandemic might have played in altering the trends trajectories. In this work, I use the *MIT Technology Review*'s annual list of the 10 breakthrough innovations to gather data on 110 radically innovative technologies which represented the input for a patent landscape research on each one of them using the free and open-source patent search engine *Patentscope*. By leveraging the patent data for each technology, I drafted patent trends in 21 different technological fields. Then I examined each trend proposing hypotheses that suggest the reasons behind changing or unchanging trajectories. The hypotheses brought forward emphasize the gaps between present and future needs that the pandemic has produced. In this regard, my work may be useful from a practical standpoint because it offers data analysis on research patterns that may point to those technology areas for which the market is expected to show more interest in the future. From an innovation research perspective, the thesis I propose could support innovation research since it offers new evidence-based technological change hypotheses that might be relevant for upcoming innovation studies.

Key-words: patent, patenting trends, innovation, COVID-19, R&D, technology.

Abstract in italiano

L'avvento del COVID-19 ha rimodellato i comportamenti di consumo nella vita quotidiana di imprese e cittadini, generando conseguenze nell'attività di innovazione. In questa tesi, analizzerò i trend brevettuali nei campi tecnologici più innovativi, concentrandomi in particolare sulle evidenze di cambiamenti nelle loro traiettorie emerse durante il biennio segnato dalla pandemia di COVID-19 (2020 – 2022). Lo scopo del lavoro è quello di verificare e osservare i principali trend di ricerca e sviluppo nell'ultimo decennio (2012 – 2022) ed esaminare evidenze preliminari dei cambiamenti nell'attività di innovazione attraverso l'analisi dei dati sui brevetti. In questo processo, propongo delle ipotesi riguardanti il ruolo che la pandemia di COVID-19 potrebbe aver giocato nell'alterare le traiettorie dei trend. In questo lavoro, utilizzo l'elenco annuale delle *10 breakthrough technologies* del *MIT Technology Review* per raccogliere dati su 110 tecnologie radicalmente innovative che hanno rappresentato l'input per una ricerca sul panorama brevettuale di ciascuna di esse utilizzando il motore di ricerca di brevetti gratuito e open-source *Patentscope*. Sfruttando i dati sui brevetti per ciascuna tecnologia, ho elaborato i trend brevettuali in 21 diversi campi tecnologici. Dopo di ciò, ho esaminato ogni trend proponendo ipotesi che suggeriscono le ragioni dietro traiettorie alterate o non alterate. Le ipotesi avanzate sottolineano il divario tra esigenze presenti e future che la pandemia ha prodotto. A questo proposito, il mio lavoro può essere utile da un punto di vista pratico perché offre un'analisi dei dati sui modelli di ricerca che possono indicare le aree tecnologiche per le quali il mercato dovrebbe mostrare maggiore interesse in futuro. Dal punto di vista della ricerca, la tesi che propongo potrebbe supportare studi sull'innovazione poiché offre nuove ipotesi di cambiamento tecnologico che potrebbero essere rilevanti in future ricerche.

Parole chiave: brevetti, trend brevettuali, innovazione, COVID-19, Ricerca e sviluppo, tecnologia.

Contents

Introduction

Patents and patent analytics are widely considered to be instruments used by scholars and practitioners to have a proxy of innovation activities in technological fields and predict technological change (B. H. Hall et al., 2005; Pavitt, 1985). In this thesis, I will analyze patent data in the most innovative technological fields to study the R&D trends that have characterized these in the last 10 years (2012 – 2022). I focus especially on evidence of changes in the same trajectories that might have emerged during the two-year period marked by the COVID-19 pandemic. As a matter of fact, the outbreak of COVID-19 greatly affected consumption behaviors of citizens and companies with potential consequences on the innovation activity, especially in terms of prioritization of technologies to face the many challenges put forward by the pandemic. The motivation behind this work, is to unravel the main R&D trends in technology and look at preliminary evidence of changes in which the pandemic could have played a role. The aim of the work is to provide evidence-based hypotheses on trajectory changes and possible reasons behind the different behaviors of these trajectories. By looking at co-occurrences of trends and pandemic years, the work cannot detect causality, but can suggest new research cues which might subsequently be investigated concerning the causality links behind COVID-19 and patenting trends.

The hypotheses proposed in this thesis mainly concern the three different ways in which COVID-19 might have influenced innovation and R&D activity.

The first hypothesis deals with the patenting trends in which data shows a not-significant variations in their trajectory during the pandemic period (2020 – 2022). Here, I hypothesized that increasing or decreasing trajectories that were already in place before the pandemic and did not deviate during the pandemic might have not been altered by COVID-19. This could potentially suggest that R&D efforts in these technological fields were already either increasing or decreasing before the outbreak and the challenges brought forward by the pandemic did not influence research trajectories in these fields.

The second hypothesis concerns patenting trends in which data shows acceleration in the trajectory during the pandemic period (2020 – 2022). In this case, I hypothesized that trends that experienced this kind of deviation might have been boosted by COVID-19. In fact, the hypotheses that I put forward for these technological fields hint at increasing R&D efforts during the pandemic, given that technologies belonging to these categories proved to be valuable instruments to face the outbreak of the virus.

The third hypothesis deals with patenting trends in which data shows deceleration in the trajectory during the pandemic period (2020 – 2022). In this instance, I hypothesized that trends that experienced this kind of deviation might have been impacted negatively by COVID-19. The hypothesis that I suggest here mainly indicate at decreasing R&D efforts during the pandemic which potentially tell that technologies belonging in these fields were overseen by scientists and inventors to direct resources into different technological categories that better supported during the crisis.

In order to choose the set of emerging technologies to study, I have drawn from the *MIT Technology Review*, which every year lists the 10 breakthrough technologies that are most likely to impact businesses and consumers in the short-medium term. I analyzed the patent landscape for each of the ten technologies every year from 2012 to 2022 using the open-source patent search tool *Patentscope*, that allowed to gather data on 110 technologies that contributed to the development of 21 different technological fields. I then analyzed the patent trends directly in the fields to capture potential changes and observe patterns of growth.

The thesis is organized as follows. Chapter 2 presents an overview of the existing literature that deals both with patent innovation and research. In particular, I focused on reviewing literature on important innovation policies and initiatives undertaken during the crisis to capture similarities with the COVID-19 pandemic, to then touch upon the role that patents and patents analytics have had in spurring innovation during the outbreak. In the conclusion of the section, I provided an overview of the main technological trends that have arisen during the COVID-19 pandemic to cope with the outbreak. In Chapter 3, I illustrate the process followed to source, extract, encode and clean the data gathered from the *MIT Technology Review* and the steps needed to re-aggregate the data into the 21 technological fields from which I have drawn the trends. Chapter 4 shows the result of the research and introduces the main hypotheses of the thesis. This part is divided in three sub-sections, according to the three different trends trajectories observed. In each subsection, specific hypothesis concerning the technological fields analyzed are presented. Finally, in the last chapter, I reflect on the results of the work, pointing out its limitations and providing some concluding thoughts.

The research highlights the discontinuities that the pandemic has created between previous and future necessities. In this regard, my work could be helpful on a practical perspective as it provides data analysis on research trends that could hint at those technological fields that are likely to receive greater interest form the market in the future. Secondly, in this work I provide a set of new hypotheses on the reasons why COVID-19 may have or not impacted patent activity in certain technological fields. This could support innovation research since it supplies new hypotheses of technological change that may be relevant for future innovation studies.

1 Literature Review

In this literature review, I will discuss the context of innovation during the COVID-19 pandemic. In looking at the innovation landscape, the first sub-section will focus on the patenting activity in the 5 world largest patent offices, namely the *European Patent Office* (EPO), the *United States Patent and Trademark Office* (USPTO), the *China National Intellectual Property Administration* (CNIPA), the *Japan Patent Office* (JPO) and the *Korean Intellectual Property Office* (KIPO). More than 85% of all patent filings worldwide in 2020 occurred in the IP offices of China, the U.S., Japan, the Republic of Korea and the EPO (*WIPO Statistics Database*, 2022). In particular, I will analyze the impact that the pandemic had on the society as a whole in the US, Europe, South Korea, Japan and China and the severity that COVID-19 disease brought in in terms of restriction for social and work environments and the consequences that they had on the patenting activity. I will also depict how the 5 major patent offices addressed the limits imposed by the pandemic and facilitated the procedures to patent new inventions, especially the ones aimed at tackling the SARS-CoV-2 virus. After having analyzed how each country's office promptly responded to the first months of the sanitary emergency, I focused on providing a general overview of the patenting activity, making use of the *EPO Patent Index Report* (2020, 2021), the *WIPO Intellectual Property Indicator* (2020, 2021) and the *IP5 Statistics Report* (2020, 2021). This line of reasoning will allow to have a more general overview of patent trends and how these are linked to government policies aimed at fostering innovative activities. Following this contextual overview, the second sub-section will introduce the theme of *Crisis Innovation*. As a matter of fact, the pandemic crisis greatly affected innovation activity, thus it is important to understand how current innovation literature proposes to face the shock. Within the innovation management context, the third sub-section will then take a close-up on patents in COVID-19 era, recognizing patent policy as one of the most critical issues in crisis innovation. Although the role of patents has been frequently associated with barriers to knowledge sharing and innovation activities, several scientists and academics believe that patents may play a key role in spurring innovation during the pandemic. Finally, the last sub-section of this literature review will deal with the main technological trends that have arisen during the COVID-19 pandemic to cope with the outbreak. This section will first analyze those technologies that contributed to smoothen the transition of work in homes, then it will deal with the potential role of artificial intelligence preventing the virus spread, and lastly it will have a look on how technology have been used to strengthen the resilience of firms during the pandemic.

1.1. Context

Tedros Adhanom Ghebreyesus, the General Director of the World Health Organization (WHO) declared the spread of COVID-19 virus a pandemic-level infection on March the 11th 2020. By then, A large number of countries worldwide had taken or where on the verge of taking measures to address the spreading of the virus. In this contextual overview, I will show how the countries where the 5 main patent offices are located (USA, EU in general, Japan, Korea, China) adapted to the emergence of the SARS-CoV-2 virus and how the landscape of innovation and patent protection changed as a consequence of the pandemic.

1.1.1. United States

The US government was one of the last to take protective measures against the pandemic. The government put in place "stay-at home" restrictions on March the 19th in California , mandating all residents to stay at home except for going to workplaces in essential jobs (i.e. hospitals, groceries stores) or shop for essential needs, and progressively extended to the other 49 states. For 42 out of 50 states, the "stay at home" restrictions regarded all the territory of the state. In Utah, Wyoming and Oklahoma only in some parts of the states were actuated even more severe "shelter-in-place" restrictions, especially in Oklahoma. North Dakota, South Dakota, Arkansas, Nebraska and Iowa were the only states in which no restrictions of any kind were applied.

COVID-19 severely hit the USA in the months of April and May 2020, causing major collapses in the sanitary system, delaying clinical trials and *Food & Drug Administration* (FDA) approvals of pharmaceuticals. The end of the restrictions came on late May 2020, from which then came a gradual re-opening of most of the activities. In general, we can say that in the USA and Europe were applied the same "lockdown" measures – namely "stay at home" measures, interruption of productive activities, denial to cross national borders and mandatory isolation for infected people (AJMC, 2021; New York Times, 2021).

For what concerns the patenting activity, the *United States Patent & Trademarks Office* (USPTO) managed to continue its operations even during the enforcement of the "stay-at-home" measures. Although their offices were closed, the USPTO the patenting activities did not stop during the first lockdown period thanks to the help of remote-working technologies. USPTO also pursued many initiatives to simplify applications procedures and granting to overcome the difficulty caused by the closure of the offices. For instance, interviews, oral hearings and meetings were entirely held by videoconference and the handwritten signature requirement entirely withdrawn. Under the *Coronavirus Aid, Relief, and Economic Security Act*, USPTO helped out applicants and assignees by extending certain patent and trademark timing-related deadlines and, especially in the first months of lockdown, the relieved patent holders from renewal and administration fees. COVID-19 was also considered an excusable nonuse reason in trademark maintenance filings. Application filing was allowed through patent electronic filing systems in response to the outbreak.

USPTO also created a fast-track program for COVID-19 related inventions, with the aim of fostering and speeding-up research on key pharmaceutical and bio-technological fields related to the fight of the COVID-19 pandemic. The fast-track program was established by means of a dedicated platform that facilitated the connections between patent holders and potential licensees in key technologies to fight the virus was launched (USPTO, 2022).

1.1.2. Europe

In Europe, the first calls-to-action were fragmented after the pandemic hit. Indeed, COVID-19 diffused in Europe with diverse intensity depending on the countries. The first countries to introduce severe virus-related restrictions were Italy, France and Spain, in which events that implied gatherings of more than 10 people were suspended by the 5th of March 2020. After that, a series of different restrictions were applied in the different countries of the EU, which can be classified in 5 main categories:

- Self-isolation in case of positive CPR
- Encouraging social distancing
- Public events cancellation
- School and workplaces closure
- Orders of mass lockdowns.

Lockdowns were set up in 10 out of 27 countries in the euro area before the 25th of March 2020. Among these, we find Italy, France, Germany, Switzerland and Great Britain, which account for more than 30% of EPO patenting activity. In general, measures were variegated taking into considerations all the countries in the Euro-area, the most uniform metric that can be considered is the number of countries that decided to institute a state of emergency which in turn meant at the time stricter restrictions both for individuals and organizations. Out of 30 countries, 17 declared the state of emergency and 21 decided to impose lockdown measures (Cornelius, 2020; DW, 2020).

Similar to the USPTO, the *European Patent Office* (EPO) continued its operations during the first lockdown thanks to the massive employment of remote-working technologies. VICO (videoconference for oral proceedings) were made available for every applicant and the possibility to file priority document electronically was established while online customer support was strengthened. In addition to that, an electronic system to update customers on progresses for their applications or patents (alert systems, mailboxes, notifications, etc.) was created. The EPO extended the time limits on renewal and paying fees and expiration deadlines and cancelled any additional fee on patent holders who could not pay renewal and paying fees. The EPO was also one of the first patent offices among the IP5 to develop initiatives and share best practices to spur and incentivize innovation, so as to support innovators and the international IP community in their contributions to the recovery of our economies and societies (D Young & Co., 2021; EPO, 2022). They pursued many initiatives such as:

- cooperation in new emerging technologies and artificial intelligence
- enhance harmonization of practices and procedures
- strengthen work-sharing efforts
- improve the quality and efficiency of examination
- further enhance access to patent information.

1.1.3. Japan

According to the national law, the Japanese government did not have the authority to enforce citywide lockdowns. Apart from individual quarantine measures, officials were not able to restrict the movement of people to contain the virus. Consequently, compliance with government requests to restrict movements was on a voluntary basis, in the form of "asking for public cooperation to 'protect people's lives' and minimize further damage to the economy".

Factually, Japan could not formally impose a lockdown on its citizens, although there are some key dates where Japan announced and imposed social restrictions in order to minimize contact among citizens. Japan managed to keep on-point records of COVID-19 infections in the period of February/March 2020, thus prolonging the beginning of restrictions to end of March/beginning of April 2020.

As reported in an article of the paper *Kyodo News* of the 6th of April 2020, on 7th of April 2020, Japanese prime minister Shinzo Abe proclaimed a one-month state of emergency from 8th April to 6th May for Tokyo and the prefectures of Kanagawa, Saitama, Chiba, Osaka, Hyogo and Fukuoka. He stated that the number of patients would peak in two weeks if the number of person-to-person contacts was reduced by -70% to -80%, and urged the public to stay at home to achieve this goal. On 16th April 2020, Abe expanded the state of emergency declaration to include every prefecture within the country. Later on 4th May 2020, Abe announced that Japanese Cabinet would expand the state of emergency declaration until end of May 2020. Then on 14th May 2020, Abe and his cabinet declared that Japanese Government decided to relieve the state of emergency declaration, excluding eight prefectures like Tokyo, Kyoto Prefecture. The *Japan times*, on an article on the 20th of May, reported that On 21st May 2020, the state of emergency was suspended in three prefectures in Kinki after they had cleared the threshold of having new infections below 0.5 per 100,000 people in the past week, resulting a total of 42 out of the 47 prefectures to be out of the state of emergency while five prefectures, such as Saitama, Kanagawa, Hokkaido, were waiting for lifting decision on 25th May 2020. Approximately, the "restrictions" period lasted from March the 5th to the 21st of May in Japan. Although there was not a formal lockdown, Japan enabled governors to enforce restrictions on single individuals, thus avoiding nationwide restrictions.

For what concerns the patenting activity, the *World Trademark Review* in its *Live updates: IP offices implement measures in wake of coronavirus crisis* reports that the *Japan Patent Office* was never formally closed since there was not a lockdown enforcement. The library was closed for a limited number of weeks but in general operations continued without closures. They handled single requests for Covid allowing some relaxing of payment and renewal fees.

1.1.4. South Korea

As reported by the website *Al Arabiya News* in an article of the 3rd of April 2020, in the first worldwide lockdowns periods, South Korea was one of the few countries that managed to face the outbreak of COVID-19 without enforcing any lockdown. One of the hallmarks of South Korea's success was that authorities reacted remarkably quickly to reports of the spread of coronavirus in nearby China.

Just one week after the country reported its first case on January 2020, the government ordered factories to start producing coronavirus test kits *en-masse*. Testing then became the main strategy of the country to locate and isolate infected people. Mass testing was only possible thanks to South Korea manufacturing capabilities which in the first two weeks after the first case already had produced more than 100,000 tests. Government rolled out over 600 testing centers making testing easy and available. This mass of data coming from testing allowed authorities to monitor the spread of the virus and treat those infected. As part of the drive to get people tested, authorities made information about the spread of the virus public. As a matter of fact, public campaigns of information came very early in the pandemic, helping Koreans to get familiar with the virus, PPDs (Personal Protection Devices) and hygiene practices to protect individuals from the spread. The government also sent texts out to residents informing them when a case was discovered nearby and allowed access to its tracking data. Thanks to this effective testing strategy and wealth of information, the government act effectively and responsibly to slow the spread of the virus – without authorities having to enforce overbearing nationwide regulations or shut down the economy. Kindergartens, schools, universities, cinemas, gyms were closed soon after the outbreak of the virus. It's important to mention that there was no general lockdown of businesses in South Korea. Supermarkets, retailers, barbers, etc. were open. To cope with mass gatherings, schools and universities had online classes since the population have access to extremely fast internet in South Korea, everywhere.

As mentioned in the *World Trademark Review* in its *Live updates: IP offices implement measures in wake of coronavirus crisis*, in South Korea, the *Korean Intellectual Property Office* (KIPO) is still offering financial support to companies affected by the virus and those helping to tackle it (through vaccine development, prevention and diagnosis). KIPO also pledged to "improve the examination and review process of patents, trademarks, and designs" and especially conduct "prompt examination" of any patents linked to the coronavirus. Finally, the KIPO conducted "emergency monitoring" on counterfeit goods that could impede the recovery and health of citizens at risk of the virus.

1.1.5. China

China was the country in which COVID-19 first developed and spread. This impacted the country choices in fighting the virus in major ways. The 23rd of January 2020 Chinese authorities imposed the first lockdown in Wuhan city. From then on, China applied strict lockdown measures in all its major provinces and cities. The methods used in Wuhan would become routinely employed in the following months as China tackled outbreaks in other major cities such as Beijing and Shanghai with immediate lockdowns and swift mass testing. Hubei province was the most affected among all the Chines provinces. Major lockdowns have been enacted with very strict restrictions (every activity was closed and only necessary outings were justified).

The *China National IP Administration* (CNIPA), reports *World Trademark Review* in its *Live updates: IP offices implement measures in wake of coronavirus crisis*, extended deadlines for any trademark applicant or registrant affected by the coronavirus outbreak. On its website, the CNIPA explained that any time limits for trademark-related matters can be suspended from when a user "was hospitalized or isolated after being infected with the novel coronavirus" or from that date that any business suspended operations "due to the prevention and control measures. For what concern patents, the CNIPA promoted some initiatives to support applicants and holders:

- Promoted online services and temporary closes some offices
- Postponed or omitted oral hearings
- Relief for deadlines, payment and renewal fees
- Increased the amount of shared information from patents obtained.

1.2. Innovation during the pandemic crisis

COVID-19 pandemic not only represented a diffused health emergency worldwide. The productive inactivity provoked by the restrictive measures to fight the spreading of SARS-CoV-2 has put entire national economies on the brink of collapse. This, in turn generated drastic financial crises in the countries that were mostly affected by lockdown measures due to COVID-19, presenting serious challenges to economic growth and consumer activity (Figure 1.1).

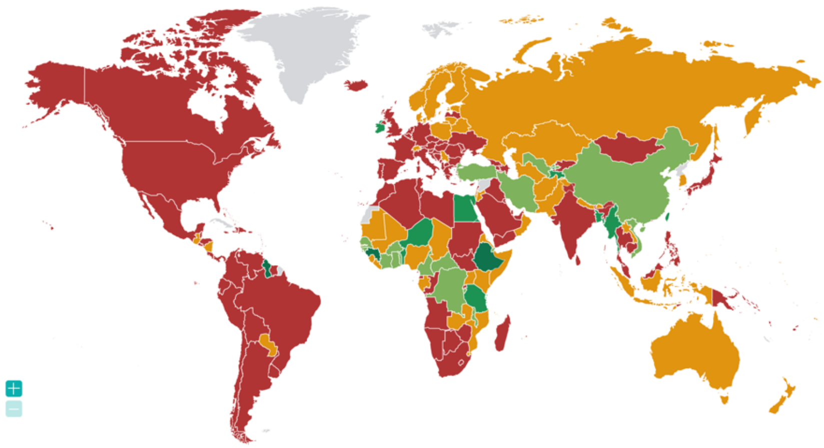

Figure 1.1. Map showing real GDP growth rates in 2020, recorded by the International Monetary Fund. Countries in red and yellow are the ones that faced a recession. In this are included most of the EU countries, USA, Japan and Korea (Source: International Monetary Fund, 2020).

Research on how financial crisis affected innovative activity is large but at the same time reports different outcomes. On the one hand, the financial crises hindered production of innovations thus reducing business dynamism and growth (Gourio et al., 2016; R. E. Hall, 2015). On the other hand, as mentioned by Babina et al. in the research *Crisis Innovation*, recessions might burst opportunities to reshape innovation efforts towards more efficient organizational forms and higher impact projects (Caballero & Hammour, 1991; Schumpeter, 2013).

1.2.1. Innovation policies during the pandemic

In the case of COVID-19, it is true that the most affected countries witnessed several modifications in their productive activities, however the scarcity of available data and a rather short time span following the economic shock does not allow to fully appreciate the changes in the innovative activity. Nevertheless, the pandemic brought forth great changes, especially in innovation policies, of which we will see the results in the years to come. As noted by Sampat and Shadlen, in the article *The COVID-19 Innovation System*, before the pandemic, biomedical R&D was mainly foraged by two different government policies: a "push" policy aimed at directing funds to support basic research and "pull" incentives in the form of patents to motivate private companies to develop drugs and vaccines. The pandemic created a major shift in innovation policy that had many consequences in terms of what kind of innovation where developed and how. The "push" mechanism during the pandemic was mostly directed at funding late-stage, clinical trial drugs and vaccines to avoid the risk of duplicative research and support manufacturing. On the "pull" side, COVID-19 switched on the use of advanced purchase agreements as innovation stimulus, since the focus to the enforcement of patent's rights was neglected by pharmaceuticals companies producing vaccines while it was privileged a *first-mover advantage* type of strategy (Liebermann & Montgomery, 1988). At the same time, attention was drawn on the matter of limiting patent rights to ensure an easy access to vaccines and more homogeneous price. The pandemic although demonstrated that limiting these rights may not be enough in crisis periods, where reaction time, manufacturing capabilities and logistics are crucial and extremely complicated to manage. Scaled-up production on a global scale needs significant technology transfer between pharmaceuticals company, a process that requires time and does not suit the immediateness of an ongoing pandemic.

1.2.2. COVID-19 Innovation context

The document *COVID-19: Insights from Innovation Economists* by Abi Younes, G. et al. (2020) also deals with the theme of crisis innovation and COVID-19. This document reports views from different economists on various sphere of COVID-19 innovations (e.g., vaccines investments, patents, recession caused by COVID-19), providing interesting conclusions on several question marks for science, technology and innovation (STI) fields during the pandemic. They deal with the concern on low R&D investments in vaccines research, arguing that the previous inexistence of sufficiently large demand for vaccines hindered the investments in the field. They also support the idea of the current *co-opetition* system that naturally established in the pharmaceutical industry to develop efficient treatments and vaccines against SARS-CoV-2. On the one hand, cooperation among research entities (i.e., universities, academic scientists, public-private joint ventures) enables the construction of larger knowledge bases and helps identifying the most promising paths for research. On the other hand, competition also drives research initiatives because it allows pharma companies to gain momentum as first-mover finding the treatment for the virus and lock in market share. That is the reason why competition behaviors among companies still prevails at international level. As for the patent system, the economists argue that although patents as policy tools might hamper research for a COVID-19 solution given the fact that they exclude other players from using, making and selling a protected invention, it is also true that in the recent past the popularity of systems such as patent pledges (disclosure to the public of protected technologies in a certain technological domain) and pools (a collection of patents from different holders available in bulk, for free or for a fee) increased. The economists believe that such systems may act as catalysts when searching for a solution to the pandemic and to COVID-19 research thanks to the high availability in one place and under clear terms of several technologies. This may also reduce litigation risks and lead to lower licensing fees among parties. They also argue that action of compulsory licensing from government to firms are a positive policy tool to enact during crisis times.

Exogenous shocks such as the COVID-19 pandemic always pose critical questions on how new technologies origin and then evolve. Solving a crisis in a short-term is a challenge that can be faced in different ways: in the case of COVID-19, it is shown that the concept of *technological exaptation* – defined as an "*innovation related to the creation of a new artifact derived from alternative uses of existing technologies*"(Garud et al., 2016) –, especially if characterized by a longer exaptive distance – time span that exist between "*the source and destination domains in a technological space*" (Andriani & Cattani, 2016) –, is a driving force of innovation coping with COVID-19 in the short term (Ardito, Coccia, & Messeni Petruzzelli, 2021). The COVID-19 pandemic shown how exaptation may be pivotal when driving innovation during unpredictable events. Clear examples are the use of the antiviral drug *Remdesivir* and the antirheumatic drug *Tocilizumab* to treat the SARS-CoV-2 disease. Moreover, research shows that longer exaptive distance may benefit the search for more innovative solutions and technological trajectories, thanks to the reduction of cognitive myopia and the promotion of a more creative problem-solving process (Ardito, Coccia, & Petruzzelli, 2021; Carnabuci & Operti, 2013; Lopez-Vega et al., 2016). In order to exploit the true advantages of exaptation, organizations should promote flexibility and agile practices that can make ex-novo R&D projects and devotion of efforts to search for potential application of existing innovations coexist.

1.2.3. Innovation as a response to critical times

The literature available so far depicts a two-faced view of innovation during crises: although crises can hamper the overall productivity of national economies thus slowing down the innovation process, it is clear that critical moments also ignite great opportunities for organizational changes and sharp steering in the field of innovation policies. In their research *Crisis Innovation Policy from World War II to COVID-19* (2021), Sampat and Gross compare and highlight the differences of the innovation policy problems exploring four key trade-offs: top-down vs bottom-up priority setting, concentrated vs. distributed funding, patent policy and managing disruption to the innovation system. They argue that in crises, a tension that drives the choices policymakers is the level of urgency that the problem at hand requires. This is why, comparably between World War II and COVID-19, top-down approaches at priority settings are preferrable in critical moments, since central agencies may better at understanding user needs and supply's constraints and have a broader perspective on the hurdles that may influence R&D, given that they are the most informed party among the involved ones. In the same way, a concentrated approach in funding may be the best choice in crises to better direct important resources to basic research that aims at solving the problems; however, when capability of scientists, firms and institutions are high and equal, the work is highly divisible and results are easy to screen, a distributed approach may yield better results. For what concerns patent policy, the authors believe that it all boils down to the trade-off between incentivizing innovation and diffusion of the results of innovation rapidly and broadly. The balance among these two factors should drive policies on the allocation of property rights, even though it can be very difficult to calibrate. On the other hand, the degree interruption of business-as-usual activities that may disrupt innovation system, is directly dependent on the gravity and urgency of the crisis. When crises are able to disrupt entire social system, short-run impacting innovations may be the only way to grant safety and success against this kind of problems, even at the cost of re-allocating inventive activity from regular R&D to crisis R&D.

