DISRUPTIVE TECHNOLOGIES AND REGIONAL INNOVATION POLICY

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Broadening innovation policy: New insights for cities and regions

Disruptive technologies and regional innovation policy

Pantelis Koutroumpis and François Lafond

While the adoption of disruptive technologies leads to an overall positive effect on the economy, the displacement of existing industries, workers and institutions represents a significant cost. In this paper, we review the literature on technological change and regional development with a particular focus on the differentiated regional repercussions of disruptive technologies. Building on a review of both the history of technological change and recent examples of disruptive technologies, we identify a number of characteristics of technologies and regions that are essential in determining their impacts. Combining these inputs, we suggest an approach to instrument choice based on analysing specific technology-region pairs and understanding interdependencies between technologies, between regions, between policy objectives and between levels of governance.

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Background information

This paper was prepared as a background document for an OECD/EC high-level expert workshop on "Developing strategies for industrial transition" held on 15 October 2018 at the OECD Headquarters in Paris, France. It sets a basis for reflection and discussion. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the OECD or of its member countries, or of the European Union. The opinions expressed and arguments employed are those of the authors.

Broadening innovation policy: New insights for regions and cities

The workshop is part of a five-part workshop series in the context of an OECD/EC project on "Broadening innovation policy: New insights for regions and cities". The remaining workshops cover "Fostering innovation in less-developed/low-institutional capacity regions", "Building, embedding and reshaping global value chains", "Managing disruptive technologies", and "Experimental governance". The outcome of the workshops supports the work of the OECD Regional Development Policy Committee and its mandate to promote the design and implementation of policies that are adapted to the relevant territorial scales or geographies, and that focus on the main factors that sustain the competitive advantages of regions and cities. The seminars also support the Directorate-General for Regional and Urban Policy (DG REGIO) of the European Commission in their work in extending the tool of Research and Innovation Strategies for Smart Specialisation and innovation policy work for the post-2020 period, as well as to support broader discussion with stakeholders on the future direction of innovation policy in regions and cities.

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1. Introduction

1. Disruptive technologies and large-scale technological transitions create winners and losers, at the same time as they bring about new forms of interactions that challenge existing social and institutional mechanisms of redistribution. Historically, technological change also reshuffled spatial hierarchies, with the decline of old sectors and the rise of new technological domains often corresponding to the progress and decline of specific places.

2. As a result, technological change is at once a constant threat and opportunity for regions. Advanced regions face the threat of missing the emergence of a new technology, but often have the opportunity to build on their existing advantage to increase their lead. Laggard regions can see technological transitions as windows of opportunity, but often lack the basic capabilities to make this happen.

3. How can innovation policy help regions benefit from new opportunities created by disruptive technologies and prepare for its challenges? Can regional innovation policy address the social consequences created by disruptive technologies without jeopardizing the pace of technological development? How can policy be more agile and adaptive to drastic technological transformations?

4. To answer these questions, we start by reviewing the literature in economics, geography and the history of innovation, asking how it sheds light, specifically, on *disruptive* technologies. We then provide an overview of the potential and characteristics of current technologies, and finally we discuss innovation policy, with a focus on regional policy.

5. Our inquiry firstly confirms that the diversity of regional characteristics (leader or follower, knowledge portfolio and industrial structure, legacy infrastructure, physical geography, proximity to other regions, cities systems and population structure and culture) makes one-size-fits-all policies inadequate. However, whilst the existing literature focuses mostly on the characteristics of regions, we argue that technologies also differ in important ways, and their specific characteristics are crucial in determining how they will impact different types of regions.

6. These characteristics include the dependence on infrastructure, the need for local adaptation, the life cycle stage, the mode of innovation, the position in technological interdependence and supply chain networks, the Jacobian vs Marshallian agglomeration economies potential, labour and skill intensity, and whether it is a product, process or service innovation.

7. The paper is organized as follows. In Section 2 we review the economic impact of technology. In Section 3 we review the literature on technology and local development. Section 4 discusses disruptive technologies in the past, present and future. Section 5 reviews the literature on innovation policy with a focus on managing disruptive technologies. Section 6 suggests a more granular approach to instrument choice, followed by a brief conclusion.

2. The economic impact of technology

2.1. Technology, productivity and economic growth

8. Technology is a fundamental determinant of economic progress. Before the work of Solow in the late 1950's, economic theory had largely neglected the importance of technological innovations, placing a greater weight on capital and labour as the key inputs for growth. The importance of technology was highlighted by economic historians first (Landes (1969[1]), Rosenberg (1982[2]), Mokyr (1992[3])) and later by macroeconomists. After the 1990s and the works of Romer (1990[4]), Grossman & Helpman (1991[5]) and Aghion & Howitt (1992[6]), technological change gradually became central to the economic growth agenda. The understanding of microeconomic aspects that affect macroeconomic outcomes (task automation, skill bias, labour substitution) helped explain the impacts of technological innovations on the broader economy.