1.3. COVID-19 and Patents

As I highlighted several times during the previous sub-chapter, the theme of patents policy is one of the most relevant in the field of crisis innovation. The *World Intellectual Property Organization* (*WIPO*) defines a patent as "*an exclusive right granted for an invention, which is a product or a process that provides, in general, a new way of doing something, or offers a new technical solution to a problem. To get a patent, technical information about the invention must be disclosed to the public in a patent application.*". The argument around patent during crises is widely divided among two different lines of thought: on the one hand, the grant of an exclusivity right to a single entity during times of crises may hinder easy transferring of importance pieces of knowledge that may help overcome the crises; on the other hand, concentrate the right to sell, distribute, manage the supply of a certain critical product or service to only one entity, may help in facing the urgency of the crises by providing reactive responses without the hassle of managing coordination among different parties (Gross & Sampat, 2021; Sampat & Shadlen, 2021; Abi Younes et al., 2020). Existing literature does not openly take a clear position towards the role of patents and the patenting system during crises, although it is agreed that policy tools such as patent pledges and patent pools can drive innovative forces and ignite public-private collaborations that bring positive outcomes and better knowledge sharing overall (Abi Younes et al., 2020).

Although the pandemic severely hit virtually all productive systems worldwide, slowing down economic activity, data from *World Intellectual Property Indicators 2021* published by WIPO, indicates that patent applications filed worldwide grew by +1.6% in 2020, with Asia being the global hub of the activity with a whopping 66.6% of applications (Figure 1.2).

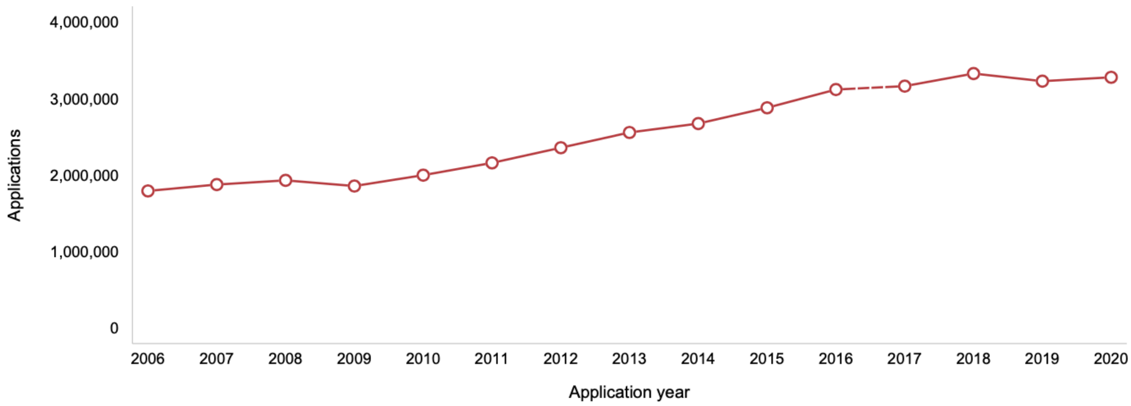

Figure 1.2. Patent applications worldwide, 2006–2020. (Source: WIPO)

This data shows that although national economies were suffering during the global pandemic due to the several restrictions and lockdown imposed by government, patenting activity was not affected by the virus, highlighting the importance that patents had during these last two years.

1.3.1. Patents as a response to the pandemic

As a matter of fact, patents were not just considered as a tool for policy-makers to regard and try to get the best out of them – spurring innovative activity but at the same time grant knowledge sharing. At firm and individual level, patents represented a crucial mean to react quickly to the virus disruption. At government level, patents were also used to identify firms that were likely to be successful in developing vaccines or treatment against COVID-19. In their research *Innovation management in crisis: patent analytics as a response to the COVID-19 pandemic* (2020), Guderian et al. show, through a series of case studies, the role that patent analytics may have for firms to direct their decision makers when drafting their crisis response strategies. In particular, the paper shows how innovation management decisions during crises moments like COVID-19 pandemic can be improved by using patent information and analytics to find data-driven solutions. In the study are evidenced several implications on the uses of patent analytics:

- Patent analytics can be applied to identify owned patent families that can be divested, sold or licensed-out considering as potential candidates the ones with a below-average internal citations metric and annuity fees considerations. This can allow firms potential cost-saving opportunities in order to save up resources during crisis times without compromising budget constraints.
- Patent analytics allows for a better understanding of firms' strategies through the examination of their patent portfolios (i.e., where to build new R&D centers, where to seek protection, where to find collaboration partners). Using quality

indicators for patent portfolios, may also provide indications for governments for data-driven innovation policy decisions (i.e., whether to shield companies from foreign acquisition or relocation).

- Information mined from patent helps measuring innovation outputs and future knowledge flows (Amelio et al., 2018; Ernst, 2003).
- Patent information may reveal data-driven predictions for firms that are likely to succeed in developing technologies and innovations to fight the crisis, as treatment or vaccination in the case of COVID-19.

1.3.2. *Crisis-critical* patents during COVID-19 pandemic

The role of patents is furtherly highlighted for the importance they assume in the developing and manufacturing of "*crisis-critical products*". These are classes of products that assume a paramount relevance as instruments to fight crises: in the case of COVID-19 pandemic, they may be treatments, vaccines or diagnostic tools and methods. It is safe to say that, given the fact that responses to the pandemic are technology driven, the stakeholders involved in the development and manufacturing of crisis-critical products are likely to face intellectual-property related challenges (i.e., patenting of vaccines, new technologies to improve tracking and diagnostics, availability of patent data on new technologies). These challenges are usually complemented by huge operational challenges to deploy critical resources, which makes other technology related challenges appear of lesser importance. However, if IP challenges are considered too late, this may lead to delays in mobilizing resources and reluctance from innovation stakeholders to engage in the development and production of crisis-critical products (Tietze et al., 2022).

Patents do not only represent an indicator of technological knowledge production only used in innovation research. Having at hand a global patent landscape may also benefit other field of science to anticipate important future technological developments. In the paper *Global landscape of patents related to human coronaviruses* (2021), Liu et al. exploit a global patent analysis to provide further resources for biological sciences for characterizing technological knowledge production in a specific field, providing groundwork for the development of vaccines and drug treatments. Thanks to the analysis conducted in this paper, it was possible to weigh the role of university and non-commercial organizations in the development of technologies related to coronaviruses. The fact that, among the top assignees, non-commercial organizations or governmental organizations stood out as a majority, indicates that governments took an active role in funding research for new treatments, underlining the rights that the public body has over therapies and vaccines developments. The analysis points out that public organizations are the ones more igniting collaboration among parties, thus favoring knowledge sharing and balancing competing interest.

1.4. Technological trends during COVID-19 pandemic

Analyzing patents and literature, it is also possible to point out the main technological trends that characterized the pandemic period. Indeed, COVID-19 had a major impact on certain technologies that mainly operate in two areas related to the virus: technologies that are related to the treatment of the virus and technologies that have been used to adapt to living under the health crisis (Brem et al., 2021)(

Table 1.1). The trends characterizing this technology will have short-and long-term consequences.

Table 1.1. Technological trends in COVID-19 pandemic with short- and long-term consequences. (Source: Brem et al., 2021)

Technology	Health/Quality of life (H/Q)	Short term consequences	Long term consequences
3D Printing	H	Fast production of medical devices	Increasing use of 3D printing in hospitals
Flexible manufacturing systems	H	Fast adaptation to manufacture medical devices	Redesign of medical devices to speed-up production
Big Data Analytics	H	Use of AI to improve diagnostics and faster development of vaccines	Increasing prevention and cyber-security solution
Health care wearables	H	Distance diagnostics	Smart health for health insurances
Distance learning	Q	Teaching under quarantine	Increasing market share of online courses
E-gaming	Q	Increase in number of tournaments	Virtual games as professional offline games
Videoconferencing	Q	Substituting in-person meetings	Full home-office working environments
Internet streaming	Q	No cinemas, theaters, concerts	Disruption of traditional media and consumption of entertainment
Cashless payment	Q	Reduce use of cash to prevent infections	Future domination of mobile payment methods
E-commerce and home delivery	Q	Increased e-commerce demand	Higher market share of e-commerce in retail

The pandemic was an element of disruption also in terms of new ways of developing, manufacturing and diffusing new technologies. For instance, it can be seen that the time-to-market for crucial technologies (e.g., respiratory ventilators) greatly diminished, cross-sectoral innovations surged thanks to partnerships among firms, social innovations and solutions that before were not popular among individuals and organizations (i.e., replace human intervention with AI and robots, telecommuting and flexible work) had the chance to prove their effectiveness (Brem et al., 2021). The pandemic even empowered technology scholars, giving them the new responsibility of collecting, analyzing and managing the huge amount of data collected during COVID-19 outbreak and build common data space to help health information systems and public health data sharing (He et al., 2021). COVID-19 not only produced micro-trends on singular technology, it also emphasized the progressive *technological convergence* phenomenon which is defined by The European Commission, in its Green Paper on Technological Convergence (1997), as: "*The ability of different network platforms to carry essentially similar kinds of services, or the coming together of consumer devices such as the telephone, television and personal computer*". Technological convergence became a major trend with the advent of digital technologies. In particular, COVID-19 allowed the creation of new technological clusters in which several groups of technology converged to build-up the characteristics of the new cluster. For instance, newly created technological clusters – such as remote controlling technologies – are mostly composed by aggregate of already existing technology clusters (i.e., IoT, Cybersecurity) (Melluso et al., 2020) (Figure 1.3).

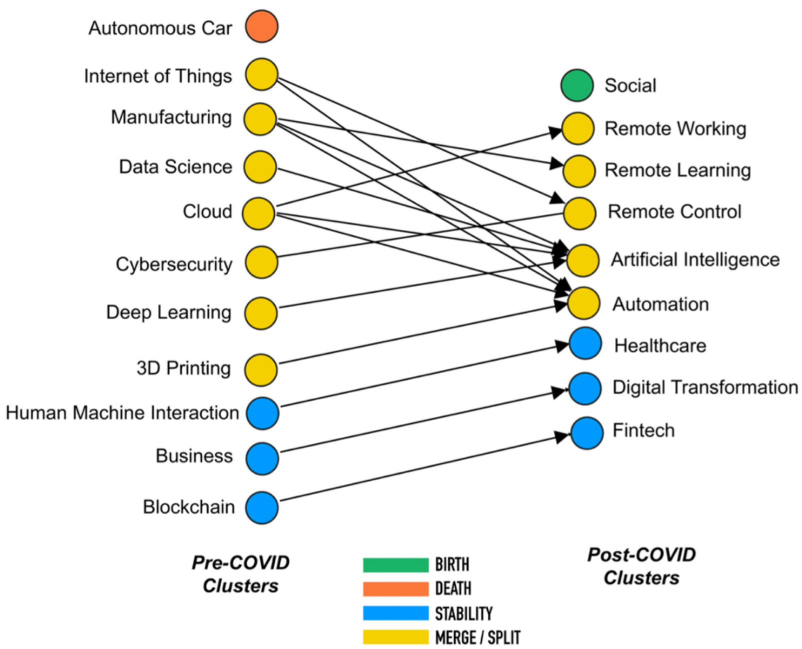

Figure 1.3. Bipartite network of pre- and post-COVID-19 technology clusters. (Source: Melluso et al., 2020)

1.4.1. Working-from-home (WFH) and remote technologies

The COVID-19 outbreak triggered great shifts in the way everyone lives their ordinary day-to-day. One of the most disruptive of all has been the transformation of the way everyone works. People were in fact constrained in their houses due to restrictions imposed by the governments; this led to the establishment of working-from-home (WFH) technologies that enabled people to respect the health-preserving measures while continuing to be productive. According to a survey available in Barrero et al. (2020), 23% of all full work days will be supplied from home after the pandemic ends, as compared to just 5% in 2017/2018. Pagano et al. (2020) also argue that firms having adopted this kind of technologies had much higher returns in the wake of COVID-19 thanks to the ability of their employees to perform their tasks remotely. In their research *COVID-19 Shifted Patent Application toward Technologies that Support Working from Home* (2021), Bloom et al. notice through a patent application analysis at USPTO that WFH share of new patent application in September 2020 reached +1.16%, more than double its January 2020 value. This growth lead to thinking that this trend will be a persistent rise in the flow of new patents that advance WFH technologies, as well as continuous ascent to tools and platform that support WFH activity even when COVID-19 outbreak is under control. Barrero, Bloom and Davies (2020) evidences other factors that will lead to a major shift in WFH after COVID-19, among these: a better-than-expected experience in WFH since pandemic struck, investment in physical and human capital that support WFH, a diminished stigma towards WFH and desire to avoid public transport and crowded facilities due to fear of infection risk.

COVID-19 also highlighted how recession and economic downturn hit unequally in different sectors. Cirelli and Gertler (2022) show how "contact" sector firms, organizations and professionals – namely those who were more exposed to the threat of COVID-19 since their jobs highly depends on social interactions and have little flexibility to work remotely (such as waiters, hairdressers, and dentists) (Kaplan et. al, 2020) – experienced contractions and slow recovery, while the entities that were capable of offering substitutes enabled by WFH technologies and embraced flexibility – namely "contact" sector winners (Cirelli & Gertler, 2022) – gained throughout the crisis, growing around 50% more with respect to "contact" sector losers. Cirelli and Gertler also predict the gap between winners and losers will persist well beyond the pandemic.

1.4.2. Preventive technologies: Artificial Intelligence against COVID-19

The focus of technology academics and scientist was not only to find the best technological means to fight the virus in the first place, much research was also dedicated to finding the right way through which another worldwide pandemic could be avoided. In this regard, Artificial Intelligence (AI) is potentially a powerful tool. The research by Wim Naudè (2020), titled *Artificial Intelligence against COVID-19: An Early*

Review, provides a selective review discussing the contributions of AI to fight COVID-19, as well as the constraints on these contributions. The author predicts six areas in which AI can contribute to the fight against COVID-19 and future pandemics.:

- Early warnings and alerts: AI application may be useful in warning early outbreaks of new pandemics with the right datasets and interpretation (see *BlueDot* and *HealthMap*).
- Tracking and prediction: dynamic neural network trained with data coming from previous pandemics, may be able to track and predict the spread of another one (Akhtar et al., 2019) (Figure 1.4).
- Data Dashboards: (related to tracking and prediction) tools to visualize actual and expected spread of the virus (see *UpCode* and *NextStrain*).

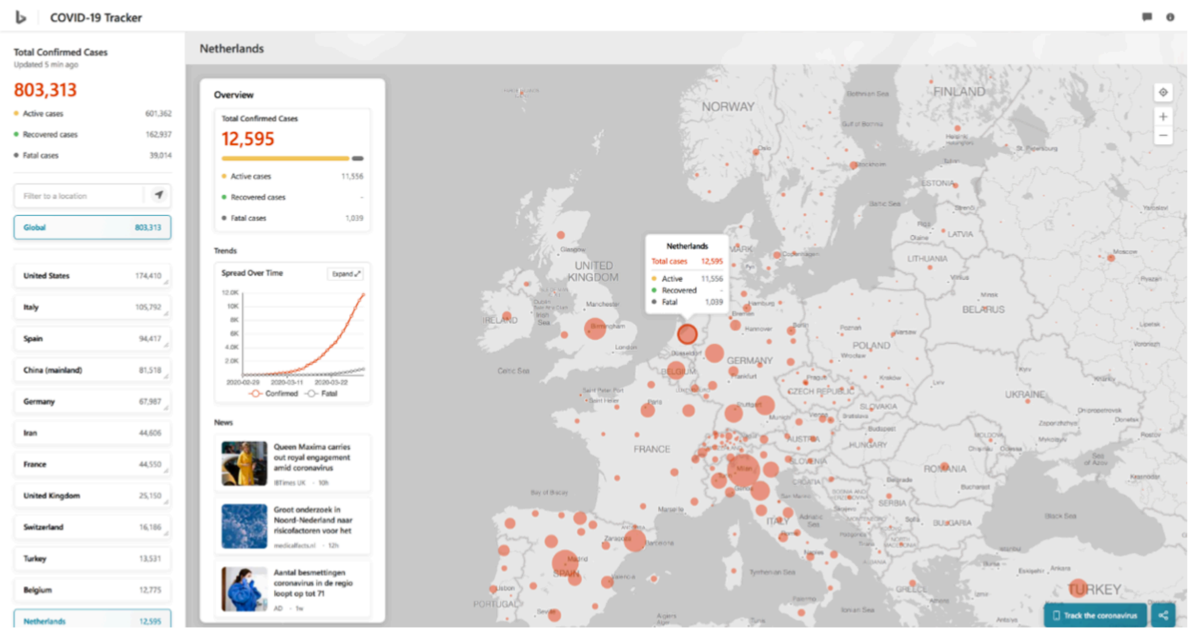

Figure 1.4. Microsoft Bing COVID-19 tracker (Source: Naudè, 2020).

- Diagnosis and prognosis: through the aid of computer vision, deep learning algorithms may be able to diagnose COVID-19 virus at early stages through CAT scans, and if fed with great amount of data can also provide a prognosis of how the patient may progress.
- Treatments and cures: through prediction algorithms that can anticipate the protein structure of a virus, AI could potentially contribute to new drug discovery (Coldeway, 2019; Nic Fleming, 2018; Segler et al., 2018; Simon Smith, 2018).

- Social Control: thermal imaging and computer vision are valuable instruments to locate infected people and make sure that social distancing rules are respected in public spaces (see *Baidu*).

Naudè also points out that the potential of AI in pandemics is severely constrained by too little or too noisy data, which is the reason behind why, among the application of AI listed before, none is at operational level.

The value of the use of AI in healthcare sector is testified by a steep increase in patents published, accounting for almost 800 hundred in 2018 as shown in Figure 1.5.

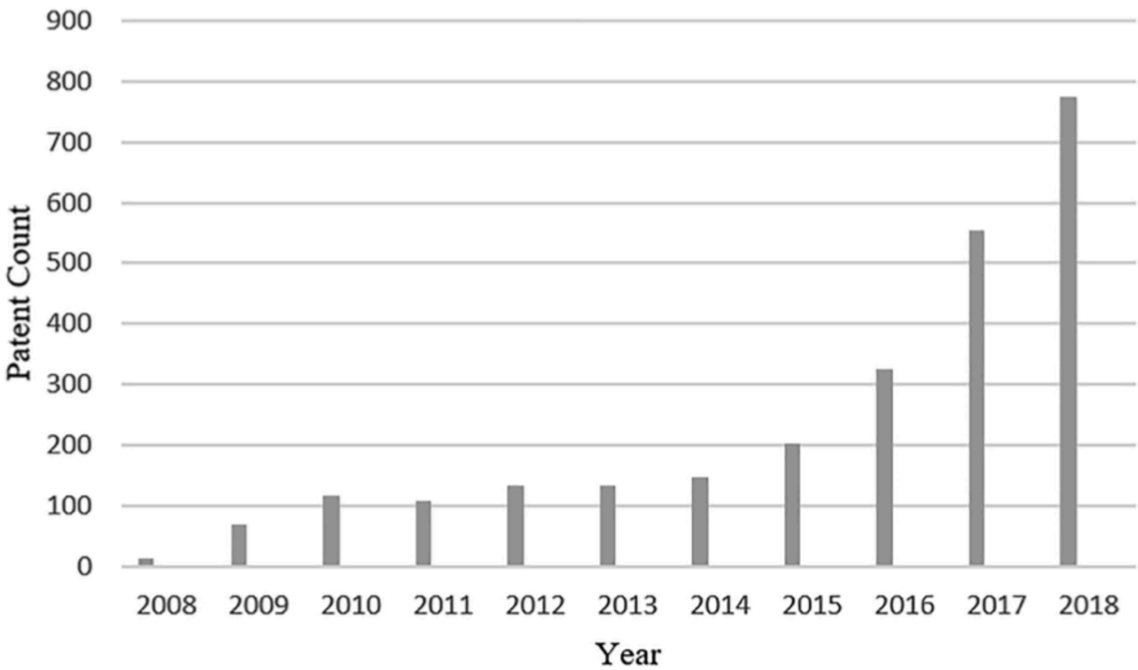

Figure 1.5. AI-healthcare patents published, 2008-2018 (Source: Wang & Lin, 2021)

Most promising AI technology in the field is in the Robotics field, which is shown to provide interesting results in surgical and diagnostic applications (Table 1.2). Diagnostics and medical imaging are particularly active fields for AI application because they contribute at enriching medical database that will be increasingly useful in the AI/healthcare field (Wang & Lin, 2022).

Table 1.2. Technology/function matrix. (Source: Wang and Lin, 2021)

Technology \ Function	Automated diagnosis/ diagnostics (F1)	Medical imaging (F2)	Surgery (F3)	Patient monitoring and care (F4)
Machine learning (T1)	**53**	13	2	0
Natural language processing (T2)	9	0	10	0
Expert systems (T3)	12	2	0	0
Computer vision (T4)	13	11	3	0
Speech recognition (T5)	**106**	5	12	3
Robotics (T6)	**150**	**45**	**343**	0

Note(s): Bold number representsmost patents'concentration between specific technologies and functions

In the wake of COVID-19, AI was not only used in developing healthcare application. During the pandemic, AI was greatly employed in the supply-chain field to help withstand the disruption brought by the pandemic. The capacity of AI algorithms to predict customer demand, depict "what-if" scenarios, show data trends and alert about risks aided in the process of redesigning supply-chains to deliver quick and accurate goods and services with the highest degree of safety and security (Sharma et al., 2022). AI-facilitated supply chains are able to recognize risks, analyze scenarios and predict variations in demand, reconfigure faster in case of security threats realigning networks and activate rules and systems quickly (Modgil et al., 2022).

1.4.3. Technology and Resilience to the Pandemic

The concept of resilience is one that has been on the rise in the wake of COVID-19. Resilience is defined as "*the capability of firms to readily respond to and quickly recover from disruptive events or crises faced*". COVID-19 outbreak tested companies' abilities in many ways, in most times greatly affecting their performances. Nevertheless, the study *Technology and Resilience* conducted by Cirera et al. (2022) shows that a high level of pre-COVID-19 technology sophistication in a firm had positive influences in performances during the pandemic, thus facilitating resilient behaviors. In particular, the authors show that increasing pre-pandemic technology readiness by one standard deviation is associated with a 3.8 percentage point in higher sales. Their empirical model accounts for two effects, as it is shown in Figure 1.6: the "direct" effect, in which technology sophistication directly help businesses navigate the shock of COVID-19, for example, by enabling a quick switch to home-based work given they are more likely to already have digital systems in place. On the other hand, technology sophistication could affect the likelihood of responding to the pandemic increasing the use or the adoption of digital technologies, which in turn enables an "indirect" effect on sales by, for instance, increasing the use of digital platforms to sell products online.

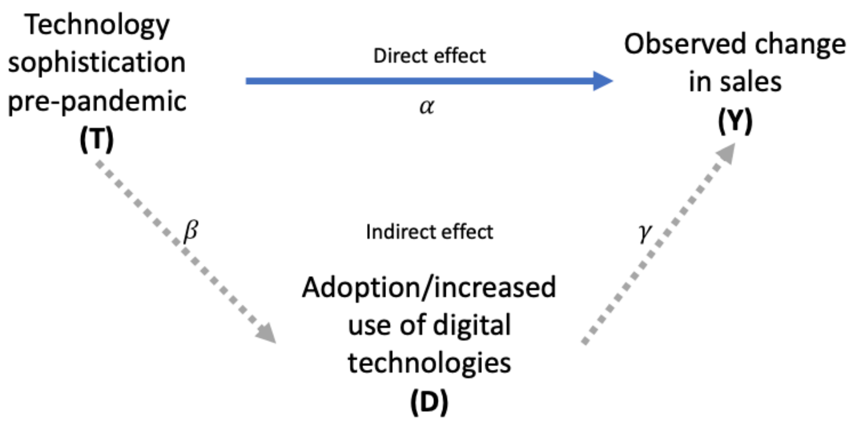

Figure 1.6. Direct and indirect effects of technology sophistication pre-pandemic on the performance of firms. (Source: Cirera et al., 2022)

As for technology sophistication, another factor playing key role in firm resilience is technology diversification. As a matter of fact, firms with higher level of diversified technology, measured as the wideness of scope of their patent application, are shown to be more profitable during natural disaster crises. This emphasizes that technological diversification helps firms survive and endure natural disasters, contributing to firm's flexibility, adaptability, and resourcefulness required to respond resiliently to natural disasters (Hsu et al., 2018).

Digital technologies were the most used to cope with the disruption brought by the COVID-19 outbreak. Firms with higher digital resilience performed significantly better during the pandemic: Raj et al., (2021) show that restaurants that already had adopted Uber Eats and delivery systems before the COVID-19 crisis experienced increase in sales and orders; Bai et al. (2021) shows that firms more prone to WFH practices before COVID-19 had higher sales and incomes during the outbreak. On the same perspective, Yoon (2021) finds that digital innovation, measured by the share of patents related to *untact* technologies. These are products, systems and methods that allow customers a non-direct face-to-face contact with employees; e.g., remote healthcare, mobile payments, e-commerce – substantially incremented in industries that already had patents related to non-face-to-face methods and technologies in response to COVID-19, testifying a growth in digital innovation activity during the outbreak. The results are driven especially by small firms, which increased their untact-related patent share by almost +45%, while large firms registered an increase of +16.3%. These results suggest that small firms found opportunities to improve their adaptation capabilities in times of crisis. Chatterjee et al. (2022) also suggest digital technologies, especially big data driven innovation, in small-medium enterprises (SMEs) impacts positively the resilience of their supply chain capability, which in turn impacts the SMEs performance in the post-COVID-19 scenario. The study builds upon the resource-based view of the firm (Barney, 1991), stating that SMEs' core digital innovation and technology capabilities (i.e., big data analytics capability, IoT capability, cloud computing capability) are valuable, rare, inimitable and non-substitutable resources when facing COVID-19 outbreak. Likewise, following the theory of dynamic capabilities (Teece et al., 1997), the authors affirm that firm's ability to integrate, build, and reconfigure internal and external technologies and capabilities (i.e., WFH practices, CRM technologies improving) is necessary to improve supply chain resilience during a pandemic. This shows how firm's performances are strictly related to their ability to withstand business activities in unprecedented scenarios and, similarly, the latter is related to the adoption of ground-breaking technologies and strength of R&D wing.

COVID-19 pandemic also played a key role in accelerating technological transitions that had already begun in the pre-COVID-19 period. For instance, digital financial technologies ("fintech") adoption increased during the outbreak: exposure to the epidemic leads to enhanced chances of individuals transacting through online and mobile payments. Results show a 10.6 percentage points growth in online and mobile transactions using the internet and bank account, and a total 4.5 percentage points increase in mobile payments using bank accounts. In addition, given the flow of banking activities did not change from the pre-COVID-19 period, this leads to thinking that COVID-19 exposure only affects the forms of banking activities and not the figure (Saka et al., 2021). COVID-19 and the threat of future pandemics are also believed to accelerate the process of automation (Chernoff & Warman, 2020). Caselli et al. (2020) studied the relationship between robots and COVID-19 risk in Italy. Their results show that industries that made greater use of robots in pre-pandemic era face lower risk from COVID-19 contagion. This remarks the trend that shows how firms' investments in technology are done according to the safeguard against COVID-19 and future pandemics.

2 Data & Methods

Creating solid databases to support the analyses and have a sound basis to draw conclusions is a key activity in research. In this research, data assumes a crucial role to identify and map the R&D trends that have been accelerated, decelerated or left unchanged during the COVID-19 pandemic. In this chapter, I will explain the sources used to intercept breakthrough technologies and technological advances that will likely be revolutionary for businesses and consumers alike (Silva et al., 2017). Afterwards, the focus of the chapter will shift to the means used to investigate how the different technologies identified influence patenting activity over a period of ten years (2012 – 2022). The research tool that I employed to detect patenting for the different technologies is *Patentscope*, an open-source portal provided the WIPO, which contains 107 million patent documents including 4.4 million published international patent applications (PCT). All the patent data available in the research was sourced out from *Patentscope*. I will then move on to introduce the process followed to extract data from *Patenscope* that entails different query search for each technology to identify their related patent landscape. Upon the extraction process, I will describe how I decided to record the data related to the patents searched for each technology and the reason behind the choice of information to be collected. After that, I will illustrate the methodology followed to clear out the data, which was particularly important for two reason:

- Eliminate patent–outliers in a technology-specific patent landscape that would increase the noise in the trends.
- Detect missing patents in a technology-specific patent landscape that may have been left out from the initial screening.

Afterwards, a sub-section will deal with the classification of the patent into 35 different technological fields from the *IPC tech concordance*. This process was necessary to aggregate the patent data on singular technologies and sort out the macro-trends per each technological field.

Finally, I dedicated the last sub-section to the description of the process used to draft the patenting trends, which makes use of the previously mentioned *classification matrix* and yearly patent publications to obtain the general contribution of each technology to the *IPC technological concordance* fields.

2.1. Data Sourcing

This research comprises a data sourcing activity divided in two sub-activities carried out in chronological order: the first part was dedicated to the identification of the object of the patenting activity I wanted to analyze, thus the technological advances and breakthrough that have been regarded as the most disruptive in the last decade; the second part was, on the other hand, dedicated to the collection of the actual patent data related to the technological breakthroughs.

2.1.1. Selection process of the technologies object of the patenting activity

In order to detect the patenting trends over the last 10 years and measure the effects of the COVID-19 pandemic, it was necessary to set-up a benchmark to identify with reasonable certainty the most impactful technologies of the last decade that could have relevant implications for businesses in the future. I decided to consult *MIT Technology Review* to identify these technologies, as it can be considered a prominent source in technology and innovation fields. The *Massachusetts Institute of Technology* (MIT) scores consistently in the first place among universities worldwide in the engineering and technology fields and it is regarded as one of the best technology research hub in the world (*QS World University Ranking*, 2022). Every year, the *MIT Technology Review* lists the 10 breakthroughs in technology believed to have the biggest impact on the world in the years to come. I collected every technology mentioned in the *Review* from the year 2012 to the year 2022, providing the name of each technology and brief description of it. For what concerns the description, I used the ones available in the *Review* and, in case of difficulties in the understanding, other reliable description found on *Google.com*. In the cases in which the technology mentioned in the *Review* was a specific application of a more generic technology, I provided a wider description referring to the technology at the base, however not changing the scope of the research. In Table 2.1 are listed all the technologies collected with their own description.

Table 2.1. List of ten 10 breakthrough technologies from 2012 to 2022, with description (Source: MIT, 2022)

Year	Technologies	Definitions
2012	Solar Microgrids	Low-cost solar-powered microgrids that can provide clean light and charge phones. The advantage of a microgrid is that the installation cost can be spread across a village. The system can also use more efficient, larger-scale generation and storage systems, lowering operational costs.
	Light-Field Photography	Record the position, color, and intensity of the light that comes through a lens. Lytro's camera does all that, but it also records the angle at which rays of light arrive. The result is a mini-databases of three-dimensional pattern of light (light-field)
	Egg Stem Cells	They are cells that can differentiate, or develop into other kinds of cells. Furthermore they could be used to rejuvenate an older woman's existing eggs
	Ultra-Efficient Solar power	Use glass lenses to concentrate incoming light, maximizing the power production of tiny photovoltaic cells
	Crowdfunding	The case of Kickstarter. This crowdfunding model offers an alternative to traditional means of raising startup funds for some types of businesses, such as Web or design firms.
	A Faster Fourier Transform	Faster way to perform the Fourier transform, a mathematical technique for processing streams of data that underlies the operation of things such as digital medical imaging, Wi-Fi routers, and 4G cellular networks.
	3-D Transistor	Faster and more energy-efficient processors
	Facebook's Timeline	The social-networking company is collecting and analyzing consumer data on an unprecedented scale
	Nanopore Sequencing	The technology offers a way to make genome sequencing faster, cheaper, and potentially convenient. Simple and direct analysis of DNA will make genetic testing routine in more situations.
	High-Speed Materials	Electric cars could travel farther, and smart phones could have more powerful processors and better, brighter screens, thanks to batteries based on new materials being developed by San Diego–based Wildcat Discovery Technologies. The company is accelerating the identification of valuable energy storage materials by testing thousands of substances at a time. In March of last year, it announced a lithium cobalt phosphate cathode that boosts energy density by nearly a third over current cathodes in popular lithium-ion phosphate batteries. The company also unveiled an electrolyte additive that allows batteries to work more reliably at higher voltages. The devices have three principal components: an anode, a cathode, and an electrolyte. Not only can each be formed from almost any blend of a huge number of compounds, but the three components have to work well together.
2013	Smartwatch	A smartwatch is a wearable computer in the form of a watch; modern smartwatches provide a local touchscreen interface for daily use, while an associated smartphone app provides for management and telemetry (such as long-term biomonitoring).
	Ultra-Efficient Solar Power	Doubling the efficiency of solar devices would completely change the economics of renewable energy
	Memory Implants	A maverick neuroscientist believes he has deciphered the code by which the brain forms long-term memories.

	Deep Learning	With massive amounts of computational power, machines can now recognize objects and translate speech in real time
	Big Data from Cheap Phones	Collecting and analyzing information from simple cell phones can provide surprising insights into how people move about and behave—and even help us understand the spread of diseases.
	Additive Manufacturing	Additive manufacturing can produce complex, precisely designed shapes like the one at right.
	Temporary Social Media	Messages that quickly self-destruct could enhance the privacy of online communication and make people feel freer to be spontaneous.
	Baxter: The Blue-Collar Robot	Baxter robot use his sensors to discover when a human is nearby, allowing him to monitor himself and work on his own.
	Supergrids	A high-power circuit breaker could finally make DC power grids practical, transporting electricity over thousands of kilometers and for long distances underwater
	Prenatal DNA Sequencing	Sequence the DNA of a human fetus before birth
2014	Genome Editing	Genome editing (also called gene editing) is a group of technologies that give scientists the ability to change an organism's DNA. These technologies allow genetic material to be added, removed, or altered at particular locations in the genome.
	Microscale 3D Printing	Microscale 3-D printing is a type of 3-D printing that makes it possible to construct objects at an extremely small scale. Some processes can create objects as small as 100 micrometers. 3-D printing at this scale has a number of applications for computing and medicine.
	Agricultural Drones	An agricultural drone is an unmanned aerial vehicle used in agriculture operations, mostly in yield optimization and in monitoring crop growth and crop production.
	Ultraprivate Smartphones	The ultra-private smartphone has features of encrypting the data. The encryption of message helps in minimal loss or transmits of personal information, and Blackphone leads the charge. Blackphone is the amalgamation of Silent circle and Geeksphone's technologies. Silent circle provides services like encrypted voice and text services, and Geeksphone made the device. A Blackphone is an ultra-private smartphone with an operating system named as PrivateOS, which helps in storing the message in an encoded form. The ultra-private smartphone provides greater control over what other people can do on their phone, encrypts data stored in the phone that provides greater security.
	Brain Mapping	Brain mapping is the study of the anatomy and function of the brain and spinal cord through the use of imaging (including intra-operative, microscopic, endoscopic and multi-modality imaging), immunohistochemistry, molecular & optogenetics, stem cell and cellular biology, engineering
	Neuromorphic Chips	Neuromorphic systems perform on-chip processing asynchronously, using event-driven processing models to address complex computing problems. Neuromorphic chips also have the ability to learn continuously. Contains electronic analog circuits to mimic neuro-biological architectures present in the nervous system. A neuromorphic computer/chip is any device that uses physical artificial neurons (made from silicon) to do computations.
	Mobile Collaboration	Mobile collaboration is the use of mobile devices and collaborative apps to allow geographically dispersed people to work together on endeavors ranging from small personal projects to high-profile enterprise teamwork.
	Agile Robots	Agile robotics defines a broad array of next-generation, intelligent, oftentimes mobile devices, vehicles and machines that reduce the need for human attention, interaction and intervention in repetitive, dangerous and inaccessible places.

	Smart Wind and Solar Power	The idea is that electric cars might store power from solar panels and use it to power neighborhoods when electricity demand peaks in the evening, and then recharge their batteries using wind power in the early morning hours.
	Augmented Reality (Oculus Rift)	Augmented reality (AR) is an enhanced version of the real physical world that is achieved through the use of digital visual elements, sound, or other sensory stimuli and delivered via technology.
2015	Supercharged Photosynthesis	The supercharged process, called C4 photosynthesis, boosts plants' growth by capturing carbon dioxide and concentrating it in specialized cells in the leaves. That allows the photosynthetic process to operate much more efficiently.
	Virtual Retina Display	Used by Magic Leap, Inc. it superimposes 3D computer-generated imagery over real world objects, by "projecting a digital light field into the user's eye", involving technologies potentially suited to applications in augmented reality and computer vision. It is attempting to construct a light-field chip using silicon photonics. A virtual retinal display (VRD), also known as a retinal scan display (RSD) or retinal projector (RP), is a display technology that draws a raster display (like a television) directly onto the retina of the eye. The user sees what appears to be a conventional display floating in space in front of them.
	Nano Architecture	nanoarchitecture (countable and uncountable, plural nanoarchitectures) The design of nanotechnology devices. A nanoscale architecture. Nanotechnology has greatly contributed to major advances in computing and electronics, leading to faster, smaller, and more portable systems that can manage and store larger and larger amounts of information.
	Vehicle-to-Vehicle Communication; Vehicular Communication Systems	Vehicle-to-vehicle (V2V) communication's ability to wirelessly exchange information about the speed and position of surrounding vehicles shows great promise in helping to avoid crashes, ease traffic congestion, and improve the environment. But the greatest benefits can only be achieved when all vehicles can communicate with each other.
	Aerial Wireless Network	Used by Project Loon, Loon LLC. Loon LLC was an Alphabet Inc. subsidiary working on providing Internet access to rural and remote areas. The company used high-altitude balloons in the stratosphere at an altitude of 18 km (11 mi) to 25 km (16 mi) to create an aerial wireless network with up to 1 Mbit/s speeds.
	Liquid Biopsy	A test done on a sample of blood to look for cancer cells from a tumor that are circulating in the blood or for pieces of DNA from tumor cells that are in the blood. A liquid biopsy may be used to help find cancer at an early stage.
	Megascale Desalination	Today there are two main types of desalination technologies – membrane (RO) and thermal (MED, MVC and MSF) desalination. Reverse Osmosis (RO) desalination uses the principle of osmosis to remove salt and other impurities, by transferring water through a series of semi-permeable membranes.
	Mobile Payment	Used by Apple Pay. A mobile payment is a money payment made for a product or service through a portable electronic device such as a tablet or cell phone.
	Brain Organoids	A brain organoid is a self-organizing three-dimensional tissue derived from human embryonic stem cells or pluripotent stem cells and is able to simulate the architecture and functionality of the human brain. Organoids can be used to study the crucial early stages of brain development, test drugs and, because they can be made from living cells, study individual patients. Additionally, the development of vascularized cerebral organoids could be used for investigating stroke therapy in the future.
	Next-Gen Genome editing	Genome editing (also called gene editing) is a group of technologies that give scientists the ability to change an organism's DNA. These technologies allow genetic material to be added, removed, or altered at particular locations in the genome

2016	Immune Engineering	Genetically engineered immune cells are saving the lives of cancer patients
	Precise Gene Editing in Plants	An easy, exact way to alter genes to create traits such as disease resistance and drought tolerance.
	Conversational Interfaces	Powerful speech technology from China's leading Internet company makes it much easier to use a smartphone, combining voice recognition and natural language to create effective speech interfaces for the world's largest Internet market
	Reusable Rockets	Rockets that can launch payloads into orbit and then land safely
	Robots that teach each other	Robots that learn tasks and send that knowledge to the cloud for other robots to pick up later.
	DNA App Store	A new business model for DNA sequencing that will make genetic information widely accessible online
	SolarCity's Gigafactory	Solar panels with gigawatt of high-efficiency per year production
	Slack	Slack gives you a centralized place to communicate with your colleagues through instant messages and in chat rooms, which can reduce time you to spend on e-mail
	Tesla Autopilot	The electric-vehicle maker sent its cars a software update that suddenly made autonomous driving a reality.
	Power from the Air	Wireless gadgets that repurpose nearby radio signals, such as Wi-Fi, to power themselves and communicate
2017	Brain Computer Interfaces (BCIs)	Used to reverse paralysis. Now, researchers have developed a new implant that is able to reverse paralysis in patients with complete spinal cord injuries. The device uses specially designed electrodes, which bring the brain back into communication with the patient's lower body.
	Self-Driving Trucks; Autonomous Vehicles	They are autonomous trucks, which supporters pitch as the remedy to a growing demand for shipping and for greater safety on the road. If the technology becomes good enough, the logistics industry will be radically changed.
	Face Recognition Payment Systems	To use FRP, users must first register their face and upload bank-card information to a mobile app. Then, they can complete payments by simply glancing at cameras positioned at the checkout in stores. FRP has become a popular payment method, used mostly in convenience stores, vending machines, and supermarkets. Users can authenticate a payment by showing their face instead of swiping their card.
	Practical Quantum Computers	Quantum computing is the study of how to use phenomena in quantum physics to create new ways of computing. Quantum computing is made up of qubits. Unlike a normal computer bit, which can be 0 or 1, a qubit can be either of those, or a superposition of both 0 and 1.
	360 Degree Camera	A 360 camera, also known as an omnidirectional camera, has a 360-degree field of view so that it captures just about everything around the sphere. 360 cameras are needed when large visual fields need to be covered, such as shooting panoramas.
	Hot Solar Cells	A team of MIT scientists is building a different story for the future of solar technology. By using some innovative engineering and material science techniques, they've been able to develop what's called a hot solar cell. This device works on the same basic foundation of converting

		sunlight into electricity with a little twist. **By first turning sunlight into heat, and then converting it back into light**, solar cell efficiency skyrockets.
	Gene Therapy 2.0	New Approach to Genetherapy. The newest approaches forgo the delivery of healthy genes and instead aim to precisely repair the gene within the cell.
	Map of the human cell	Used by "The Cell Atlas" Project. The Cell Atlas, part of the Human Protein Atlas, is an open-access database providing high-resolution insights into the spatial-temporal distribution of proteins within human cells. It an important resource for exploring details of individual genes and proteins of interest, analyzing cells transcriptomes and proteomes in broader contexts, in order to increase our understanding of human cells.
	Botnets of Things; IoT Botnet	An IoT botnet (Internet of Things botnet) is a group of hacked computers, smart appliances and Internet-connected devices that have been co-opted for illicit purposes. A conventional botnet is made up of computers that have been remotely accessed without the owners' knowledge and set up to forward transmissions to other computers on the Internet.
	Reinforcement Learning	Reinforcement Learning (RL) is the science of decision making. It is about learning the optimal behavior in an environment to obtain maximum reward. Reinforcement learning is a type of machine learning method where an intelligent agent (computer program) interacts with the environment and learns to act within that.
2018	3-D Metal Printing	Now printers can make metal objects quickly and cheaply
	Artificial Embryos	Without using eggs or sperm cells, researchers have made embryo-like structures from stem cells alone, providing a whole new route to creating life
	Sensing City	A Toronto neighborhood aims to be the first place to successfully integrate cutting-edge urban design with state-of-the-art digital technology
	AI for Everybody	Cloud-based AI is making the technology cheaper and easier to use
	Dueling Neural Networks	Two AI systems can spar with each other to create ultra-realistic original images or sounds, something machines have never been able to do before
	Babel-Fish Earbuds	Near-real-time translation now works for a large number of languages and is easy to use
	Zero-Carbon Natural Gas	A power plant efficiently and cheaply captures carbon released by burning natural gas, avoiding greenhouse-gas emissions
	Perfect Online Privacy	Computer scientists are perfecting a cryptographic tool for proving something without revealing the information underlying the proof
	Genetic Fortune Telling	Scientists can now use your genome to predict your chances of getting heart disease or breast cancer, and even your IQ
	Materials' Quantum Leap	IBM has simulated the electronic structure of a small molecule, using a seven-qubit quantum computer
2019	Gut Probe in a Pill	These swallowable devices can detect and potentially prevent diseases that cause malnutrition and stunted growth in millions of children worldwide.
	Custom Cancer Vaccines	Personalized cancer vaccines, targeting only the cancerous cells and leave healthy cells alone, could help ensure faster recovery times and pose fewer risks to patients.
	Meat-free Burgers	Plant-based and lab-grown food products will ideally alleviate the environmental impact of the livestock industry.

	Smooth-talking AI assistants	The AI assistants of the future will have even more human-like conversations to personally engage customers. Companies would see measurable benefits, with just one breakthrough here garnering a 5% jump in productivity.
	Sanitation without sewers	Improperly drained sewage causes death in one out of every nine children. Sanitation that doesn't require sewers would not only prevent exposure diseases but also help turn waste into useful products like fertilizer.
	ECG on your wrist	While most medical ECGS have up to 12 nodes to detect abnormalities, today's wearables typically have only one. An ECG on the wrist would help reduce the risk of heart disease by monitoring changes and patterns in daily life.
	Robot Dexterity	Advancements in robotics will enable the natural dexterity required to complete a greater range of tasks, such as helping an ailing loved one out of bed, doing the laundry, or building toys.
	Predicting Preemies	Premature births are the leading cause of death for children under five years old. Tests to detect the possibility of a premature birth could be available in doctors' offices in as little as five years.
	Carbon Dioxide Catcher	Carbon dioxide catchers filter out CO_2 from the air and capture it for other uses. These include synthetic fuel creation, CO_2 for soft drinks, and plant growth in greenhouses.
	New-wave Nuclear Power	Traditional nuclear reactors produce ~1,000 megawatts (MW), while these proposed mini-reactors would produce tens of megawatts — making them safer, more stable, and more financially viable for potential users.
2020	Unhackable internet	An internet based on quantum physics will soon enable inherently secure communication. In the last few years, scientists have learned to transmit pairs of photons across fiber-optic cables in a way that absolutely protects the information encoded in them. A team in China used a form of the technology to construct a 2,000-kilometer network backbone between Beijing and Shanghai—but that project relies partly on classical components that periodically break the quantum link before establishing a new one, introducing the risk of hacking. The technology relies on a quantum behavior of atomic particles called entanglement. Entangled photons can't be covertly read without disrupting their content.
	Hyper-personalized medicine	That's about to change, thanks to new classes of drugs that can be tailored to a person's genes. If an extremely rare disease is caused by a specific DNA mistake—as several thousand are—there's now at least a fighting chance for a genetic fix. The new medicines might take the form of gene replacement, gene editing, or antisense (the type Mila received), a sort of molecular eraser, which erases or fixes erroneous genetic messages. What the treatments have in common is that they can be programmed, in digital fashion and with digital speed, to correct or compensate for inherited diseases, letter for DNA letter.
	Digital money	The rise of digital currency has massive ramifications for financial privacy.
	Anti-aging drugs	The first wave of a new class of anti-aging drugs have begun human testing. These drugs won't let you live longer (yet) but aim to treat specific ailments by slowing or reversing a fundamental process of aging. The drugs are called senolytics—they work by removing certain cells that accumulate as we age. Known as "senescent" cells, they can create low-level inflammation that suppresses normal mechanisms of cellular repair and creates a toxic environment for neighboring cells.
	AI discovered molecules	The universe of molecules that could be turned into potentially life-saving drugs is mind-boggling in size: researchers estimate the number at around 1060. That's more than all the atoms in the solar system, offering virtually unlimited chemical possibilities—if only chemists could find the worthwhile ones. Now machine-learning tools can explore large databases of existing molecules and their properties, using the information to generate new possibilities. This could make it faster and cheaper to discover new drug candidates.

	Satellite mega constellations	Satellites that can beam a broadband connection to internet terminals. As long as these terminals have a clear view of the sky, they can deliver internet to any nearby devices. SpaceX alone wants to send more than 4.5 times more satellites into orbit this decade than humans have ever launched since Sputnik.
	Quantum supremacy	Quantum computers store and process data in a way completely differently from the ones we're all used to. In theory, they could tackle certain classes of problems that even the most powerful classical supercomputer imaginable would take millennia to solve, like breaking today's cryptographic codes or simulating the precise behavior of molecules to help discover new drugs and materials.
	Tiny AI	AI has a problem: in the quest to build more powerful algorithms, researchers are using ever greater amounts of data and computing power, and relying on centralized cloud services. This not only generates alarming amounts of carbon emissions but also limits the speed and privacy of AI applications. But a countertrend of tiny AI is changing that. Tech giants and academic researchers are working on new algorithms to shrink existing deep-learning models without losing their capabilities. Meanwhile, an emerging generation of specialized AI chips promises to pack more computational power into tighter physical spaces, and train and run AI on far less energy.
	Differential privacy	So the Census Bureau injects inaccuracies, or "noise," into the data. It might make some people younger and others older, or label some white people as black and vice versa, while keeping the totals of each age or ethnic group the same. The more noise you inject, the harder de-anonymization becomes.
	Climate change attribution	The group, World Weather Attribution, had compared high-resolution computer simulations of worlds where climate change did and didn't occur. In the former, the world we live in, the severe storm was as much as 2.6 times more likely—and up to 28% more intense. Earlier this decade, scientists were reluctant to link any specific event to climate change. But many more extreme-weather attribution studies have been done in the last few years, and rapidly improving tools and techniques have made them more reliable and convincing. This has been made possible by a combination of advances. For one, the lengthening record of detailed satellite data is helping us understand natural systems. Also, increased computing power means scientists can create higher-resolution simulations and conduct many more virtual experiments.
2021	Messenger RNA vaccines	The new covid vaccines are based on a technology never before used in therapeutics, and it could transform medicine, leading to vaccines against various infectious diseases, including malaria. And if this coronavirus keeps mutating, mRNA vaccines can be easily and quickly modified. Messenger RNA also holds great promise as the basis for cheap gene fixes to sickle-cell disease and HIV. Also in the works: using mRNA to help the body fight off cancers.
	GPT-3	Large natural-language computer models that learn to write and speak are a big step toward AI that can better understand and interact with the world. GPT-3 is by far the largest—and most literate—to date. Trained on the text of thousands of books and most of the internet, GPT-3 can mimic human-written text with uncanny—and at times bizarre—realism, making it the most impressive language model yet produced using machine learning. But GPT-3 doesn't understand what it's writing, so sometimes the results are garbled and nonsensical. It takes an enormous amount of computation power, data, and money to train, creating a large carbon footprint and restricting the development of similar models to those labs with extraordinary resources. And since it is trained on text from the internet, which is filled with misinformation and prejudice, it often produces similarly biased passages.
	Data trusts	Technology companies have proven to be poor stewards of our personal data. Our information has been leaked, hacked, and sold and resold more times than most of us can count. Maybe the problem isn't with us, but with the model of privacy to which we've long adhered—one in which we, as individuals, are primarily responsible for managing and protecting our own privacy. Data trusts offer one alternative approach that some governments are starting to explore. A data trust is a legal entity that collects and manages people's personal data on their behalf. Though the structure and function of these trusts are still being defined, and many

		questions remain, data trusts are notable for offering a potential solution to long-standing problems in privacy and security.
	Lithium metal batteries	Electric vehicles come with a tough sales pitch; they're relatively expensive, and you can drive them only a few hundred miles before they need to recharge—which takes far longer than stopping for gas. All these drawbacks have to do with the limitations of lithium-ion batteries. A well-funded Silicon Valley startup now says it has a battery that will make electric vehicles far more palatable for the mass consumer. It's called a lithium-metal battery and is being developed by QuantumScape. According to early test results, the battery could boost the range of an EV by 80% and can be rapidly recharged. The startup has a deal with VW, which says it will be selling EVs with the new type of battery by 2025.The battery is still just a prototype that's much smaller than one needed for a car. But if QuantumScape and others working on lithium-metal batteries succeed, it could finally make EVs attractive to millions of consumers.
	Digital contact tracing	As the coronavirus began to spread around the world, it felt at first as if digital contact tracing might help us. Smartphone apps could use GPS or Bluetooth to create a log of people who had recently crossed paths. If one of them later tested positive for covid, that person could enter the result into the app, and it would alert others who might have been exposed. But digital contact tracing largely failed to make much impact on the virus's spread. Apple and Google quickly pushed out features like exposure notifications to many smartphones, but public health officials struggled to persuade residents to use them. The lessons we learn from this pandemic could not only help us prepare for the next pandemic but also carry over to other areas of health care
	Hyper-accurate positioning	We all use GPS every day; it has transformed our lives and many of our businesses. But while today's GPS is accurate to within 5 to 10 meters, new hyper-accurate positioning technologies have accuracies within a few centimeters or millimeters. That's opening up new possibilities, from landslide warnings to delivery robots and self-driving cars that can safely navigate streets. China's BeiDou (Big Dipper) global navigation system was completed in June 2020 and is part of what's making all this possible. It provides positioning accuracy of 1.5 to two meters to anyone in the world. Using ground-based augmentation, it can get down to millimeter-level accuracy. Meanwhile, GPS, which has been around since the early 1990s, is getting an upgrade: four new satellites for GPS III launched in November and more are expected in orbit by 2023.
	Remote everything	The covid pandemic forced the world to go remote. Getting that shift right has been especially critical in health care and education. Some places around the world have done a particularly good job at getting remote services in these two areas to work well for people. Snapask, an online tutoring company, has more than 3.5 million users in nine Asian countries, and Byju's, a learning app based in India, has seen the number of its users soar to nearly 70 million. Unfortunately, students in many other countries are still floundering with their online classes. Meanwhile, telehealth efforts in Uganda and several other African countries have extended health care to millions during the pandemic. In a part of the world with a chronic lack of doctors, remote health care has been a life saver.
	Multi-skilled AI	Despite the immense progress in artificial intelligence in recent years, AI and robots are still dumb in many ways, especially when it comes to solving new problems or navigating unfamiliar environments. They lack the human ability, found even in young children, to learn how the world works and apply that general knowledge to new situations. One promising approach to improving the skills of AI is to expand its senses; currently AI with computer vision or audio recognition can sense things but cannot "talk" about what it sees and hears using natural-language algorithms. But what if you combined these abilities in a single AI system? Might these systems begin to gain human-like intelligence? Might a robot that can see, feel, hear, and communicate be a more productive human assistant?
	Tik Tok recommendations algorithms	Since its launch in China in 2016, TikTok has become one of the world's fastest-growing social networks. It's been downloaded billions of times and attracted hundreds of millions of users. Why? Because the algorithms that power TikTok's "For You" feed have changed the way people become famous online. While other platforms are geared more toward highlighting content with mass appeal, TikTok's algorithms seem just as likely to pluck a new creator out of obscurity as they are to feature a known star. And they're particularly adept at feeding relevant content to niche communities of users who share a particular interest or identity. The ability of

		new creators to get a lot of views very quickly—and the ease with which users can discover so many kinds of content—have contributed to the app's stunning growth. Other social media companies are now scrambling to reproduce these features on their own apps.
	Green Hydrogen	Hydrogen has always been an intriguing possible replacement for fossil fuels. It burns cleanly, emitting no carbon dioxide; it's energy dense, so it's a good way to store power from on-and-off renewable sources; and you can make liquid synthetic fuels that are drop-in replacements for gasoline or diesel. But most hydrogen up to now has been made from natural gas; the process is dirty and energy intensive. The rapidly dropping cost of solar and wind power means green hydrogen is now cheap enough to be practical. Simply zap water with electricity, and presto, you've got hydrogen. Europe is leading the way, beginning to build the needed infrastructure.
2022	End of passwords	Passwords are inherently insecure. They can be stolen, guessed, or brute-forced. But mostly, people just use bad ones. (And, worse, reuse them.) The real action is in eliminating passwords altogether. The process is already underway. Enterprise-oriented companies like Okta and Duo, as well as personal identity providers like Google, offer ways for people to log in to apps and services without having to enter a password. Apple's facial recognition system has taken biometric login mainstream. Most notably, Microsoft announced in March 2021 that some of its customers could go completely password-less, and it followed up in September by telling people to delete their passwords altogether. Those other methods of authentication? They're finally winning.
	Covid variant tracking	The pandemic brought unprecedented investment in genomic sequencing and dramatically expanded the capacity for this type of monitoring around the world. Better surveillance has allowed scientists to track the spread of the covid virus and to quickly spot and warn about new variants.
	Long-lasting grid battery	We're using more renewable power than ever. But what happens when the sun sets or the wind stops? Grid operators need a way to store electricity for later. New iron-based batteries may be up to the task. They're made using abundant materials and could be cheaper and more practical than other types of grid storage.
	AI for protein folding	Nearly everything your body does, it does with proteins. And the way a protein folds determines its activity. But figuring out proteins' structure can take months. Now an AI called AlphaFold2 has solved this longstanding biological puzzle, which could make it possible to quickly design drugs for a wide range of diseases.
	Malaria vaccine	Malaria kills more than 600,000 people a year, most of them children younger than five. A new malaria vaccine approved by the World Health Organization could help save hundreds of thousands of lives every year. It's also the world's first vaccine for a parasitic infection.
	Proof of stake	Cryptocurrencies like Bitcoin use huge amounts of electricity. This is due to the way transactions are verified, which now requires significant computing power. Proof of stake offers a way to verify transactions without using so much energy. Ethereum plans to transition to the system this year, cutting energy use by 99.95%.
	A pill for Covid	A new drug from Pfizer provides effective and broad protection against the covid-19 virus, including the newest variants. Now other companies are developing similar medicines. Combined with vaccines, these pills could provide a way for the world to finally exit the pandemic.
	Practical fusion reactors	The promise of limitless, carbon-free electricity has for decades inspired researchers to try to make fusion power work. Now one startup plans to deliver it to the grid by the early 2030s. Its design relies on a powerful new magnet that shattered records and should allow the company to build smaller, less expensive reactors.
	Synthetic data for AI	Training AI requires vast amounts of data. Oftentimes, though, that data is messy or reflects real-world biases, or there are privacy concerns around the information included. Some companies are starting to create and sell synthetic data to avoid these problems. It's not perfect, but it could be a better way to train AI.

	Carbon removal factories	Reducing emissions is a key step to mitigating climate change. But it's not enough, according to the UN. To avoid catastrophic future warming, we must also remove carbon dioxide from the air. The world's biggest carbon removal factory recently opened in Iceland to do just that.

Once the technologies were gathered, I identified the keywords that describe each technology. For instance, the technology *Hyper-personalized medicine* (year 2020, second line) can be also referred as *precision medicine* and, more generally, it refers to particular techniques in the scope of *genome editing* or *replacement* technologies. I pinpointed the keywords by further exploring descriptions available online and consulting specialized literature on *scopus.com*. The identification of the keywords paved the way for the patent search on *Patentscope*.

2.1.2. Sourcing of patent data from *Patentscope* from 2012 to 2022

The second step of the sourcing activity involved the search of patent information for each of the technology listed in

Table 2.1. The *WIPO Patentscope* is an open-source online service database made available by the WIPO to facilitate access to information on patent filings worldwide. It is one of the most complete database for patent search available and allows for advanced searches through the use of queries that support own field codes that limit the research to restricted fields and the use of Boolean and wildcards operators. I conducted my research using the advanced research tool from the database, using the following field codes and operators (Table 2.2, Table 2.3):

Table 2.2. Tables of used field codes.

Field Codes	Description
FP:	Search text or numeric information on the front page of a patent document.
EN_TI:	Search text or numeric information on the title of a patent document only in English language.
AD:	Allows to search for the application date in patent document.

DP: (…AND…)	Allows to search information during an indicated period of time marked by two dates (it has to be used concurrently with the Boolean operator AND).
IC:	Searches through indicated codes from the IPC classification.
CPC:	Searches through indicated codes from the CPC classification.

Table 2.3. Table of used operators.

Operators	Example	Explanation
BOOLEAN		Always use in capital
AND	train AND plane	Returns all documents that contain both the first term and the second term.
OR	train OR plane	Returns all documents that contain both the first term or the second term.
NOT	NOT plane	Returns all documents that do not contain the term.
ANDNOT	train ANDNOT plane	Returns all documents that contain the first term and not the second term.
WILDCARD		
*	electr*	Searches terms with 0 or more characters replaced either in the middle of the term or at the end of the term

Apart from the use of field codes and operators to search patent data on a specific technology, I conducted the research by limiting the search to the offices in which the patent application was first filed only in USPTO, EPO, CNIPA, KIPO, JPO and PCT applications (WIPO). I also restricted to patent information in English language or translated in English. The search used stemmed keywords, in order to include in the research also inflected words reduced to their stem or root form. I ran two different types of patent search. First, I looked for single-family members patents in order to avoid counting multiple times the same patent file, thus limiting the risk of duplicates. Second, I carried out the same research for all patent family members, in order to have a more significant estimate of the number of patents filed in the 5 offices taken into account, after adding also PCT applications. An example of patent search is provided in Figure 2.1.

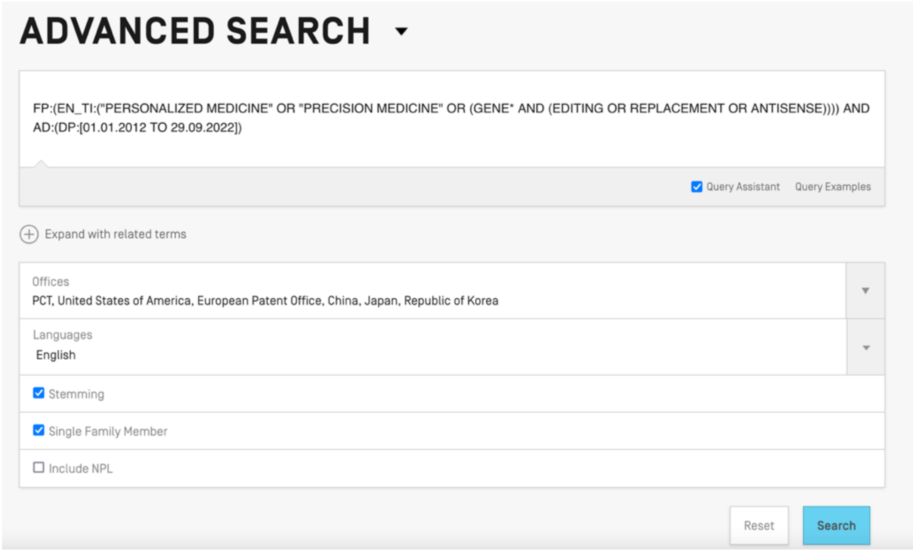

Figure 2.1. Example of advanced search for a specific technology.

For some technologies, it was not possible to conduct a comprehensive search due to different reasons. *Egg Stem Cells* (2012) was in fact found to be non-existing in a 2020 study (Wagner et al., 2020). In the same way, *Memory Implants* (2013) are not a patentable technology as it makes use of cognitive psychology techniques that, if employed with malicious purposes, violate the lawfulness requirements for patentability. *Ultra-private smartphones* (2014) have been dismissed from production due to low customer demand (Kristin Majcher, 2015) and never got to patenting stage. For what concerns *SolarCity Gigafactory* (2016), there is not a specific technological innovations attached to it, but it is rather a different use of already existing technologies such as ultra-efficient solar panels that have already been investigated in this research. In the case of *AI discovered molecules* (2020) and *AI for protein folding* (2022), the patentability problem resides on the determination of the inventor: as it is an intelligent machine creating a new molecule, this opens up a grey area in patenting in which the list of inventors should include non-human entities. For this reason, patenting is very limited for these technologies. *Climate Change Attribution* (2020), as for *SolarCity Gigafactory*, does not involve any specific technological innovations but different uses of already existing ones.

2.2. Data Extraction and Encoding

I conducted the activity of data extraction concurrently to the activity of data encoding, using data from *Patentscope* and using *Microsoft Excel* as a database manager. For each data on a specific technology, I created a table file in which I recorded the data related to the search. In particular, I collected four types of patent data in the preliminary patent search:

- *Patentscope* research: I recorded the query used to draw out the preliminary patent screening on a specific technology.
- IPC relevant codes: I recorded the first 4 digits of the *International Patent Cooperation* (IPC) codes that appeared in the patent documents resulting from the search, together with the amount of times they appear for each one of them. In particular, I only collected the ones that I deemed to be relevant and reflecting the description of the specific technology, thus avoiding the collection of codes that were not connected to the technology description. The first 4 digits indicate (WIPO, 2022):
    - First letter: Section (e.g., H = all inventions related to ELECTRICITY)
    - Second and Third Number: Class (e.g., H01 = all inventions related to BASIC ELECTRIC ELEMENTS)
    - Fourth letter: Subclass (e.g., H01S = all inventions related to DEVICES USING THE PROCESS OF LIGHT AMPLIFICATION BY STIMULATED EMISSION OF RADIATION [LASER] TO AMPLIFY OR GENERATE LIGHT)
- Year of first publication: I recorded the year in which the first patent publication appeared.
- Total number of patents found.

These data were easily collected thanks to the *analysis* interface available in *Patentscope*. This interface presented different kinds of information related to the patent search (Figure 2.2):

- The distribution of the total number of patents application in the 5 different countries in analysis and PCT applications.
- The most relevant applicants/assignees based on the number of applications filed.
- The most relevant inventors based on the number of applications filed.
- The distribution of IPC codes appeared in the total number of applications ordered decreasing.

- The distribution of application published from 2012 to 2022.

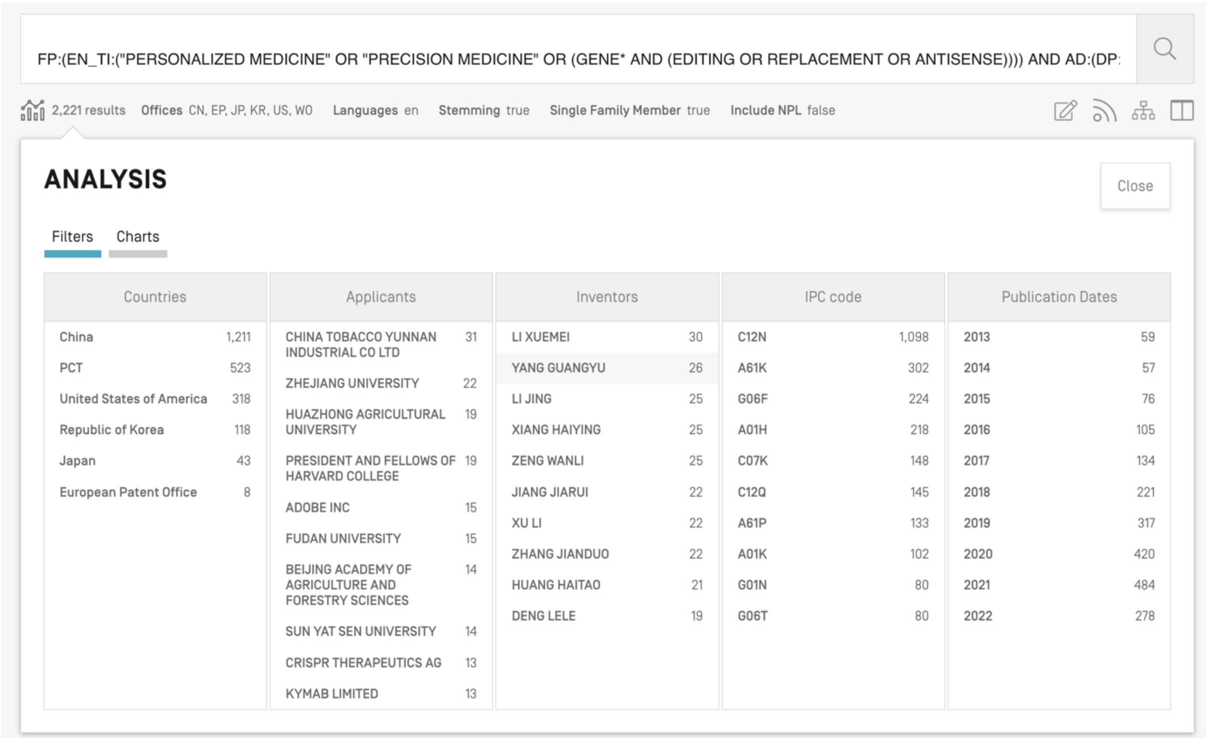

Figure 2.2. View of the "analysis" function on *Patenscope*.

The queries that I ran in order to get the patents information for the preliminary search were all keyword-based. In particular, I looked for the keyword that characterized a specific technology inside the title of the patent, also adding the condition to search for all patent filings during the period from January the 1st 2012 to September the 29th 2022, which was the last day in which I conducted the patent search. In this way, I was able to immediately distinguish the IPC codes that reflected the technology description. Equation (2.2. 1) displays the basic query format that I employed in the preliminary search.

FP:" (EN_TI: KEYWORD OR KEYW* OR "KEYWORD") AND AD:(DP:(01.01.2012 TO 29.09.2022)).

(2.2. 1)

2.3. Data Cleaning

After having extracted and encoded the patent data, I proceeded to refine the research and obtain a more fine-grained analysis from which then draw the patent trends. Fine-tuning the research was particularly useful for two reasons:

- Eliminate patent–outliers in a technology-specific patent landscape

- Detect missing patents in a technology-specific patent landscape.

For this purpose, the process used to clean data collected was the one of data saturation, which refers to *"the point in the research process when no new information is discovered in data analysis, and this redundancy signals to researchers that data collection may cease"* (Faulkner & Trotter, 2017). In my case, I applied a data saturation method in order to be certain that the amount of patent information collected for each technology was consistently representing their specific patent landscape, thus ensuring that excessive noise in the data would not undermine the definition of the trends.

2.3.1. First phase

In the first phase of data cleaning, I ran a new research query on *Patentscope* that had the objective to capture the overall patent landscape of technologies defined by the relevant IPC codes found in the extraction phase. The type of research I conducted was characterized by a query that looked into each relevant IPC codes for a specific technology, during the period from January the 1st 2012 to September the 29th 2022 (Equation (2.3. 1); Figure 2.3)

$$AD: (DP: (01.01.2012\ TO\ 29.09.2022))\ AND\ IC: ("X12Y"\ OR\ \dots)" \qquad (2.3.\ 1)$$

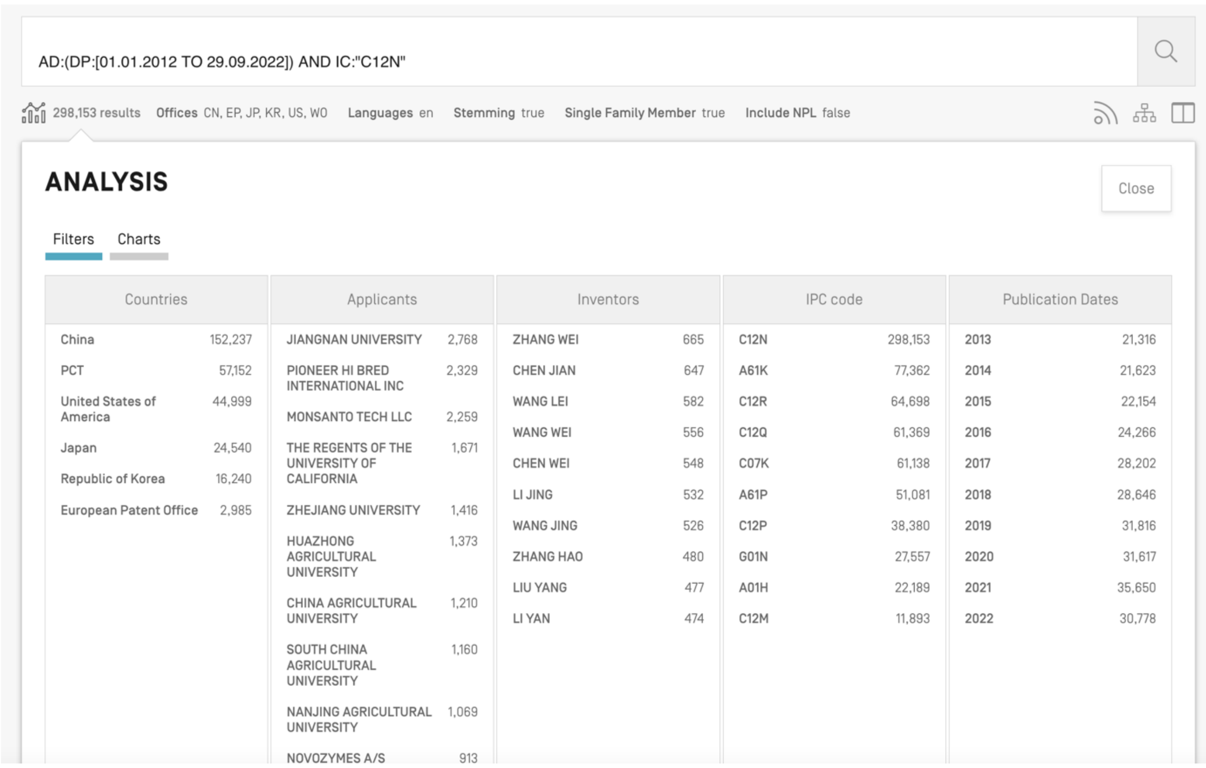

Figure 2.3. View of a first phase research on *Patentscope*.

The first phase of the search aimed at minimizing omittances, by including all the potentially relevant technologies. By doing this, I aimed at reducing *type II* errors in the patent search, given that the research query in the extraction phase was excessively narrow and might have left out some "*false negatives*" patent documents from the end results. The search resulted in a very broad set of outcomes, that includes several technologies patented in a span of more than 10 years. From this approximate domain defined by the relevant IPC 4-digits codes, the second phase will be then dedicated to a refinement based on the specific technology in analysis.

2.3.2. Second phase

The second phase of research aimed at minimizing the inclusion of non-pertinent patents, by means of a careful data cleaning process. In this phase, I aimed at reducing instead *type I* errors in the patent search, gradually offsetting the broadness of the research to exclude "*false positives*" patent documents. I began the actual procedure of clearing out the data until saturation. I started from the research obtained in phase 1 thanks to (2.3. 1), by gradually adding in the research query keyword terms that could identify the specific technology at hand. In particular, I used the field code *FP:()* which scans the specific terms looked for inside the text fields in the front page of a patent document, thus abstract and title. The query search utilized was the following (Equation (2.3. 2), Figure 2.4):

AD:(DP: DP:(01.01.2012 TO 29.09.2022) AND IC:("X12Y" OR …)
AND FP:("KEYWORD" OR KEYWORD OR KEY*)

(2.3. 2)

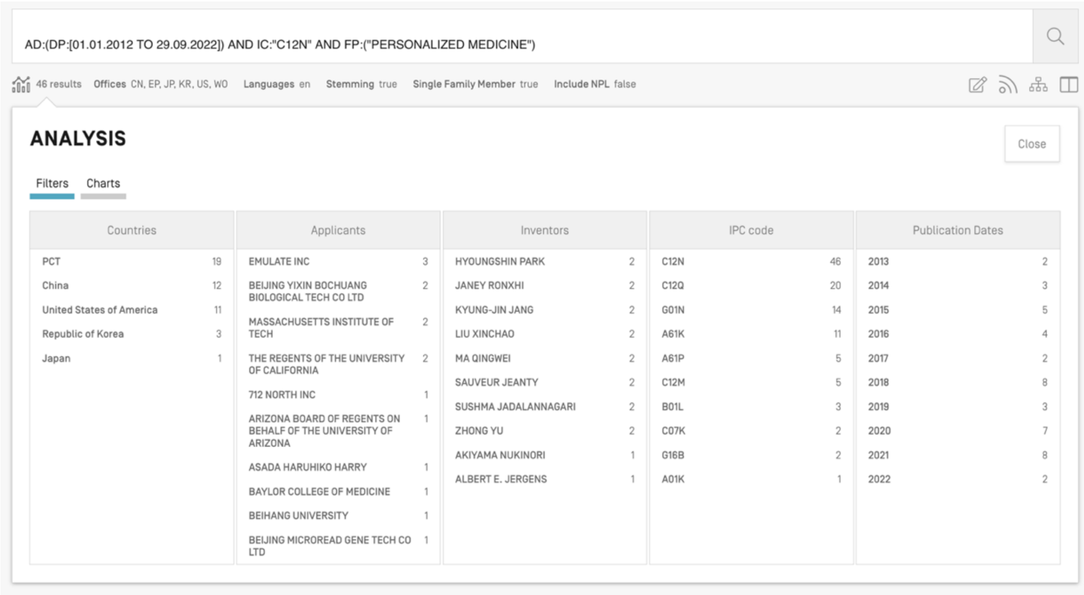

Figure 2.4. View of the research obtained in the second phase.

During this refining process, I also recorded the level of reduction in patents found in the research which served as an indicator of data saturation (Equation (2.3. 3)).

$$1 - \frac{Number\ of\ patents\ found\ in\ refining\ phase}{Number\ of\ patent\ found\ in\ first\ phase} \qquad (2.3.3)$$

2.3.1 Third phase

The third phase entailed a recursive round of the fine-grain refinements of the first and second phases and validation. In this case, I carefully checked the results, adding other keyword terms inside the *FP:()* field in order to intercept additional patents that may have been left out, with the aim to obtain a patent sample which was the most representative of the specific technology. Concurrently, I continued using (2.3. 3) to check out the level of saturation of the research whenever I gradually added keywords. In this phase, I aimed at obtaining the highest level of saturation possible for each technology, obtaining in all cases a level of reduction of at least 95% from the first phase. I stopped researching with additional keywords in *FP:()* field whenever I obtained additional level of saturation less than or equal to +0,005% (Figure 2.5).

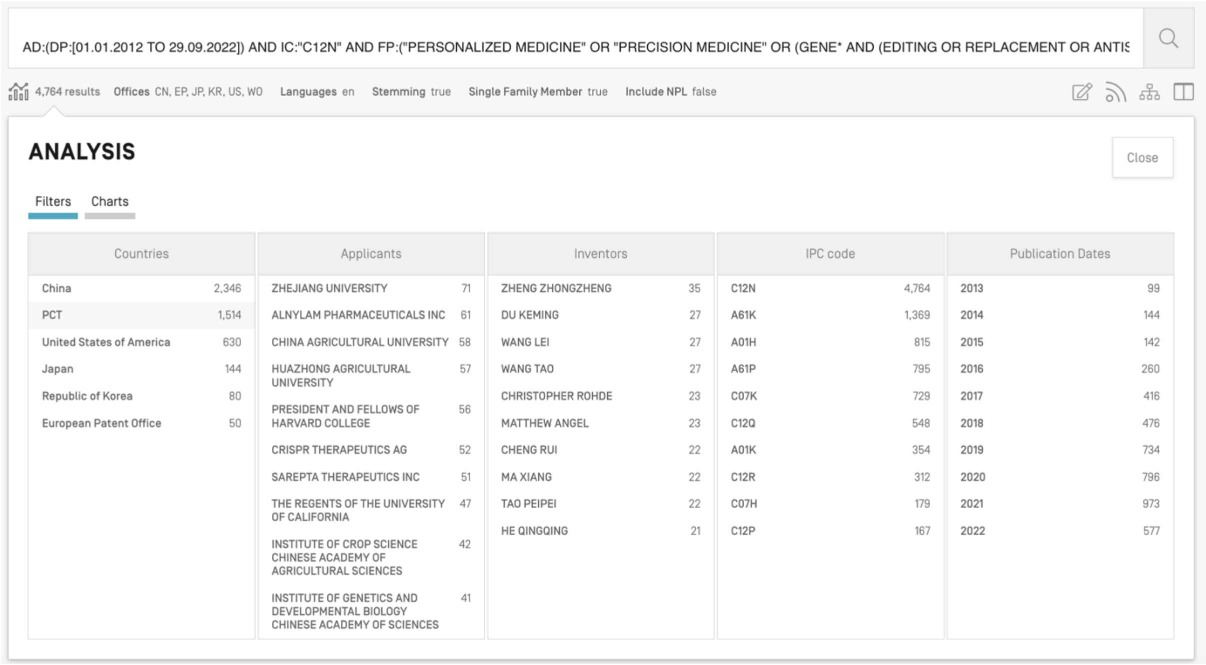

Figure 2.5. View of a final refined research on Patentscope.

In order to be completely sure of the saturation level of the research, I switched in the research query the field code *FP:()* with *EN_ALLTXT:()*, which returns all the patent documents that present the input keyword in all the text fields of a patent in English – namely: abstract, title, description, claims. In all cases, this research did not produce substantially differential results from the *FP:()* research.

Once obtained all the end results for each technology, I recorded new information on the table collecting all the data:

- *Patentscope* final refined research: I recorded the query used to draw out the final patent screening on a specific technology.
- IPC relevant codes: I recorded the first 4 digits of the *International Patent Cooperation* (IPC) codes that appeared in the patent documents resulting from the final search, together with the amount of times they appear for each one of them.
- Level of saturation: Equation (2.3. 3)
- Year of first publication: I recorded the year in which the first patent publication appeared.
- Number of patents obtained after the final search.

2.3.3. Disclaimers and Exceptions

It is important to state that for all the technologies for which it was not possible to conclude a comprehensive research – *Egg Stem Cells* (2012), *Memory Implants* (2013), *Ultra-private smartphones* (2014), *SolarCity Gigafactory* (2016), *AI discovered molecules* (2020) *AI for protein folding* (2022) and *Climate Change Attribution* (2020) – were excluded from the refinement phase.

Additionally, for technologies considered impactful in the field of sustainability (e.g., Ultra-efficient solar power, 2012), the query I used also included the search condition *AND CPC:"Y"*, which is the Y code from the *Cooperative Patent Classification* (CPC). This code includes most of the new technologies developed in the field of sustainability and technologies for mitigation or adaptation to climate change (USPTO, 2022a). This were:

- Solar Microgrids (2012).
- Ultra-efficient Solar Power (2012, 2013).
- Smart Wind and Solar Power (2014).
- Hot Solar Cells (2017).
- Sanitation without Sewers (2019).

2.4. Technology Classification Process

When the final sample was completed, I dedicated a phase for re-aggregating the singular IPC codes obtained from the previous phases. This process proved especially useful in drawing out the macro trends in the *Results*, given that the aggregation of singular IPC codes in macro-categories better represents a trending scenario in R&D fields, while providing a trend analysis only on singular IPC codes would have been excessively specific and may have hindered reflections on the innovation implications since trends in specific IPC codes are characterized by major fluctuations year by year. I divided this process in two distinctive phases:

- I dedicated the first phase to merging each IPC code found into specific technology fields and assessing how much every technology analyzed contributed to the development of a specific technological sector.
- In the second phase, I retrieved patent data for every technology and recorded the count of applications published every year from 2012 to 2022 for each technology through the analysis function of *Patentscope.*

2.4.1. Merging of IPC codes and contribution assessment

In the first phase of the classification process, the first activity I did was grouping all the relevant IPC codes found in the refined research into specific technological sectors.

I followed the approach of the *IPC technological concordance*, a paper commissioned by WIPO that explains the current concordance table for 35 different fields of technology. Every technological field listed in the table contains a set of IPC codes that are considered to be related to that specific technological field. The 35 fields are the following (Table 2.4):

Table 2.4. Technological fields from IPC technological concordance (Source: WIPO).

Electrical machinery, apparatus, energy	Optics	Biotechnology	Micro-structural and nano-technology	Other special machines
Audio-visual technology	Measurement	Pharmaceuticals	Chemical engineering	Thermal processes and apparatus
Telecommunications	Analysis of biological materials	Macromolecular chemistry, polymers	Environmental technology	Mechanical elements
Digital communication	Control	Food chemistry	Handling	Transport
Basic communication processes	IT Methods for Management	Basic materials chemistry	Machine tools	Furniture, games
Computer technology	Medical technology	Materials, metallurgy	Engines, pumps, turbines	Other consumer goods
Semiconductors	Organic fine chemistry	Surface technology, coating	Textile and paper machines	Civil engineering

Once every IPC code was assigned to the pertinent technological field, I employed a classification matrix to understand how the technologies of the research can be identified inside these categories. I employed a share classification system based on the ratio of the number of times a specific IPC codes appears in a patent search for a specific technology and the total number of times the technology relevant IPC codes appear in a patent search for a certain technology. For instance, the patent search for the technology *Robot Dexterity* (year 2019) presents 3 different relevant IPC codes:

- B25J (384 times)
- G06N (169 times)
- G05D (136 times)

Specifically, the code B25J belongs to the *Handling* field, G06N to the *Computer technology* and G05D to the *Control* field. The summation of the number of times each IPC code appear in the patent search, represents the total times all the relevant IPC codes appear in the patent search. By using Equation (2.4. 1):

$$Contribution\ share\% = \frac{times\ a\ singular\ IPC\ code\ appears\ in\ a\ patent\ search}{total\ times\ relevant\ IPC\ codes\ appear\ in\ a\ patent\ search} \quad (2.4.1)$$

It is easy to understand that the technology *Robot Dexterity* contributes for 55,7% in the *Handling* field, for 24,5% in the *Computer technology* field and for 19,8% to the *Control* field.

I repeated the same exercise in every research year from 2012 to 2022 and for each of the ten 10 breakthrough technologies found in every year. Throughout this, I produced a classification matrix that aimed at synthesizing the extent to which the 10 breakthrough technologies contribute to each of the 35 technological fields every year. Table 2.5 provides an example of the final classification matrix in the year 2019.

Table 2.5. View of the year 2019 classification matrix. In yellow are highlighted the contributions share of each technology to a certain technological field.

	Gut Probe in a Pill	Custom Cancer Vaccine	Meat-free Burgers	Smooth-talking AI assistants	Sanitation without sewers	ECG on your wrist	Robot Dexterity	Predicting Preemies	Carbon Dioxide Catcher	New-wave Nuclear Power
Tech / IPC fields	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"A61B" AND FP:((DIGITAL OR ELECTRONIC) AND PILL OR DEVICE AND INGESTIBLE)	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:("A61K" OR "A61P") AND FP:((CANCER OR TUMOR) AND VACCINE* AND (PERSONALIZED OR CUSTOM*))	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"A23" AND FP:(("PLANT-BASED" OR VEGET*) AND MEAT AND PROTEIN*)	AD:(DP:[01.01.2012 TO 29.09.2022]) IC:("G06" OR "G10L") AND FP:(("VOICE SYNTHESIS" OR "SENTIMENT ANALYSIS"))	FP:(EN_TI:("Dry toilets" OR "composting toilets" OR "dehydration toilets" OR "urine diversion dry/dehydration toilet" OR "urine diversion flush toilet" OR "Solid–liquid separating toilets" OR "Biogas toilets")) AND AD:(DP:[01.01.2012 TO 29.09.2022]) AND CPC:"Y"	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"A61B" AND FP:(("ECG" OR "ELECTRO-CARDIOGRAM") AND (SMARTWATCH OR WEARABLE DEVICE))	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:("B25J" OR "G05D" OR "G06N") AND FP:((ROBOT* AND DEXTER*) OR (REINFORCEMENT LEARNING AND ROBOT*))	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"C12Q" AND FP:("CELL-FREE" AND (DNA OR RNA))	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"B01D" AND FP:("CARBON-CAPTURE")	AD:(DP:[01.01.2012 TO 29.09.2022]) AND IC:"G21C" AND FP:(NUCLEAR AND ("REACTOR*" OR "MINI-REACTOR" OR "SMALL REACTOR") AND MODULAR)
IPC CODES	A61B(33)	A61K(64) A61P(29)	A23L(649) A23J(272) A23K(246) A23P(96) A23C(83) A23B(15)	G06F(1,215) G10L(1,142) G06N(583) G06Q(332) G06K(325)	A47K(46)	A61B(1400)	B25J(384) G06N(169) G05D(136)	C12Q(544)	B01D(373)	G21C(102)
Electrical machinery, apparatus, energy	0	0	0	0	0	0	0	0	0	0
Audio-visual technology	0	0	0	0	0	0	0	0	0	0
Telecommunications	0	0	0	0	0	0	0	0	0	0
Digital communication	0	0	0	0	0	0	0	0	0	0
Basic communication processes	0	0	0	0	0	0	0	0	0	0
Computer technology	0	0	0	1	0	0	0,245	0	0	0
Semiconductors	0	0	0	0	0	0	0	0	0	0
Optics	0	0	0	0	0	0	0	0	0	0
Measurement	0	0	0	0	0	0	0	0	0	0
Analysis of biological materials	0	0	0	0	0	0	0	0	0	0
Control	0	0	0	0	0	0	0,198	0	0	0
Medical technology	1	0	0	0	0	1	0	0	0	0
Organic fine chemistry	0	0	0	0	0	0	0	0	0	0
Biotechnology	0	0	0	0	0	0	0	1	0	0
Pharmaceuticals	0	1	0	0	0	0	0	0	0	0
Macromolecular chemistry, polymers	0	0	0	0	0	0	0	0	0	0
Food chemistry	0	0	1	0	0	0	0	0	0	0
Basic materials chemistry	0	0	0	0	0	0	0	0	0	0
Materials, metallurgy	0	0	0	0	0	0	0	0	0	0
Surface technology, coating	0	0	0	0	0	0	0	0	0	0
Micro-structural and nano-technology	0	0	0	0	0	0	0	0	0	0
Chemical engineering	0	0	0	0	0	0	0	0	0	0
Environmental technology	0	0	0	0	0	0	0	0	0	0
Handling	0	0	0	0	0	0	0,557	0	0	0
Machine tools	0	0	0	0	0	0	0	0	0	0
Engines, pumps, turbines	0	0	0	0	0	0	0	0	0	1
Textile and paper machines	0	0	0	0	0	0	0	0	0	0
Other special machines	0	0	0	0	0	0	0	0	0	0
Thermal processses and apparatus	0	0	0	0	0	0	0	0	0	0
Mechanical elements	0	0	0	0	0	0	0	0	0	0
Transport	0	0	0	0	0	0	0	0	0	0
Furniture, games	0	0	0	0	1	0	0	0	0	0
Other consumer goods	0	0	0	0	0	0	0	0	0	0
Civil engineering	0	0	0	0	0	0	0	0	0	0

2.4.2. Count of applications published every year from 2012 to 2022

The last phase of the classification process entailed the retrieving of comprehensive patent publication data from the previously search for every focal technology (Figure 2.6). This process, coupled with the classification, will be the fundamental input for the subsequent analysis.

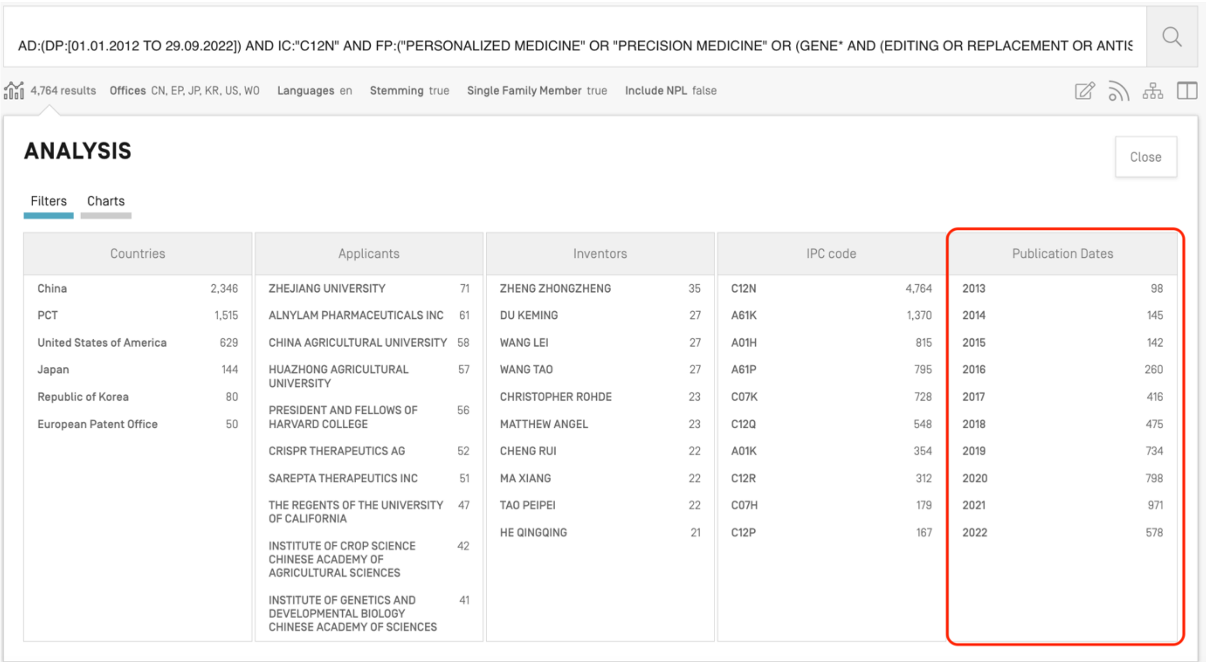

Figure 2.6. In red, the publication data retrieved from an example of patent search on Patentscope.

2.5. Method for obtaining the patenting trends

In this sub-section, I will illustrate how the final patenting trends have been found, building on the groundwork provided in the methodology chapter. The data necessary to plot the trends came from the classification matrixes and from the count of the applications published every year. For each yearly list of 10 breakthrough technologies from 2012 to 2022, I created a new table that aimed at gathering the count of applications published every year for each IPC technological concordance field (

Table 2.6).

Table 2.6. Generic appearance of table for the count of applications published every year for each IPC technological concordance field.

Year	Computer technology (1)	Semiconductors (2)	… (the remaining IPC tech fields) (n)
2013	$a_{1,2013}$	$a_{2,2013}$	…
2014	$a_{1,2014}$	…	…
…	…	…	…
…. (until 2021) (m)	…	…	…

The data points for each year were calculated multiplying the contribution shares of the 10 technologies in each technological field by the count of publications of a certain technology in a specific year. I then repeated the same process with the count of publications in the following year to obtain the next data point, until 2021 (Equation (2.5. 1)).

$$a_{n,m} = contribution\ share_{tech1,n} \times count_{tech1,m} + contribution\ share_{tech2,n} \times count_{tech2,m} + \ldots + contribution\ share_{techn,n} \times count_{techm,m} \tag{2.5. 1}$$

For clarifications purposes, I will report the process to calculate the first two data points (2013, 2014) of the technological field "*Computer technology*" for the 10 breakthrough technologies of 2019.

In the year 2019, two technologies contributed to the development in patenting of the *Computer technology* field:

- *Smooth talking AI assistant* with a contribution share of 1 (contributed only to the development of the *Computer technology* field).
- *Robot dexterity* with a contribution share of 0,245 (contributed for 24,5% to the development of the *Computer technology* field).

In the year 2013, published applications for *Smooth talking AI assistant* were 65, while for *Robot dexterity* were 2.

To calculate the data point of the count of application published in the field *Computer technology* in 2013, I used (2.5. 1):

$$a_{computer\ technology,2013} = contribution\ share_{Smooth\ talking\ AI\ assistant,computer\ technology} \times count_{Smooth\ talking\ AI\ assistant,2013} + contribution\ share_{Robot\ dexterity,computer\ technology} \times count_{Robot\ dexterity,2013} = 1 \times 65 + 0{,}245 \times 2 \approx 65$$

In the year 2014, published applications for *Smooth talking AI assistant* were 81, while for *Robot dexterity* were 5.

To calculate the data point of the count of application published in the field *Computer technology* in 2014, I used (2.5. 1) that yielded:

$$a_{computer\ technology,2013} = 1 \times 81 + 0{,}245 \times 5 \approx 82$$

In this way, I calculated every data point for each of the 210 technologies examined in this research from the year 2012 to 2021.

Once all data points were available, I aggregated them to build a table that gathered the general patenting trends per each technological field from the year 2013 (first year of publications) to 2021. Data points in this table were represented by the summation of the values obtained from the previous calculations, considering all the technologies in each year of analysis from 2012 to 2022 (Table 2.7). In some cases, the analysis did not return enough data to conduct a consistent analysis in some fields, therefore at the end I have analyzed patenting trend in 21 out of 35 technological fields. The excluded categories were: *Basic communication processes; Surface technology, coating; Chemical engineering; Textile and paper machines; Mechanical elements; Furniture, games; Other consumer goods; Civile engineering; Macromolecular chemistry, polymers; Organic fine chemistry; Micro-structural and nano-technology; Engines, pumps and turbines; IT methods for management; Basic material chemistry.*

Table 2.7. Generic appearance of the general trend table with aggregate data from every research year.

Year	**Computer technology (1)**	**Semiconductors (2)**	**… (the remaining IPC tech fields) (n)**
2013	$\sum_{2012}^{2022} a_{1,2013,2012} + a_{1,2013,2013} + \ldots + a_{1,2013,2022}$	$\sum_{2012}^{2022} a_{2,2013,2012} + a_{2,2013,2013} + \ldots + a_{2,2013,2022}$	…
2014	$\sum_{2012}^{2022} a_{1,2014,2012} + a_{1,2014,2013} + \ldots + a_{1,2014,2022}$	…	…
…	…	…	…
…. (until 2021) (m)	…	…	…

3 Results

In this chapter, I will illustrate the results of the research conducted in *Patenscope* and the analyses on the patenting trends that arose from it. The chapter aim is to reflect on the concurrence between patents trends and the pandemic event worldwide. Although the methodology proposed in this thesis is not suitable to investigate causality between the pandemic and the patent trends observed, the analyses suggest a set of articulated hypotheses about the ways in which the pandemic might have contributed to cause the trends found.

First, I will briefly describe how I obtained the forecasted data for the year 2022. I will then proceed to introduce three different sub-sections:

- The first sub-section will be devoted on the patenting trends that have remained unchanged during the COVID-19 pandemic (2020 – 2022), leading to hypothesize that the exogenous shock brought by the virus might have not deviated an already existing trend trajectory.
- The second sub-section will deal with the trends that instead have experienced an acceleration during the pandemic (2020 – 2022), leading to hypothesize a promotion of the patenting activity in certain technological domains that proved to be useful in fighting COVID-19.
- Lastly, the third sub-section will outline the patenting trends in those technological domains that have shown a deceleration concurrently with the pandemic (2020 – 2022), leading to hypothesize that scientists and inventors might have de-emphasized the relevance of innovations in field that were less likely to help in coping with the pandemic.

3.1. Plotting the patent trends

After having obtained all the data points in the general table, I proceeded to chart a graphical representations of the patenting trends from 2013 to 2022. A trend in statistics is defined as "*A long-term movement in an ordered series, say a time series, which may be regarded, together with the oscillation and random component, as generating the observed values*" (OECD, 2005). In the following sub-sections, I will introduce the most relevant patenting trends found among the technological fields of the *IPC tech. concordance* and hypothesize on potential concurrencies with the pandemic, based on observed changes of their trajectories.

The data for the year 2022 had to be forecasted, given the fact that my research only covered the first three quarters of 2022 and, considered the high uncertainty related to patent publications that can be uploaded on *Patentscope* several months in the future, it was not possible to adjust the value from the available data. I forecasted the data points for 2022 directly using the aggregate data from the general trend table, operating a polynomial regression forecast with 5th degree polynomials for each technological field until obtaining a R^2 value higher than or equal to 95%. Clearly, this method has limitations, which will be discussed in the *Limitations and Discussion* chapter.

3.1.1. Trends remained unchanged during the pandemic

Several technological fields have been experiencing different patterns of growth in patents in the last 10 years. The ones examined in this section, were characterized by unchanged trends trajectory until 2021 and a trend forecast that did not deviate from the initial trajectory in 2022. This led me to hypothesize that the pandemic event (2020 – 2022) has not significantly influenced research focus and innovation activities in these technological fields, leading to suppose an overall independence.

Below, I will list and visually show the most relevant technological fields for which the patenting trajectory has not changed, commenting with potential hypothesis on the reasons why the pandemic may not have interfered with the trends.

3.1.1.1. Computer technology, Audio-Visual Technologies, Optics

These technological fields have been characterized by an increasing growth over the last 6 years, in particular *Computer technology* was the field in which more patents were published in terms of volume in the last 10 years. The field of *Computer technology* includes many computer components, parts and technologies, as well as methods, algorithms and enablers of the digital technologies world. Technologies such as *Deep Learning*, *Tiny AI*, *Data trusts* and *Sensing City* are included in this field where the IPC codes that begin with "G06" are mostly featured. In *Audio-Visual technologies* are included several technologies shared in common with *Computer technology* such as *Augmented Reality (Oculus Rift)* and *Remote everything*. In these technological fields are identifiable all the radically innovative digital technologies and innovations that have experienced great diffusion over the last decade, such artificial intelligence, Internet of Things, mobile payments, Big Data and augmented and virtual reality. From the charts below (Figure 3.1, Figure 3.2), it is easy to understand that the increasing growth that has been characterizing these fields are steady, and after the year in which the pandemic sparked (2020), both the 2021 data and 2022 forecast do not change the trajectory of the trend. This is also testified by an almost constant growth rate among 2020 and 2022 in *Computer technology*, which has been +28,03% in 2020, +29,08% in 2021 and forecasted +28,17% in 2022, while for *Audio-visual technologies* was +18,33% in 2020, +15,47% in 2021 and forecasted +14, 27% in 2022.

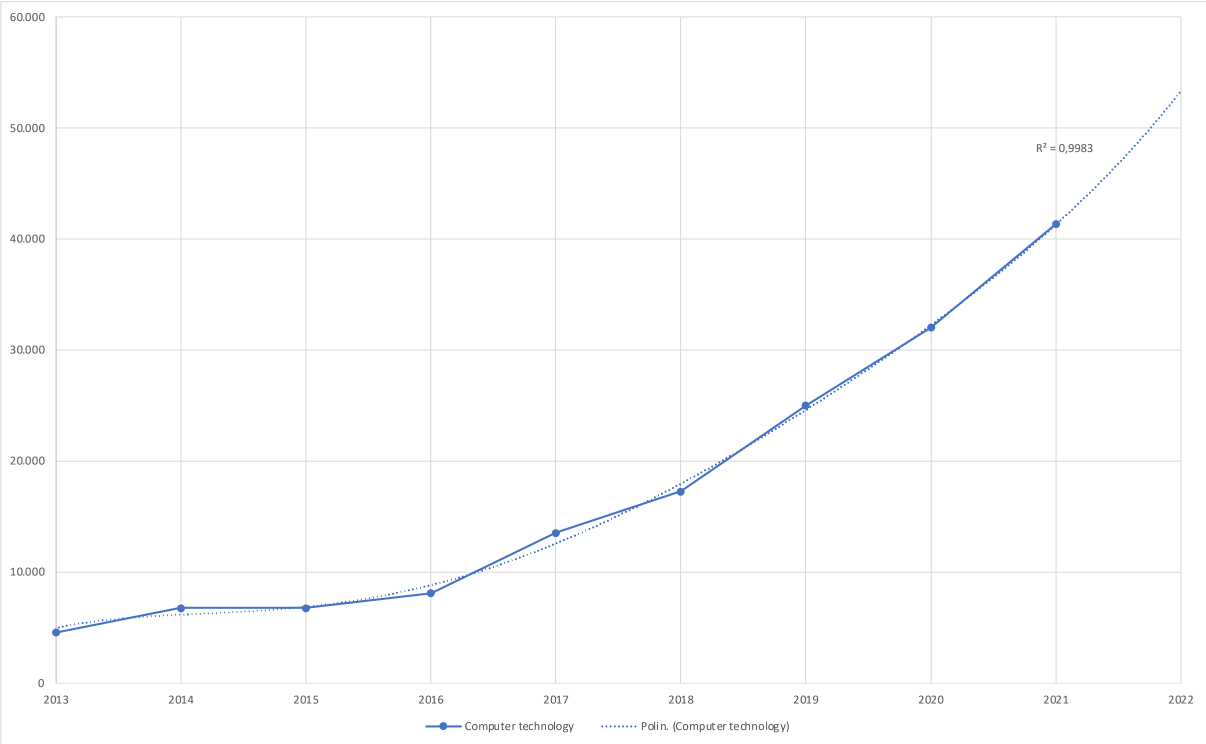

Figure 3.1. Computer technology patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

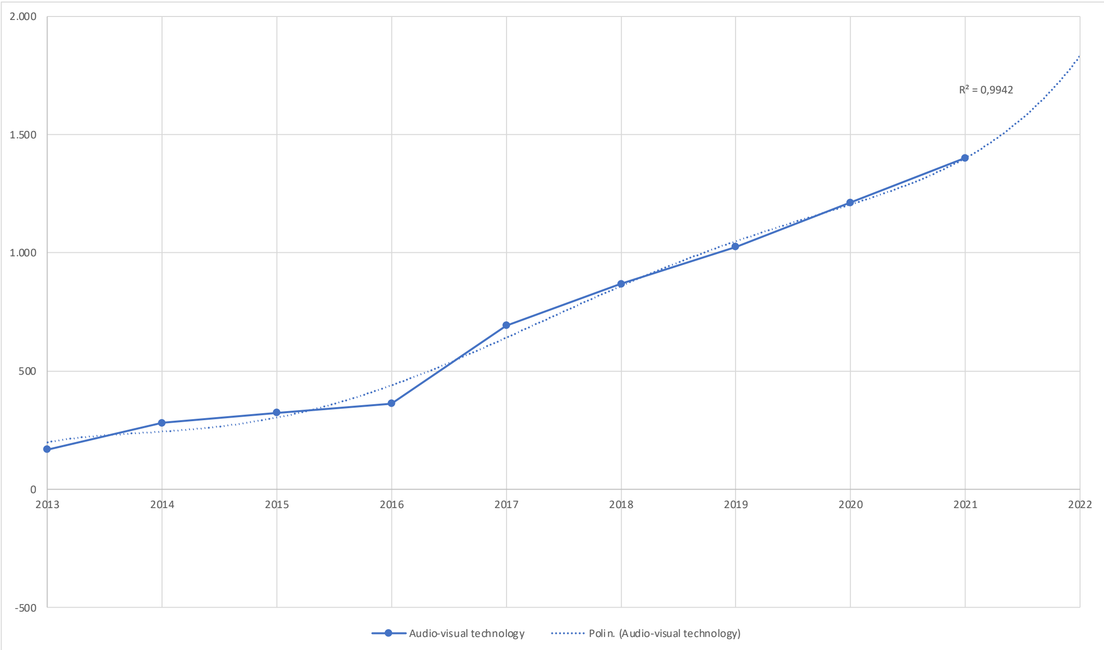

Figure 3.2. Audio-Visual technology patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

The remarkable patent activity in these fields is not matched with significant changes in the trend trajectory. This led me to suggest that COVID-19 might have not interfered with the R&D efforts towards the technologies specific to this categories, as the pervasiveness of digital in every aspect of the daily life has led scientists and inventors to support the continuous growth in this field, also considering the rapid diffusion process that this kind of technologies experience for businesses and end-consumers.

Another technological category that experienced the same growth trajectory as *Computer Technology* and *Audio-visual technologies* is the *Optics* field. In fact, the technologies belonging to this field are all included inside *Audio-visual technologies*; therefore this led me to hypothesize the same suggestions considered before. In this field, data shows a decelerating trajectory starting from the year 2018 which continued until 2022 (Figure 3.3). Thus, it appears that the pandemic might have not influenced the trend in this field.

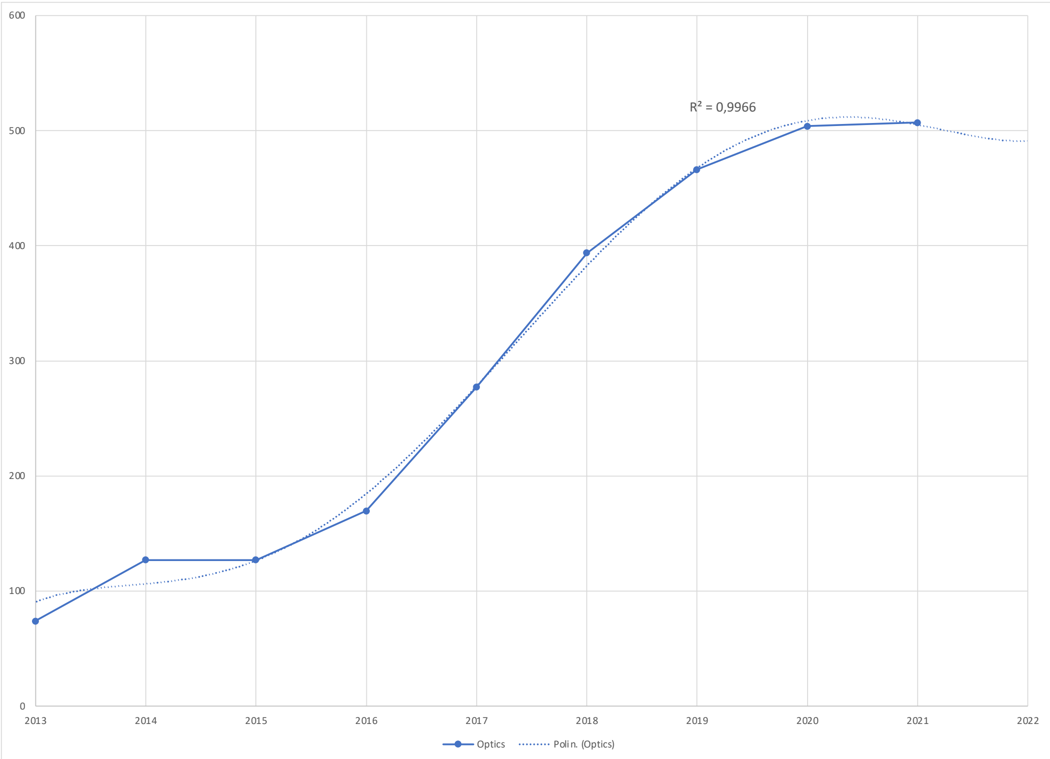

Figure 3.3. Optics patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

3.1.1.2. Control, Measurement

All the relevant breakthroughs included in the fields *Control and Measurement* are common to both fields. These categories represent instruments and methods used to steer and allow communication between machines or robots. The breakthroughs connected to these categories are all related to the field of autonomous vehicles, such as *Tesla Autopilot* and *Vehicle-to-vehicle communication; Vehicular communication systems*. Data shows for both of these fields a steady growth over the first 9 year of the examination time span. The forecasted data for 2022, show a drop in patenting activity for *Control* and linear growth patterns for *Measurement* (Figure 3.4, Figure 3.5).

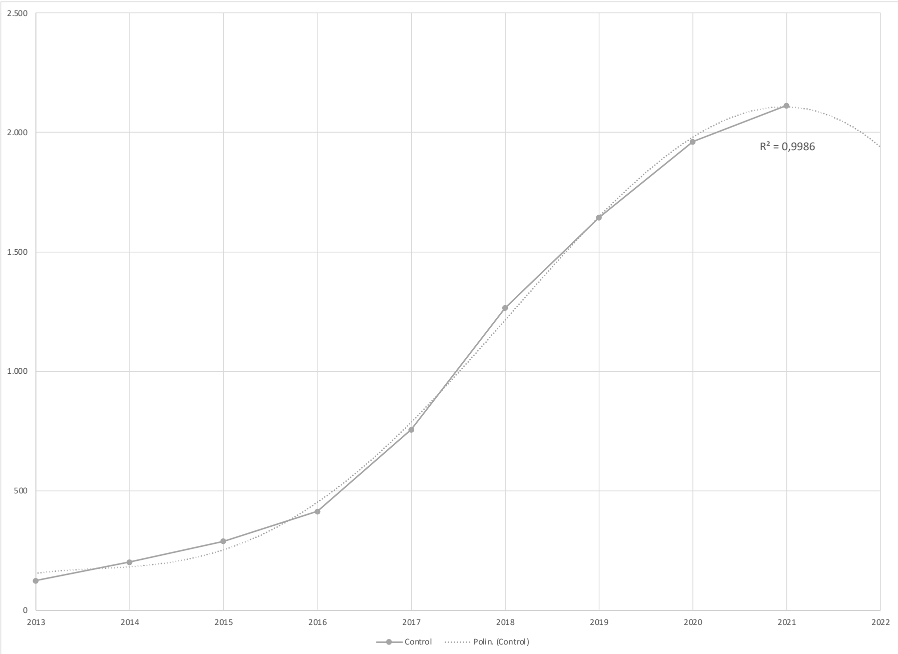

Figure 3.4. Control patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

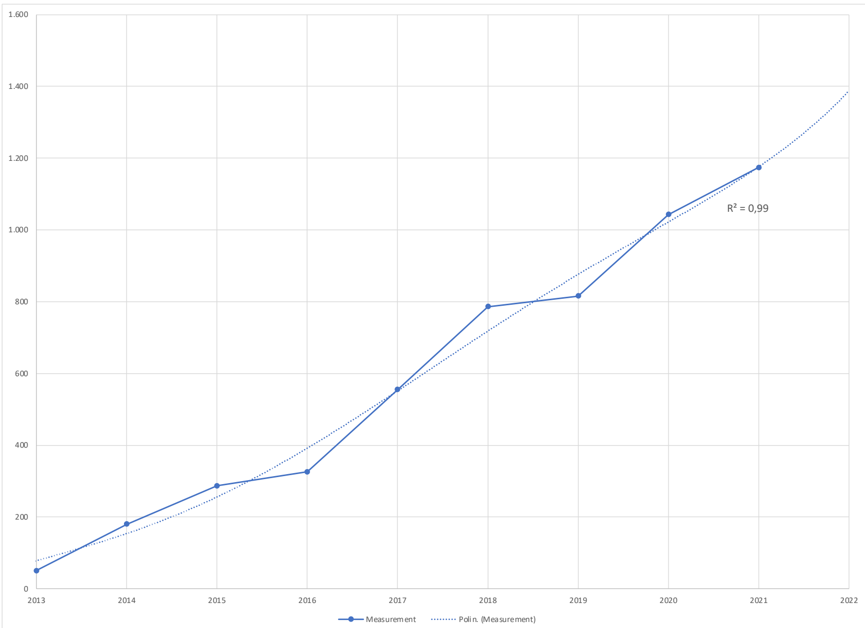

Figure 3.5. Control patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

Although, from the visual inspection, *Control* seems to encounter a sharp deceleration only after 2021, data from growth rates shows that the process of decelerations in patenting activity in this technological field started in 2018, going from a +67,48% in

2018 to only +7,68% in 2021. For what concerns *Measurement*, results growth rate data shows an overall decelerating trend from 2018 to 2022, going from a +41,57% in 2018 to a forecasted +18,45% in 2022. Considering the results obtained, I hypothesized that the pandemic might have not influenced the trend patterns in these two technological fields, given that decelerations were already starting from 2018. This could indicate that the most intensive phase of the R&D development was terminated and the resulting technologies were sufficiently well-functioning to move towards their market application.

3.1.1.3. Handling, Machine Tools, Other Special Machines, Materials, metallurgy, Transport

The *Handling* technological field have been witnessing a steady growth over the last 6 years, which was mostly trailed by innovations for robotic industrial machines. Indeed, in this category are included technologies such as *Robot dexterity* and *Robots that teach each other*. The *Machine tools, Other special machines* and *Materials, metallurgy* categories are instead very broad categories, including innovations in printing machines and components for additive manufacturing and drones. Technologies such as *Agricultural drones* and *3-D metal printing* belong to these categories. *Transport* field instead includes technologies related to the field of autonomous vehicles, such as *Tesla Autopilot* and *Vehicle-to-vehicle communication; Vehicular communication systems*. In these fields, it is visible a steady decline over the time period 2019-2022 for *Other special machines*, over the time period 2020-2022 for *Machine tools* and over 2018-2022 for *Materials, metallurgy,* while for *Transport* the decelerations of the growth pattern date back already in 2017. The trend patterns in all four categories are very different: on the one hand, it is reasonable to assume that the *Handling* field have benefitted of the improvements in the machine learning algorithms that allow robots to handle increasingly complex tasks and complete tasks more rapidly than humans. This led to hypothesize that, given that the demand for industrial robots has increased over time, this might have reflected in research effort from scientists to deliver always more innovations in this field. On the other hand, technologies such as drones and 3D printing machines have found their way into the consumer market, although their impact on industrial and commercial environment are yet to be completely explored. The hypothesis here is that these technologies have suffered a lack of attention from scientists in the last 4 years, but once adoption increases on the industrial level, an acceleration of R&D efforts in these fields might be visible. In both cases, data seem to show that COVID-19 might not have had much effect in their trends trajectories (Figure 3.6, Figure 3.7, Figure 3.8, Figure 3.9). Autonomous vehicles-related technologies instead have been growing in the past 10 years, thanks to the improvements in machine learning algorithms, although it can be suggested that the R&D effort may be focused more on the integration between hardware – the vehicle – and software – monitoring and communication system, possibly hinting at steady decelerations in the *Transport* field (Figure 3.10).

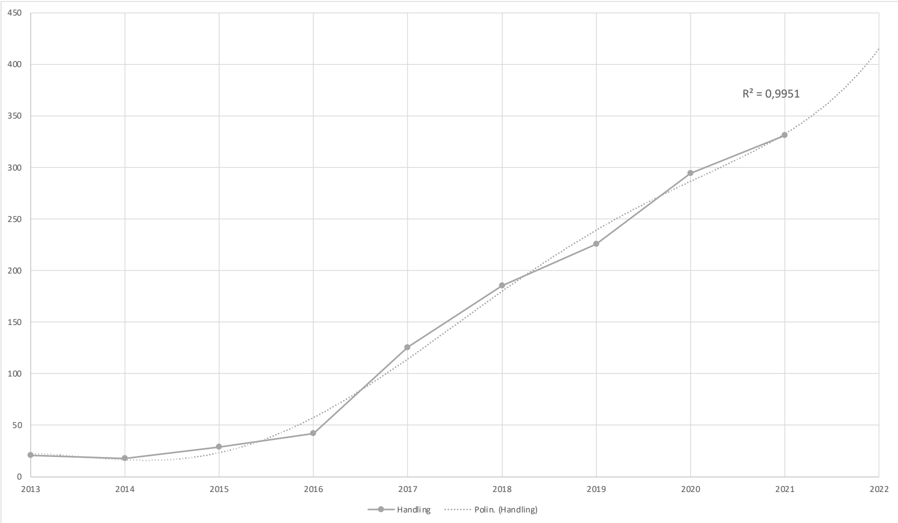

Figure 3.6. Handling patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

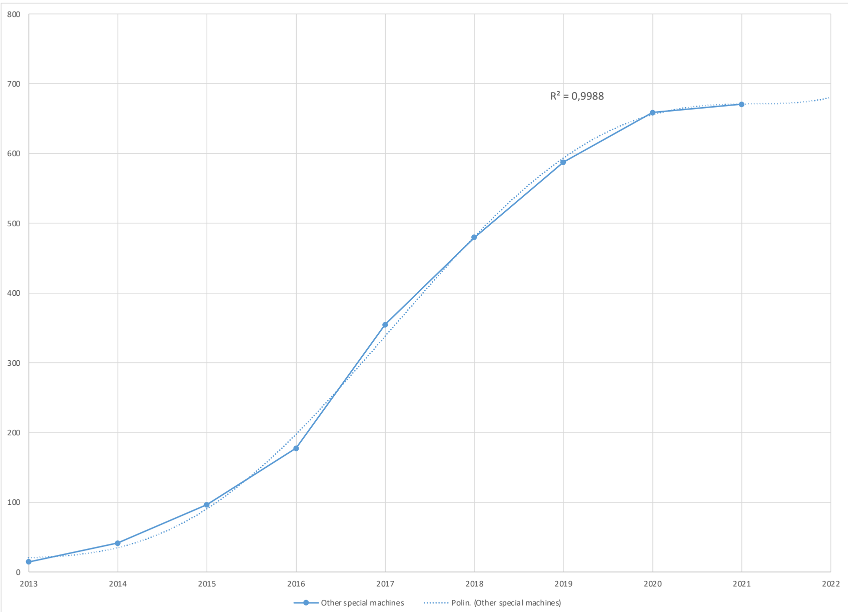

Figure 3.7. Other special machines patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

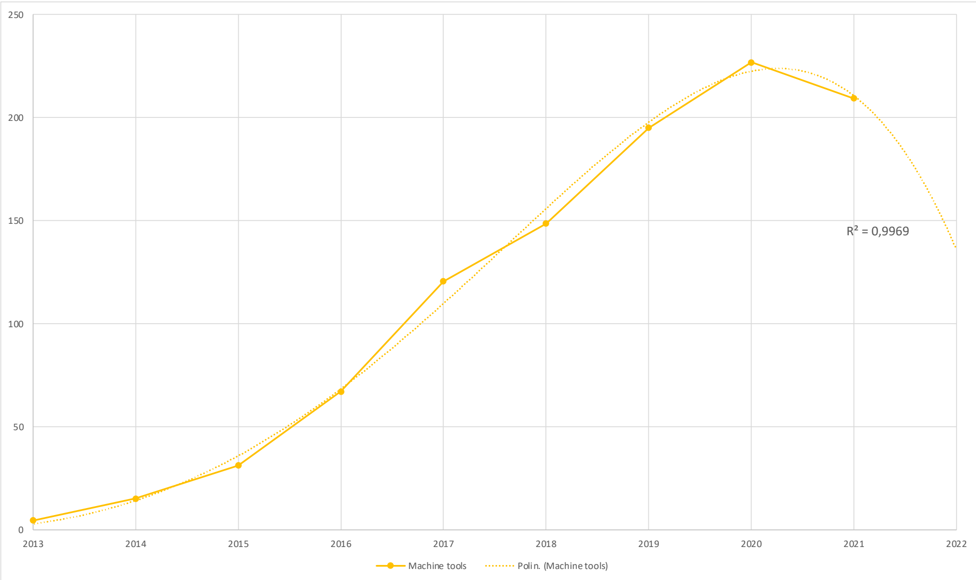

Figure 3.8. Machines tools patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

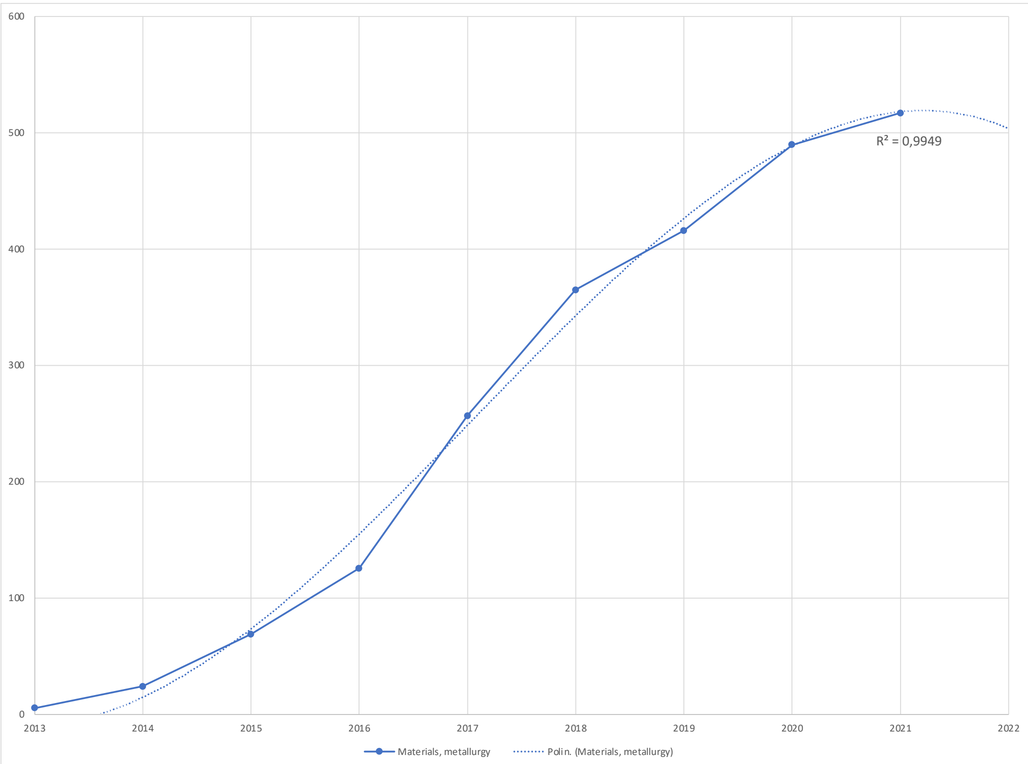

Figure 3.9. Materials, metallurgy patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

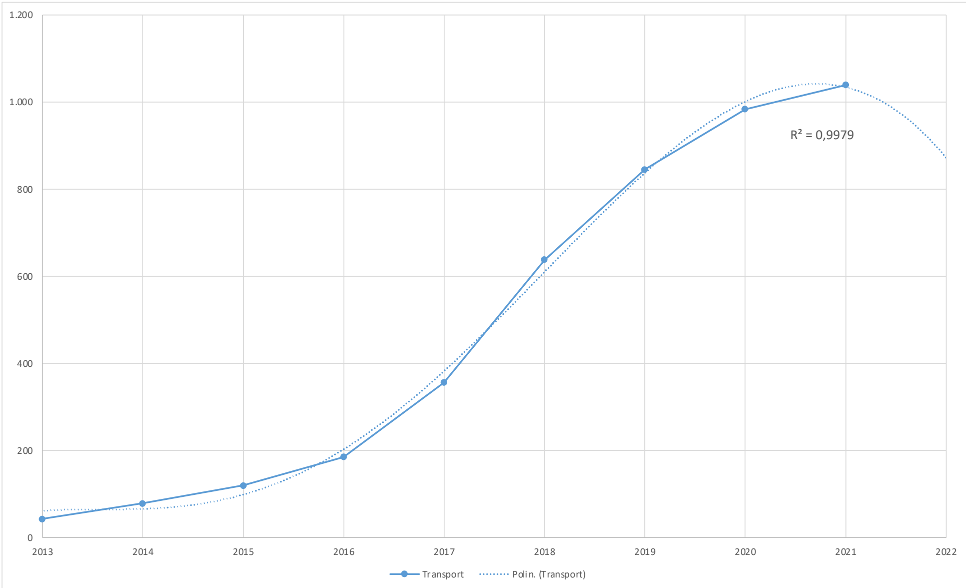

Figure 3.10. Transport patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

3.1.1.4. *Food Chemistry*

Food chemistry is a technological field that has received growing interest in the last 4 years, where data shows an exponential growth trajectory from the year 2019 to 2022 (Figure 3.11). The advent of plant-based and lab-grown food will ideally alleviate the environmental impact of the livestock industry and, in times where consumers are much more aware of their environmental footprint, sustainable engineered has lively sales prospects for the future.

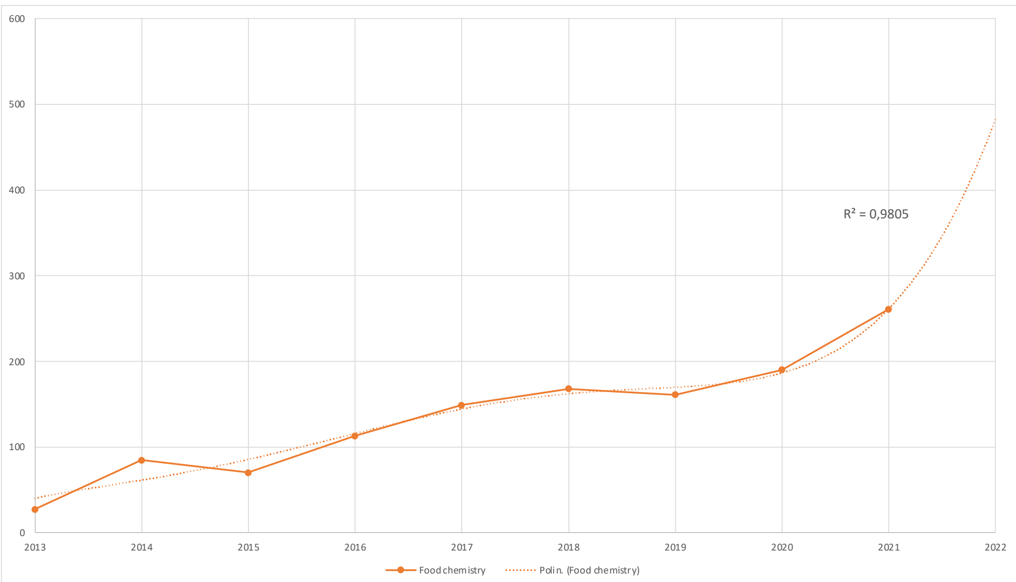

Figure 3.11. Food chemistry patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

In *Food chemistry*, the shift to the exponential growth in 2019 might have been caused by the commercialization of meat-free burgers, which is the staple innovation in this industry. This might have contributed to the entrance of new-comers and innovative start-ups in the market that, thanks to their patenting activity, shifted the trends trajectory to an exponential one. In this case, in Figure 3.11 it is clearly visible that the exponential patenting trend on the curve starts at the year 2019, therefore I assumed the pandemic might not have played a role in the change of trajectory.

3.1.1.5. *Environmental technology*

The Environmental technology field gathers several different breakthrough that have the objective to contribute to the abatement of carbon footprint in the industrial sectors. Data shows this field has been witnessing a steady growth over the last ten years (Figure 3.12) with a relevant patent activity, given that it is one of the categories in the analysis with the highest count of publications. Technologies such as *Green hydrogen*, *Zero carbon natural gas* and *Carbon removal factories* all belong to this field.

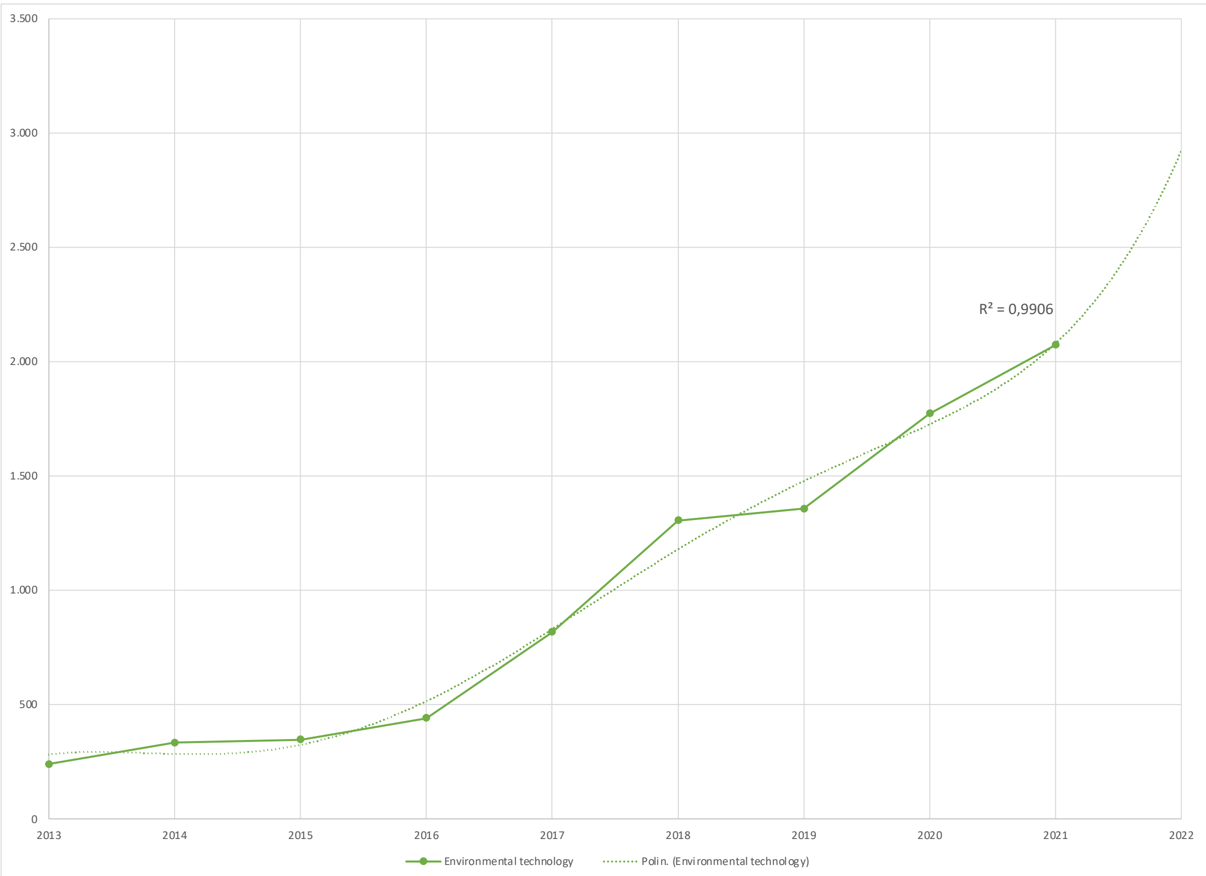

Figure 3.12. Environmental technology patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

As it can be seen by Figure 3.12, the trend trajectory in this category remains nearly unchanged during the examined time span. This led me to hypothesize that the *Environmental technology* field might have not been influenced by the pandemic in a substantial way. This hypothesis suggest that research efforts directed to environmental technologies have been constantly growing over the years, as evidence that scientists interest in developing this kind of breakthrough was mostly influenced by the urgency of facing climate-change challenges.

3.1.2. Trends accelerated during the pandemic

The trend analyzed in this section experienced accelerations in their trajectories during the years of the pandemic (2020-2022). This lead me to hypothesize that COVID-19 might have impacted positively R&D efforts in these technological fields so as to suppose a potential concurrency.

As for the previous sub-sections, here I will illustrate how in several technological fields the patenting trajectory has accelerated, supposing potential hypotheses on the reasons why the pandemic could have played a role in these accelerations.

3.1.2.1. Telecommunication, Digital communications

Telecommunications and *Digital communications* have a fair share of technologies in common. These categories include different breakthroughs that have played a vital role during the pandemic (2020 – 2022), as they enabled the execution of productive activities through remote communication systems. Indeed, these categories include technologies such as *Slack* and remote everything, as well as technologies concerning digital communication systems for autonomous vehicles (*Self-driving trucks; autonomous vehicles*) and machines, such as *end of passwords* and *proof of stake*.

Although data shows that *Telecommunications* witnessed a smaller patent activity than *Digital communications* in terms of volume, they both had similar trend trajectories. As a matter of fact, these fields have undergone similar growth patterns until 2020, but the results obtained show an upward trajectory over the year 2021 and the forecasted value of 2022, testified by a growth rate of +23,97% in 2021 and forecasted +42,45% in 2022 for *Telecommunications* and forecasted +44,11% in 2022 for *Digital communications* (Figure 3.13, Figure 3.14, Figure 3.15, Figure 3.16).

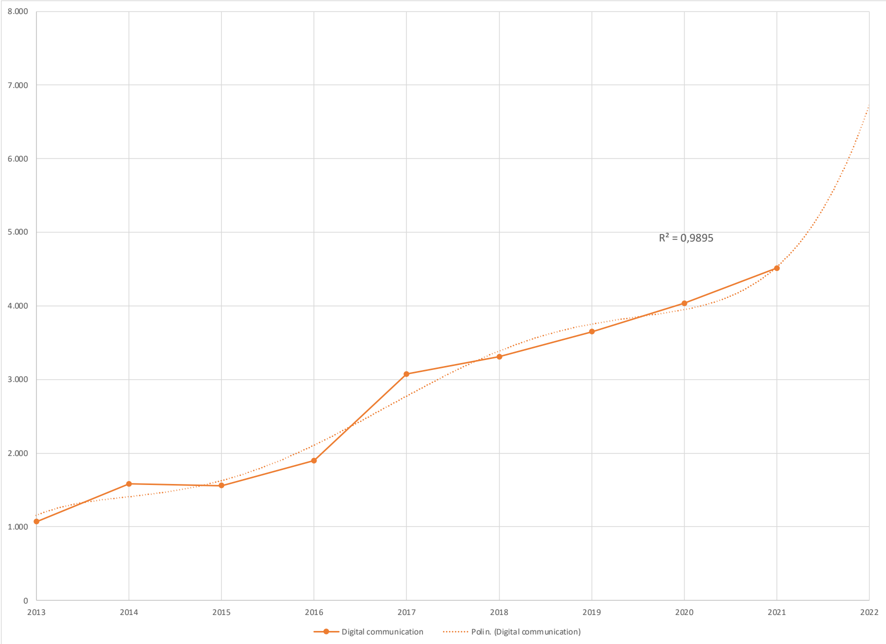

Figure 3.13. Digital communication patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

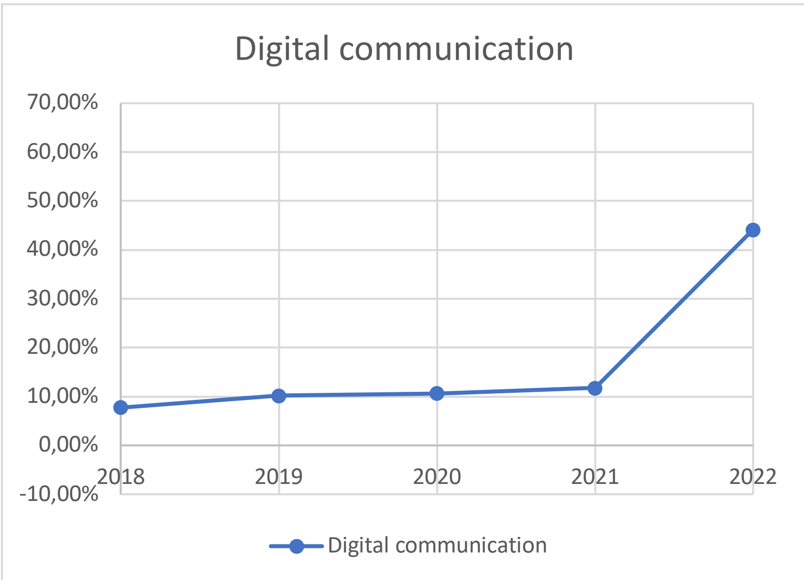

Figure 3.14. Digital communication patent applications growth rate curve (2018-2021; forecasted 2022).

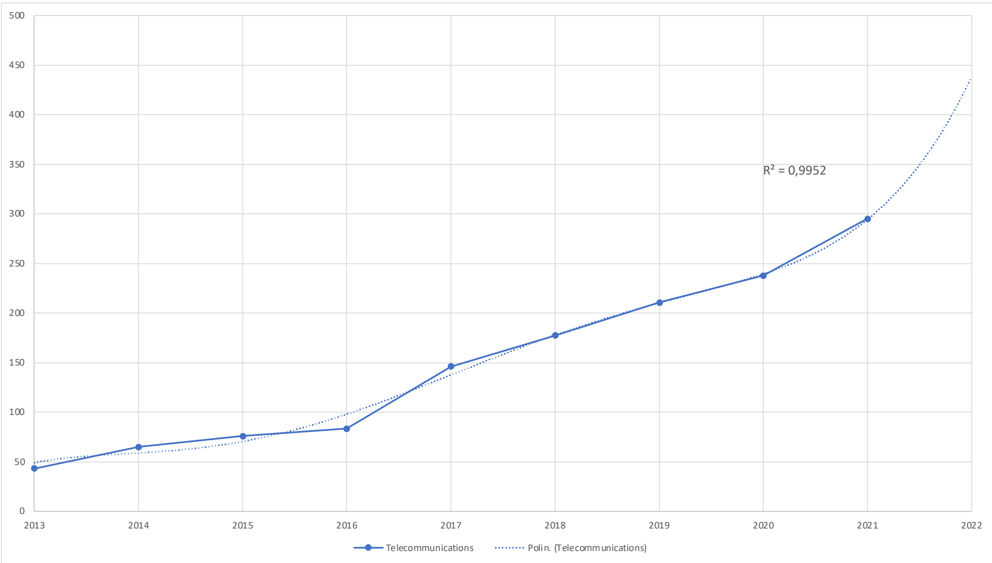

Figure 3.15. Telecommunications patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

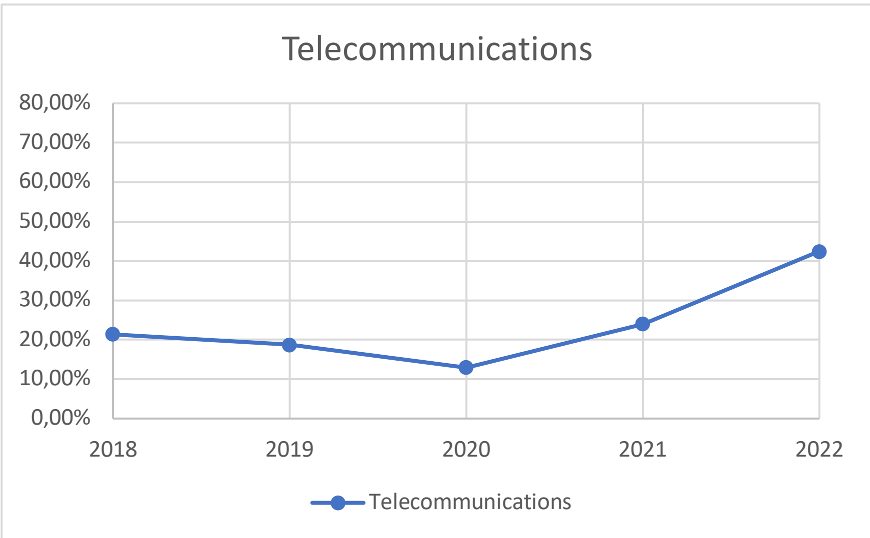

Figure 3.16. Telecommunications patent applications growth rate curve (2018-2021; forecasted 2022).

Results data seem to show acceleration patterns in the patent activity of both technological fields concurrently to the pandemic event. These trajectories might suggest that COVID-19 may have positively influenced research efforts in these categories. This could be justified by market needs, as during forced social distancing and closure of most productive activities, the demand for products belonging to this field increased drastically, therefore motivating scientists and inventors in increasing patent activity towards this kind of technologies. In fact, remote technologies have been the main enabler for phenomena such as remote work and remote healthcare, helping the population cope with restrictions offering them a possibility to engage in productive activities as well as leisure.

It is worth saying that the hypothesis argued for *Digital Communication* are drown in consequence of the observation of a sharp acceleration in the trend trajectory from the year 2021 to the forecasted 2022 (Figure 3.14). Given the uncertainty of the forecasted data, it may also be reasonable to hypothesize that the patenting activity in this category was already witnessing accelerations before the pandemic, therefore in this eventuality COVID-19 might not have impacted relevantly the growth of the field.

3.1.2.2. Analysis of biological material, Medical technology

The technological field *Analysis of biological material* has been characterized by a relatively small volume patent activity but in constant growth over the last 10 years. In particular, it can be seen that in the two-year period from 2020 to 2022 it has witnessed an acceleration of +30,07% in 2021 and prospected +69,29% in 2022 (Figure 3.17, Figure 3.18). For what concerns the *Medical technology* field, the patent activity in terms of count of publications was larger but registered smaller average growth acceleration, namely +20,22% over the period 2021-2022 (Figure 3.19, Figure 3.20). From results data, it is visible that these two technological categories experience a boost during the pandemic period, as the inventions included in these fields allowed to better tracking and tracing of infections and were crucial for the diagnostics industry. Breakthroughs such as *Nanopore sequencing, gut probe in a pill* and *ECG on your wrist* are some of the technologies that are common to these fields.

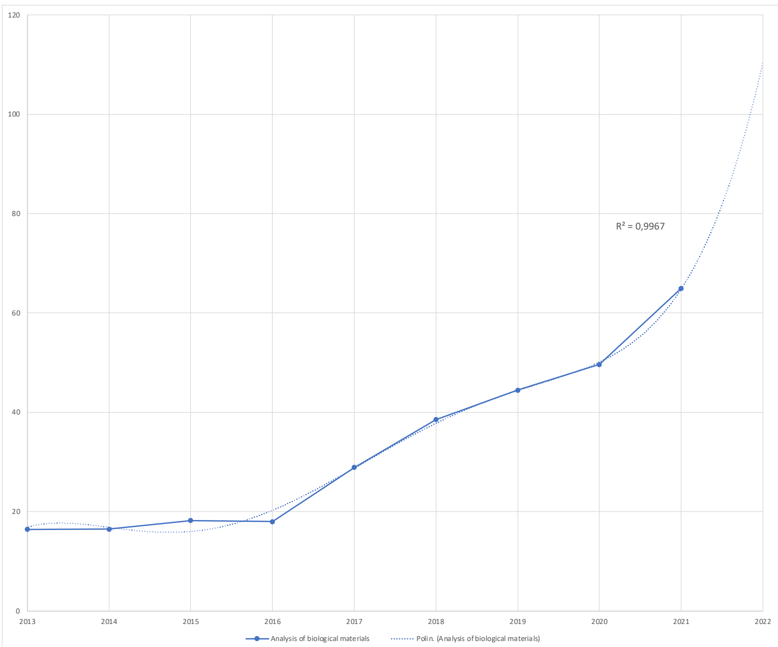

Figure 3.17. Analysis of biological material patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

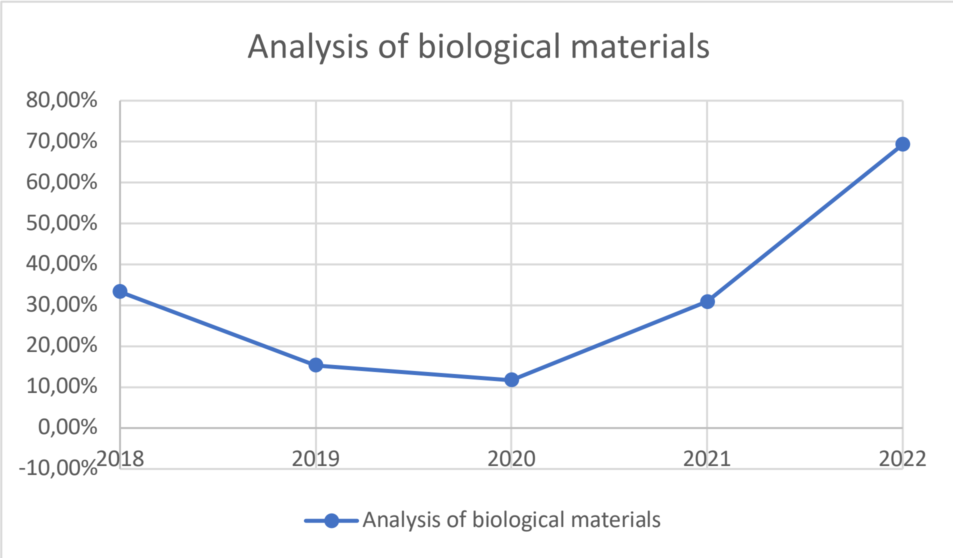

Figure 3.18. Analysis of biological materials patent applications growth rate curve (2018-2021; forecasted 2022).

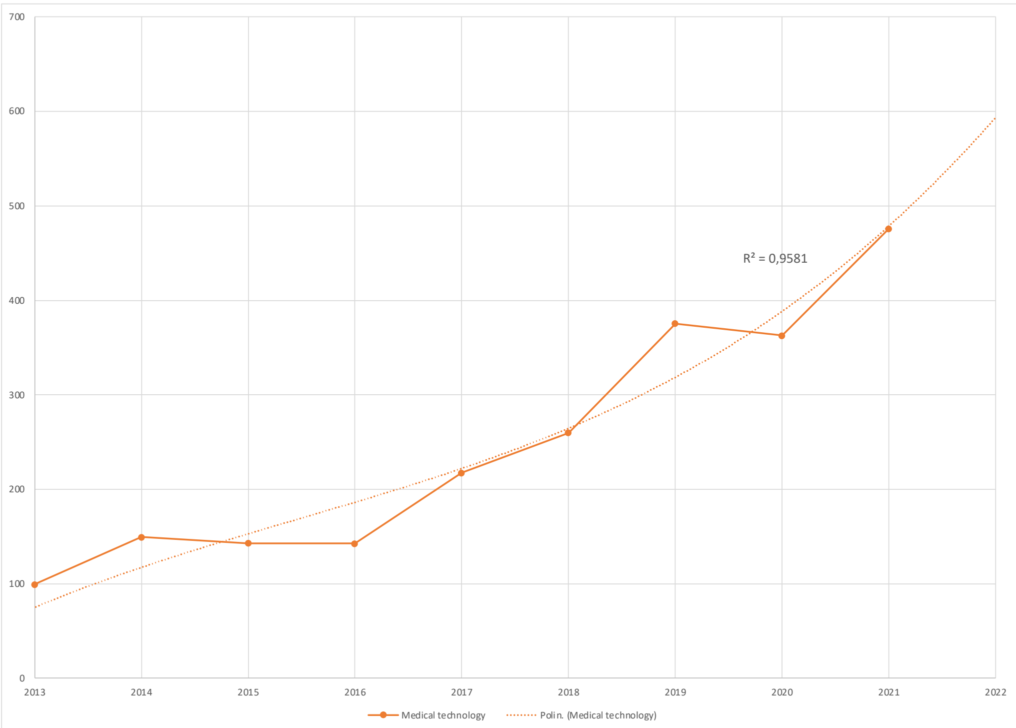

Figure 3.19. Medical technology patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

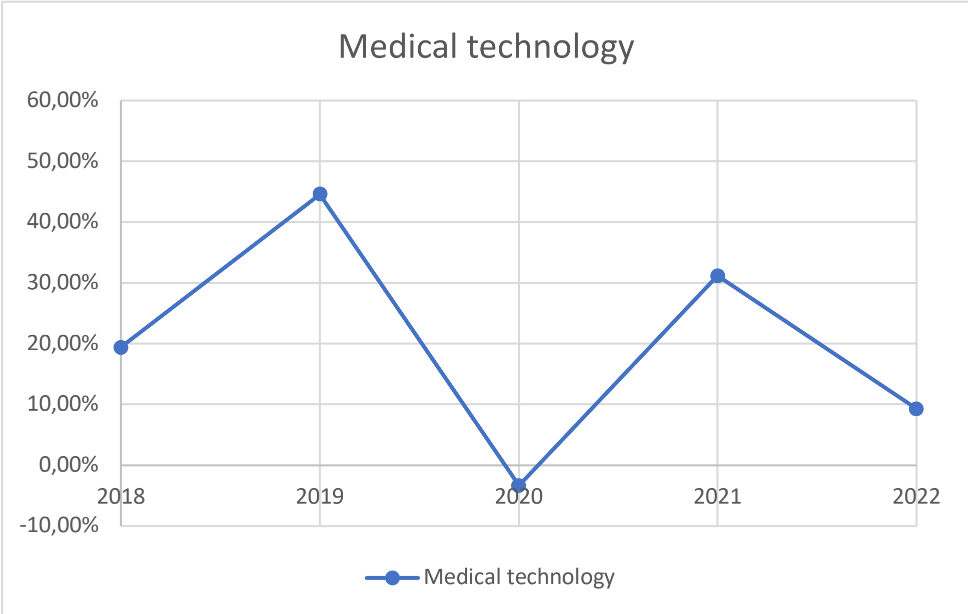

Figure 3.20. Medical technology patent applications growth rate curve (2018-2021; forecasted 2022).

Although with different growth patterns, the data show that both these technological fields have been experiencing rebound accelerations during the pandemic. From this phenomenon, I hypothesized that COVID-19 may have revitalized the research effort in these technological categories, suggesting that innovation activity refocused on diagnostics and medical monitoring concurrently to the spread of the virus. In particular, as medical and diagnostic devices embed always more digital capabilities, R&D functions might have directed their inventive activity towards them, given that these devices are able to generate large amounts of patients data that contribute to better understanding of the disease and increase predictive capabilities on the diffusion of deadly viruses.

3.1.2.3. *Biotechnology , Pharmaceuticals*

The technological fields of *Biotechnology* and *Pharmaceuticals* have been growing steadily over the examination time span. If, on the one hand, the resulting data on publications count show a constant upward trend for both categories over the last 10 years, on the other hand the growth rate over the two-year period of the pandemic (2020 – 2022) allows to clearly see that both these fields have experienced accelerations, respectively +18,36% in 2021 and forecasted +17,39% in 2022 for *Biotechnology* and +24,67% in 2021 and forecasted +38,60% in 2022 for *Pharmaceuticals* (Figure 3.21, Figure 3.22, Figure 3.23, Figure 3.24). Both these categories gather relevant inventions that represented innovations strongholds in the healthcare sector, especially in the development of drugs for rare or genetic diseases and therapies and methods to cure the most widespread pathologies. These technological field played an important role also during the pandemic: breakthrough such as *Messenger RNA vaccines*, which is the fundamental technology behind most of the COVID-19 on the market, are part of these categories. Other relevant breakthrough included are *Gene therapy, Immune engineering, Malaria vaccine* and *Custom cancer vaccine*.

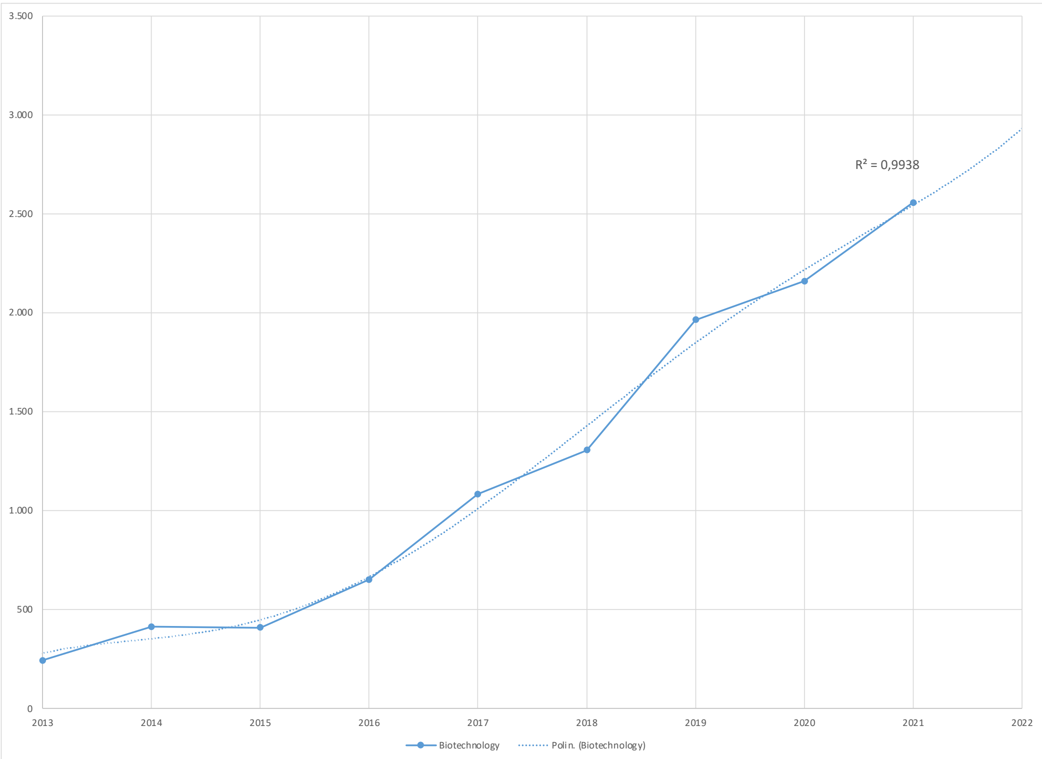

Figure 3.21. Biotechnology patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

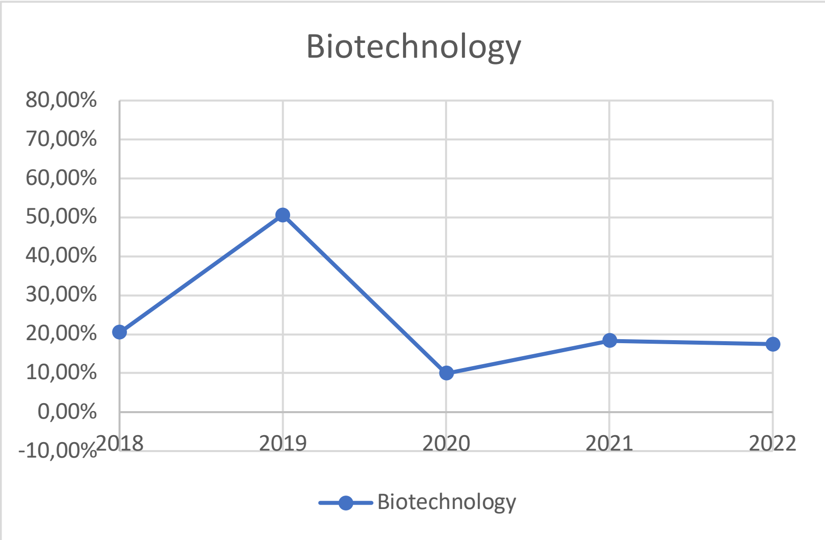

Figure 3.22. Biotechnology patent applications growth rate curve (2018-2021; forecasted 2022).

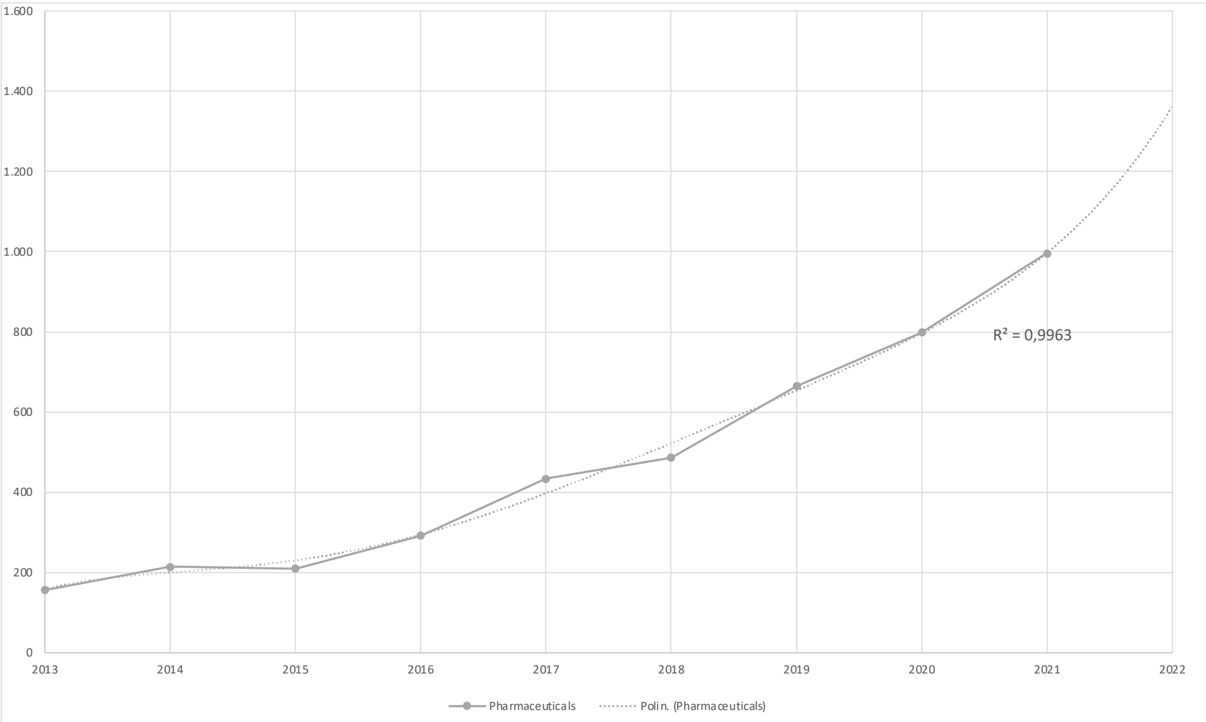

Figure 3.23. Pharmaceuticals patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

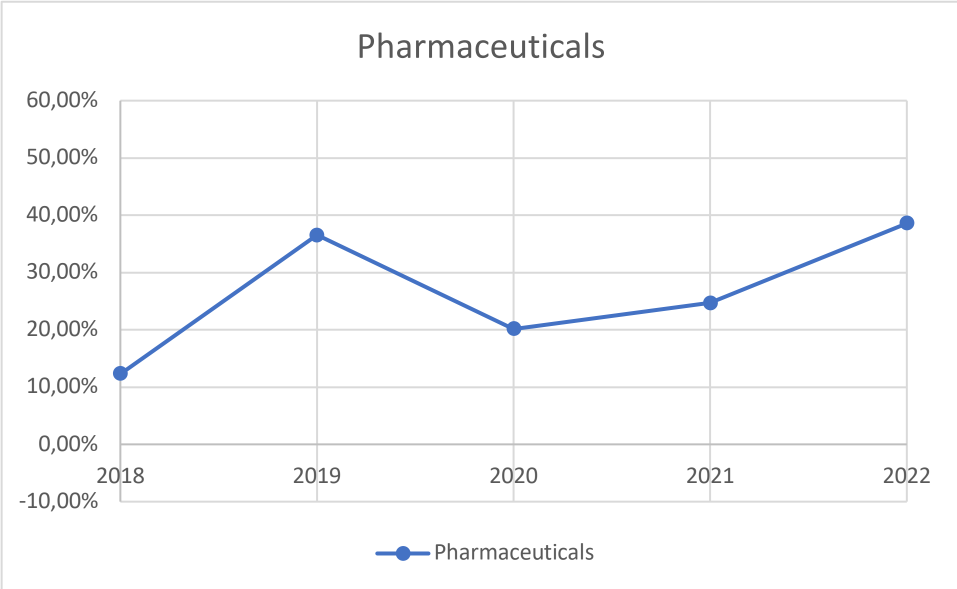

Figure 3.24. Pharmaceuticals patent applications growth rate curve (2018-2021; forecasted 2022).

Even though the entity of the accelerations in these two fields is smaller compared to the ones previously illustrated, from the data available I hypothesized that the pandemic might have influenced positively research trajectories in these two categories. In fact, *Biotechnology* and *Pharmaceuticals* are fields in which patenting activity over the last ten years was prolific. The urgency of addressing a worldwide challenge such as COVID-19, might have played a role in furtherly increasing innovativeness in these fields, directing majorly R&D efforts into finding new solution to dab the spread of the pandemic, as it has been testified by the fast adoption of M-RNA technology to develop vaccines for Sars-CoV-2 disease.

3.1.3. Trends decelerated during the pandemic

In this section I will analyze trends that experienced decelerations in during the pandemic time (2020 – 2022). This led me to hypothesize that COVID-19 might have impacted negatively R&D efforts in these technological fields so as to suppose a potential concurrency.

As for the previous sub-sections, here I will illustrate how in several technological fields the patenting trajectory has decelerated, commenting with potential hypothesis on the reasons why the pandemic could have played a role in these decelerations.

3.1.3.1. Electrical machinery, energy and apparatus, Semiconductors, Thermal process apparatus

The technological fields of *Electrical machinery, energy and apparatus* and *Semiconductors* have experienced a rather constant growth from 2013 until 2020, followed by decelerations in their patent activity in the two-year period of the pandemic. This can be visually seen on the count of applications publications count data, where the curve of the *Electrical machinery, energy and apparatus* reached the peak in 2021 with 9012 publications to then plateau off with a forecasted 9000 in 2022, and in the case of semiconductor an apex in 2021 at 2899 and a forecasted 2760 in 2022 (Figure 3.25, Figure 3.27). Growth rata data confirm these decelerations, showing for both fields downward trends and low growth rates in the last two years (Figure 3.26, Figure 3.28). Included in these technology categories are several common technologies that mostly impact the field renewable energy generation through solar and wind power, such as *Hot Solar Cells* and *Ultra-efficient solar power*.

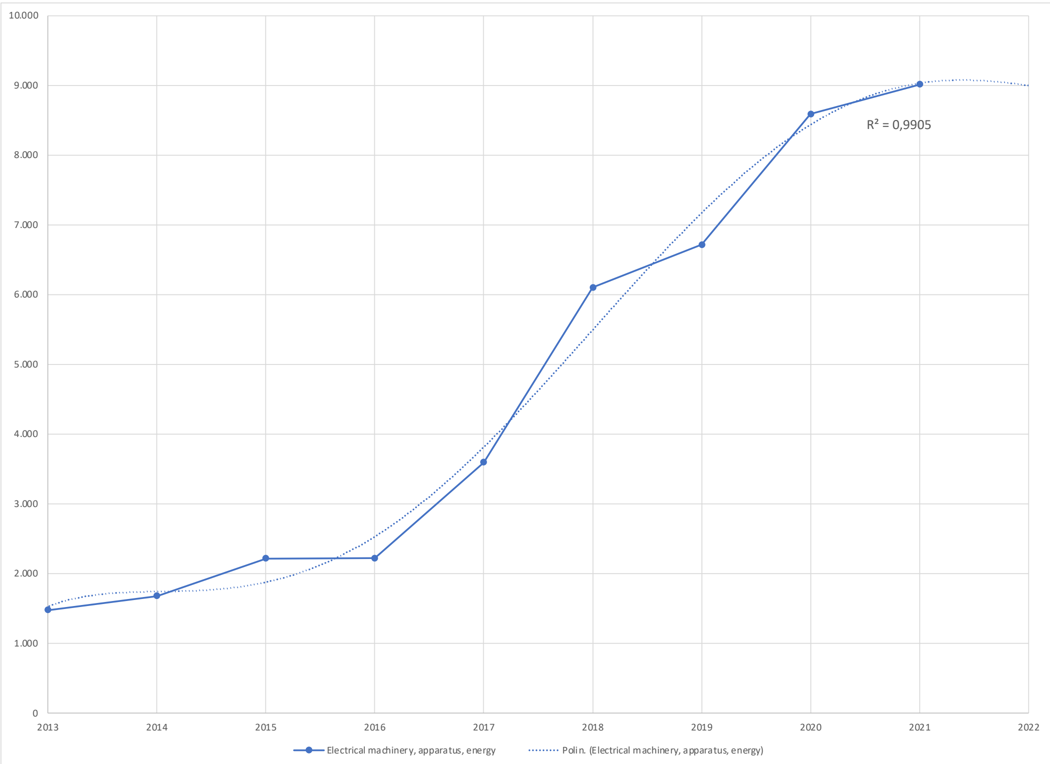

Figure 3.25. Electrical machinery, apparatus and energy patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

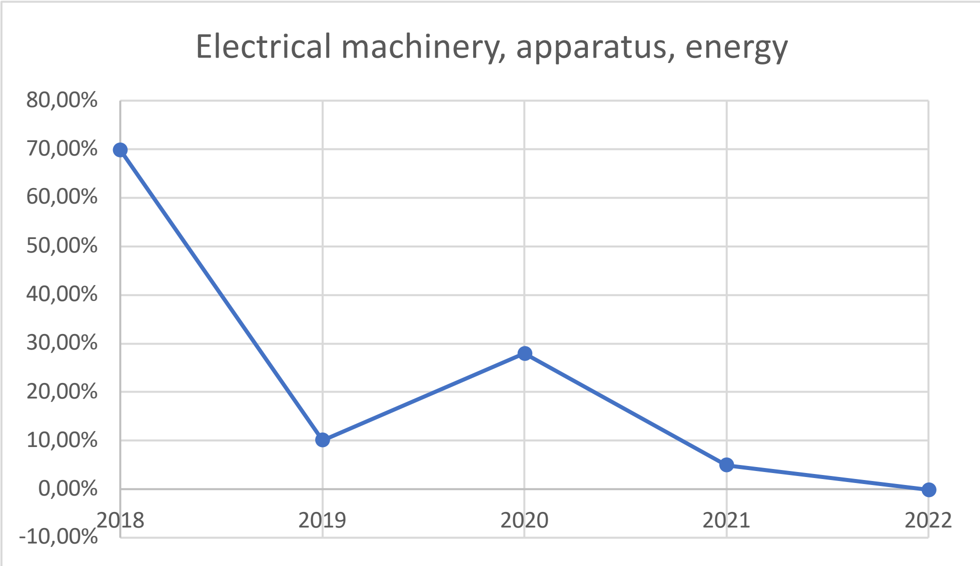

Figure 3.26. Electrical machinery, apparatus and energy patent applications growth rate curve (2018-2021; forecasted 2022).

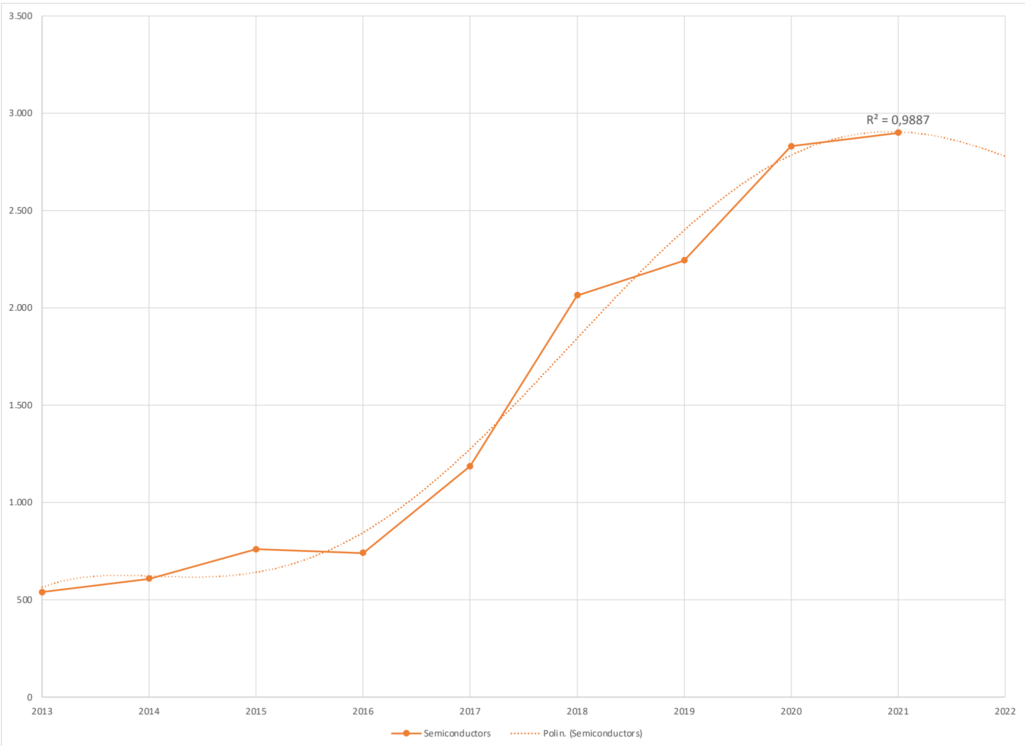

Figure 3.27. Semiconductors patent application publications curve and polynomial regression forecast with R^2 (2013-2021; forecasted 2022).

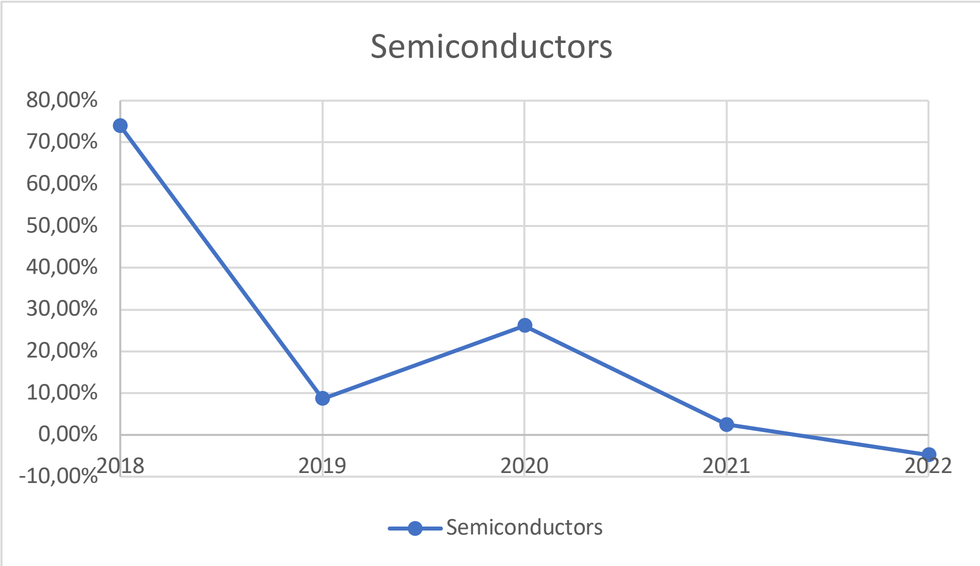

Figure 3.28. Semiconductors patent applications growth rate curve (2018-2021; forecasted 2022).

From analyzing the data, I made some considerations on the decelerations that affected these two technological fields. As a matter of fact, I hypothesized that COVID-19 might have partially impacted negatively the growth patterns of these technologies. The technologies that are included inside this categories reached high level of maturity in terms of development in performance: solar panels and wind turbines are well-known technologies for which already improvements have been designed to improve their efficiency in energy production, especially in solar panels. This might have hindered research efforts in these fields to focus R&D activities to more crisis-critical sector directly addressing the pandemic. It is also worth mentioning that the semiconductor markets has been hit by a wide unavailability of chip in 2021 (J.P. Morgan, 2022). This event might be related to the patent activity down-growth.

For what concerns *Thermal processes apparatus*, this sector covers the same exact technologies of *Electrical machinery, energy and apparatus*, therefore this led me to hypothesize the same suggestions considered before. *Thermal processes apparatus* reached the growth peak in 2021 with 1508 publications count, with a 2022 forecast of 1470 (Figure 3.29).

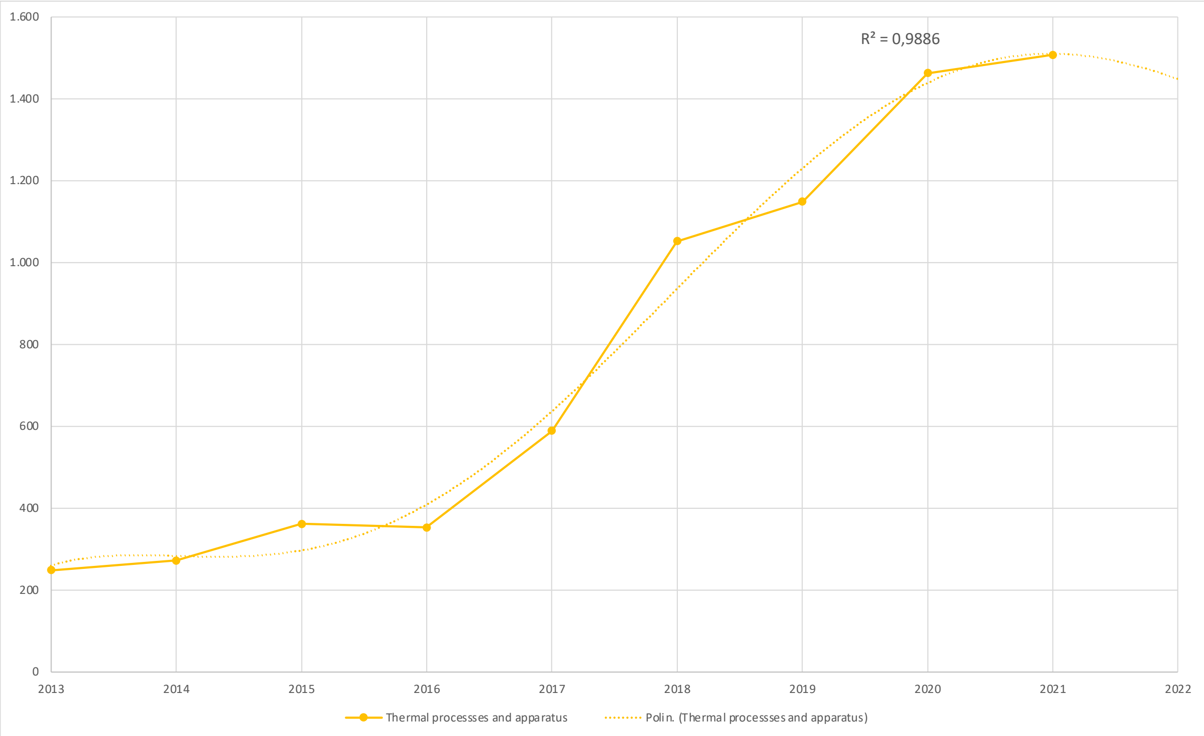

Figure 3.29. Thermal processes and apparatus patent application publications curve and polynomial regression forecast with R2 (2013-2021; forecasted 2022).

4 Limitations and Discussion

In this chapter, I will summarize the research standpoints of the thesis and discuss the main entailments it has both on practical and scientific view. Being patents and analyses on patent statistics one of the main ways in which it is possible to obtain a proxy of innovative outputs and technological change (B. H. Hall et al., 2005; Pavitt, 1985), the core objective of the thesis was to reflecting around patterns of change in the worldwide patenting activity before, during and after the COVID-19 pandemic, with the aim of formulating hypotheses on whether the exogenous shock of the pandemic could have played a role in changing innovation activity.

To do this, I consulted patent data from the WIPO *Patentscope* open-source tool focusing the analysis in the last 10 years (2012 – 2022) to intercept potential changes in the patenting activity concurrently to the pandemic period (2020 – 2022), after having observed an established trend trajectory in the previous 8 years. The area of analysis was focused on radical technologies listed in the *MIT technology review*, which every year covers the 10 breakthrough technologies that are believed to have the biggest impact on business and consumers in the years to come. This gave me the chance to investigate patenting activity on a total of 110 radically innovative technologies from 2012 to 2022, which allowed me to have a significant sample of count of publication of patent applications data to draw the results of the research in 21 different technological fields.

The results depict three different scenarios that have emerged from the data analysis. In a first set of technological fields I observed unchanged trend trajectories during the COVID-19 pandemic. The fields identified were the following: *Computer technology; Audio-visual technologies; Optics*; *Control*; *Measurement*; *Handling*; *Machine tools; Other special machines; Materials, metallurgy; Transport*; *Food chemistry* and *Environmental technology.*

Through the analysis on these technological field, I highlighted potential hypotheses on the reasons why the pandemic event might have been relatively uninfluential in the development of the trends patterns. For what concerns *Computer technology*, *Audio-visual technologies* and *Optics*, I found it plausible that COVID-19 might not have interfered in their general growth in patenting activity, given that the technologies included these categories mostly are radically innovative digital technologies that have experienced great diffusion over the last decade, therefore they were greatly backed up by R&D efforts over the whole examination period, also considering the growing pervasiveness of digital in every aspect of the daily life both for businesses and consumers. In the case of *Control* and *Measurement* technological field, I hypothesized that the pandemic might not have been influential in their decelerating trend patterns since the technologies included in these categories are mostly related to instruments and methods used to steer and allow communication between machines, especially autonomous vehicles, which already encountered performance maturity and are now moving towards market application, overcoming the phase of R&D development. In the technological fields *Handling*, *Machine tools*, *Other special machines* and *Transport*, I notice that in the field evidencing always increasing growth (*Handling*), there has been a concurrent increase in demand that was reflected in the innovation activity over the whole examination time span. Conversely, in fields like *Machine tools*, *Other special machines* and *Transport*, data evidences slower patterns of growth that may indicate either a still low market applicability of the technologies or a focus in different steps of the innovation process may hint at steady decelerations in these fields. *Food chemistry* field experienced exponential growth patterns starting from 2019 thanks to the advent of meat-free burgers, which might have contributed to the entrance of new-comers and innovative start-ups in the market that, thanks to their patenting activity, shifted the trends trajectory to an exponential one. This is suggesting that the pandemic might not have played a role in the growth patterns of this field. In the case of *Environmental technologies*, I hypothesized that research efforts have been constantly growing over the years, suggestive that scientists interest in developing this kind of breakthroughs was mostly influenced by the urgency of facing climate-change challenges that could have not been related to COVID-19.

In a second set of second technological fields, I observed accelerations in innovation trajectories during the years of the pandemic (2020-2022), hinting at a potential positive impact of the pandemic event in the growth of these categories. These fields were: *Telecommunication*, *Digital communications*, *Analysis of biological material*, *Medical technology*, *Biotechnology* and *Pharmaceuticals*.

For what concerns *Telecommunication* and *Digital communications*, I suggest that COVID-19 may have positively influenced research efforts in these categories as, during forced social distancing and closure of most productive activities, the demand for products belonging to this field increased drastically, therefore motivating scientists and inventors in increasing patent activity towards this kind of technologies. *Analysis of biological material* and *Medical technology* encountered rebound accelerations during the pandemic. Thus, I hypothesized COVID-19 may have revitalized the research effort in these technological categories, suggesting that innovation activity refocused on diagnostics and medical monitoring concurrently to the spread of the virus. For *Biotechnology* and *Pharmaceuticals*, I suggested that the urgency of addressing a worldwide challenge such as COVID-19, might have played a role in increasing innovativeness in these fields, directing majorly R&D efforts into finding new solution to dab the spread of the pandemic.

In a third set of technological fields, I observed decelerations in innovation trajectories during the years of the pandemic (2020-2022), suggesting at a potential negative impact of the COVID-19 in their development. These fields were: *Electrical machinery, energy and apparatus*; *Semiconductors*; *Thermal process apparatus*.

In all three of these categories, I hypothesized that the technologies included in these fields categories reached high level of maturity in terms of development in performance that might have hindered research efforts in these fields to focus R&D activities to more crisis-critical sector directly addressing the pandemic.

Certainly, the research I conducted has several limitations. Firstly, data gathered to obtain the patenting trends was exclusively sourced from the yearly 10 breakthrough technologies published in the *MIT Technology Review*. Having a single-source to extract the technological trends undoubtedly limits the broadness of the research and can hinder other relevant patent trends that may exist in research. Consequently, the thesis does not necessarily catch the entire innovation developments in the technological landscape. Secondly, due to the relatively short temporal proximity to the outbreak of COVID-19, the methodology used in this research lacks a consistent amount of data points posterior to the pandemic event. I collected data up until the third trimester of 2022 and forecasted 2022 using polynomial regressions. Third, the research was based only on one forecasting method. Many alternative and more accurate methods exist and the use of different methods of forecasting would strengthen the research robustness, alleviating the weaknesses of one method by using the strength of others (Kucharavy & de Guio, 2005). Furthermore, the unavailability of information on external factors that may influence the patent trends (e.g., the seasonality in the counts of patent publications of applications) poses a problem in determining the accuracy of the forecast when using forecasting approaches such as the polynomial regression, even if the fit of the forecasting models used in this research have all R^2 values higher or equal than 95%.

It is important to stress that, due to the methods used, this thesis is not aimed at drawing causality links between the trends presented and the pandemic, but rather to generate evidence-based hypotheses that reflect how patent activity might have changed in consequence or in response to the pandemic in the most radically innovative technologies in the market. I hope that these hypotheses will be further investigated in the future with more data and tested with suitable techniques.

As a matter of fact, the pandemic has caused discontinuity between previous and future necessities, such as a greater need to access technologies enabling remote working and healthcare or the urgency to commercialize vaccines to fight the spread of the virus. In this regard, my research may serve as a base point to further explore in the future innovation activities in several technological fields to understand whether COVID-19 has shifted R&D efforts directing technological change to specific areas. In particular, I believe that the thesis has implications for innovation research in two different areas. First of all, the methodology used in this dissertation can be useful for the identification of the technological research trends within the data. This could be helpful in understanding what differences subsist between consumer habits and new research trajectories. In fact, identifying R&D trends within patent data may be beneficial for spotting availability of new technological ideas in the future and target the ones that are likely to receive greater interest from the market with additional research. On a managerial perspective, this could help businesses and research hubs to steer their investment decisions or direct initiatives of corporate venture capital. Secondly, my research points out several hypotheses on the reasons why the pandemic may or may not have impacted patent activity in certain technological fields. This adds up to an already wide literature of patent analytics approaches to preview technological developments, contributing with an analysis on a highly disrupting factor such as COVID-19. The thesis can also be helpful in innovation research since it supplies new hypotheses on technological change that may be relevant for future innovation studies. In conclusion, I invite future research to investigate the impact of the pandemic in different technological fields and in a more detailed fashion, possibly outlining causality links between the outbreak of the virus and patenting activity, using different sets of data and more advanced forecasting methods in order to provide an even more accurate overview of future R&D development.

Bibliography

AJMC. (2021, January 1). *A Timeline of COVID-19 Developments in 2020*. AJMC.

Akhtar, M., Kraemer, M. U. G., & Gardner, L. M. (2019). A dynamic neural network model for predicting risk of Zika in real time. *BMC Medicine*, *17*(1), 171. https://doi.org/10.1186/s12916-019-1389-3

Amelio, A., Buettner, T., Hariton, C., Koltay, G., Papandropoulos, P., Sapi, G., Valletti, T., & Zenger, H. (2018). Recent Developments at DG Competition: 2017/2018. *Review of Industrial Organization*, *53*(4), 653–679. https://doi.org/10.1007/s11151-018-9671-7

Andriani, P., & Cattani, G. (2016). Exaptation as source of creativity, innovation, and diversity: introduction to the Special Section. *Industrial and Corporate Change*, *25*(1), 115–131. https://doi.org/10.1093/icc/dtv053

Ardito, L., Coccia, M., & Messeni Petruzzelli, A. (2021). Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. *R and D Management*, *51*(4). https://doi.org/10.1111/radm.12455

Ardito, L., Coccia, M., & Petruzzelli, A. M. (2021). *Technological exaptation and crisis management: Evidence from COVID-19 outbreaks*.

Barney, J. (1991). Firm Resources and Sustained Competitive Advantage. *Journal of Management*, *17*(1), 99–120. https://doi.org/10.1177/014920639101700108

Brem, A., Viardot, E., & Nylund, P. A. (2021). Implications of the coronavirus (COVID-19) outbreak for innovation: Which technologies will improve our lives? *Technological Forecasting and Social Change*, *163*. https://doi.org/10.1016/j.techfore.2020.120451

Caballero, R., & Hammour, M. (1991). *The Cleansing Effect of Recessions*. https://doi.org/10.3386/w3922

Carnabuci, G., & Operti, E. (2013). Where do firms' recombinant capabilities come from? Intraorganizational networks, knowledge, and firms' ability to innovate through technological recombination. *Strategic Management Journal*, *34*(13), 1591–1613. https://doi.org/10.1002/smj.2084

Chernoff, A. W., & Warman, C. (2020). *NBER WORKING PAPER SERIES COVID-19 AND IMPLICATIONS FOR AUTOMATION COVID-19 and Implications for Automation*. www.ipums.org

Cirelli, F., & Gertler, M. (2022). *Economic Winners Versus Losers and the Unequal Pandemic Recession*.

Coldeway, D. (2019, October 3). *Molecule.one uses machine learning to make synthesizing new drugs a snap.* . TechCrunch.

Cornelius, H. (2020, March 31). *Europe's coronavirus lockdown measures compared*. Politico.

D Young & Co. (2021, January 8). *Coronavirus: IP offices in Europe – changed practice*. D Young & Co.

DW. (2020). *Coronavirus: What are the lockdown measures across Europe?* DW.

Epo. (n.d.). *Patent Index 2021 - statistics at a glance*.

EPO. (2022). *European Patent Office*. EPO.

Ernst, H. (2003). Patent information for strategic technology management. *World Patent Information*, *25*(3), 233–242. https://doi.org/10.1016/S0172-2190(03)00077-2

Faulkner, S. L., & Trotter, S. P. (2017). Data Saturation. In *The International Encyclopedia of Communication Research Methods* (pp. 1–2). Wiley. https://doi.org/10.1002/9781118901731.iecrm0060

Garud, R., Gehman, J., & Giuliani, A. P. (2016). Technological exaptation: a narrative approach. *Industrial and Corporate Change*, *25*(1), 149–166. https://doi.org/10.1093/icc/dtv050

Gourio, F., Messer, T., & Siemer, M. (2016). Firm Entry and Macroeconomic Dynamics: A State-Level Analysis. *American Economic Review*, *106*(5), 214–218. https://doi.org/10.1257/aer.p20161052

Gross, D. P., & Sampat, B. N. (2021). *Crisis Innovation Policy from World War II to COVID-19*.

Hall, B. H., Jaffe, A., & Trajtenberg, M. (2005). Market Value and Patent Citations. *The RAND Journal of Economics*, *36*, 16–38.

Hall, R. E. (2015). Quantifying the Lasting Harm to the US Economy from the Financial Crisis. *NBER Macroeconomics Annual*, *29*(1), 71–128. https://doi.org/10.1086/680584

He, W., Zhang, Z. (Justin), & Li, W. (2021). Information technology solutions, challenges, and suggestions for tackling the COVID-19 pandemic. *International Journal of Information Management*, *57*. https://doi.org/10.1016/j.ijinfomgt.2020.102287

Hsu, P. H., Lee, H. H., Peng, S. C., & Yi, L. (2018). Natural disasters, technology diversity, and operating performance. *Review of Economics and Statistics*, *100*(4), 619–630. https://doi.org/10.1162/rest_a_00738

J.P. Morgan. (2022, August 2). *Supply Chain Issues and Autos: When Will the Chip Shortage End?* J.P. Morgan.

Kristin Majcher. (2015). What Happened to Ultraprivate Smartphones? *MIT Technology Review*.

Kucharavy, D., & de Guio, R. (2005). Problems of Forecast. *ETRIA TRIZ Future 2005*, 219–235.

Lopez-Vega, H., Tell, F., & Vanhaverbeke, W. (2016). Where and how to search? Search paths in open innovation. *Research Policy*, *45*(1), 125–136. https://doi.org/10.1016/j.respol.2015.08.003

Melluso, N., Bonaccorsi, A., Chiarello, F., & Fantoni, G. (2020). Rapid detection of fast innovation under the pressure of COVID-19. *PLoS ONE*, *15*(12). https://doi.org/10.1371/journal.pone.0244175

MIT. (2022). *MIT Technology Review*.

Modgil, S., Gupta, S., Stekelorum, R., & Laguir, I. (2022). AI technologies and their impact on supply chain resilience during -19. *International Journal of Physical Distribution and Logistics Management*, *52*(2), 130–149. https://doi.org/10.1108/IJPDLM-12-2020-0434

New York Times. (2021, July 1). *See Reopening Plans and Mask Mandates for All 50 States*. New York Times.

Nic Fleming. (2018). Computer-calculated compounds. *Nature*, S55–S57.

OECD. (2005). *Glossary of Statistical Terms*.

Pavitt, K. (1985). Patent statistics as indicators of innovative activities: Possibilities and problems. *Scientometrics*, *7*(1–2), 77–99. https://doi.org/10.1007/BF02020142

QS World University Ranking. (2022, October).

Saka, O., Eichengreen, B., & Aksoy, C. G. (2021). *Epidemic Exposure, Fintech Adoption, and the Digital Divide*.

Sampat, B. N., & Shadlen, K. C. (2021). The covid-19 innovation system. *Health Affairs*, *40*(3). https://doi.org/10.1377/hlthaff.2020.02097

Schumpeter, J. A. (2013). *Capitalism, Socialism and Democracy*. Routledge. https://doi.org/10.4324/9780203202050

Segler, M. H. S., Preuss, M., & Waller, M. P. (2018). Planning chemical syntheses with deep neural networks and symbolic AI. *Nature*, *555*(7698), 604–610. https://doi.org/10.1038/nature25978

Sharma, M., Luthra, S., Joshi, S., & Kumar, A. (2022). Developing a framework for enhancing survivability of sustainable supply chains during and post-COVID-19 pandemic. *International Journal of Logistics Research and Applications*, *25*(4–5), 433–453. https://doi.org/10.1080/13675567.2020.1810213

Silva, G. M., Styles, C., & Lages, L. F. (2017). Breakthrough innovation in international business: The impact of tech-innovation and market-innovation on performance. *International Business Review*, *26*(2), 391–404. https://doi.org/10.1016/j.ibusrev.2016.10.001

Simon Smith. (2018, September 19). *6 Things We Learned about Artificial Intelligence in Drug Discovery from 330 Scientists.* BenchSci Blog.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Tietze, F., Vimalnath, P., Aristodemou, L., & Molloy, J. (2022). Crisis-Critical Intellectual Property: Findings From the COVID-19 Pandemic. *IEEE Transactions on Engineering Management*, *69*(5), 2039–2056. https://doi.org/10.1109/TEM.2020.2996982

USPTO. (2022a). *CPC Scheme Classification*.

USPTO. (2022b). *USPTO: United States Patents & Trademarks Office*. USPTO.

Wagner, M., Yoshihara, M., Douagi, I., Damdimopoulos, A., Panula, S., Petropoulos, S., Lu, H., Pettersson, K., Palm, K., Katayama, S., Hovatta, O., Kere, J., Lanner, F., & Damdimopoulou, P. (2020). Single-cell analysis of human ovarian cortex identifies distinct cell populations but no oogonial stem cells. *Nature Communications*, *11*(1), 1147. https://doi.org/10.1038/s41467-020-14936-3

Wang, Y. H., & Lin, G. Y. (2022). Exploring AI-healthcare innovation: natural language processing-based patents analysis for technology-driven roadmapping. *Kybernetes*. https://doi.org/10.1108/K-03-2021-0170

WIPO. (2022). *Guide to the International Patent Classification (2022)*. https://www.wipo.int/classifications/ipc/

Younes, G. A., Ayoubi, C., Ballester, O., Cristelli, G., van Den, M., Ling, H., Postdoc, Z., Pellegrino, G., Gaétan De Rassenfosse, P. :, & Foray, D. (2020). COVID-19: Insights from Innovation Economists. In *derassenfosse@epfl.ch Version* (Vol. 1, Issue 2). https://ssrn.com/abstract=3575824

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