9. Traditionally, economists viewed technology as an efficiency improvement, which can lead to lower costs per unit or higher outputs from existing resources. This progress may not have been uniform over time or across industries, but was largely considered to be smooth from a macroeconomic perspective. Mokyr (1992[3]) distinguishes between "micro" and "macro" (or general purpose technologies) innovations. The former represents incremental changes in processes or products that lead to marginal or relatively small improvements in the efficiency of everyday business processes. The latter refers to major discontinuities that – sooner or later – lead to new processes or products, new markets and essentially change the existing conditions in an economy.

10. The macroeconomic effects of GPTs can include periods of rapid acceleration and deceleration (Crafts, 2004[7]). In the early stages, the impact of a GPT on Total Factor Productivity (TFP) growth is often small and the realization of its potential can take years or even decades. Typical examples of this adoption process include the steam engine and electricity (David, 1991[8]). After the broad range of "micro" innovations gradually becomes depleted, the scope of the technology and its impact on growth will eventually fade away. If, in the meantime, there has been no other GPT evolving in the labs or already invented, it is likely that we would observe a hiatus in the growth process - like the slow growth process between the steam engine and electricity (Lipsey, Bekar and Carlaw, 1998[9]). Surprisingly, these questions are still puzzling researchers today. Firstly, it is not easy to identify whether a technology will, in fact be a GPT *ex-ante*, as many of the practical uses can be driven by factors that are hard to foresee. Secondly, the emergence of competing technologies can affect the choice of a previously dominant one. Thirdly, policies that prevent or incentivize certain types of behaviour for firms or individuals can accelerate or impede the impacts of GPTs.

11. Notably, the recent productivity slowdown observed in the past decades across Europe and the US has created a division among researchers, between those that consider technological adoption – or the lack thereof– as the main source of the slowdown and those that are less optimistic about technological capabilities (for a review, see Goldin, Koutroumpis, Lafond, Rochowicz, & Winkler (2018[10])). Crafts (2018[11]) concludes that 'there is a decent chance that technological progress will deliver a revival of productivity growth in the medium term'. Gordon (2017[12]) on the other hand, challenges the usefulness of new technologies and argues that these do not measure up to past industrial revolutions. Brynjolfsson, Rock, & Syverson (2017[13]) are more optimistic, and suggest that Artificial

Intelligence (AI) can leverage rapid advances in other sectors in the future, but point to time lags involved in the adoption process, and in the development and adoption of complementary innovation and management practices.

2.2. What drives innovation?

12. Technological disruption results from new scientific discoveries, profit incentives or a combination of both. In the "science-driven" view of innovation, the current knowledge or science frontier represents a constraint to individuals in their pursuits. Scientific breakthroughs are amongst the strongest catalysts for innovation but these breakthroughs are uncommon and rather unpredictable. Typical examples include electricity, antibiotics, computers, the internet and others.

13. In the famous quote by Isaac Newton, science progresses in discrete steps and every new invention "stands on the shoulders of giants", which alludes to the property of universal knowledge building on prior findings. The role of great inventors in the history of modern computing is one example where the sheer importance of scientific discoveries overshadowed profit incentives (Ceruzzi, 2000[14]). These inventions took place *"despite the belief of many important figures in the development of the computer, such as Howard Aiken, that there would not be more than a handful of personal computers in the United States"* (Ceruzzi, 2000, p. 13[14]) .The invention of the phonogram was also not initially intended for music reproduction or market dominance. Thomas Edison first thought of using the phonograph for making dolls *"speak, sing, cry"* or for recording *"the last words of dying persons"* (Knowles, 2003[15]). The invention itself was not driven by profit maximization, but was mostly intended to push the audio recording frontier further. The examples of scientists pushing innovation further without a direct material incentive are many. After the end of the World War II, two US government agencies, NASA and DARPA, received significant public funding to attract high quality researchers and produce internationally leading research. Apollo 11, the Space Shuttle and the internet are the results of this collaboration (Mazzucato, 2015, p. xxiii[16]). Paul Berg, the Nobel laureate in Chemistry, reflected a similar science-driven view and criticized the appropriation of basic science findings by venture capitalists in Silicon Valley (Henderson and Schrage, 1984[17]). Economic historians including Rosenberg (1974[18]) and Scherer (1984[19]) support this view of innovation as often science, rather than profit-driven.

14. On the other hand, it is true that for a long time inventions and innovations were not based on scientific understanding necessarily. The first industrial revolution, and to some extent the second, has been an age of Great Inventors, suggesting trial and error by individual genius and entrepreneurs as a major source of creativity. The development of chemistry and electricity is often considered to mark a shift from the tinkering of individual inventors to science-based technological development. Large R&D laboratories, exemplified early by Edison's Menlo Park labs, emerge as central to innovation theory, with Schumpeter's turn from Mark I (entrepreneurs as source of innovation) to Mark II (programmed innovation in large companies). The Second World War, which acted as a catalyst for important technological results, also marked this turning point. The 1945 Bush report (Bush, 1945[20]) adopted what became known as the Linear Model theory of innovation, with basic research funding ultimately being reflected in productivity and welfare. In the 1970's and 80's, increasing evidence revealed that formal R&D was far from the only source of innovation, with many improvements coming from learning-by-doing and the interactions with suppliers (Kline and Rosenberg, 2010[21]).

15. Economists have broadly supported the "profit-maximizing" view, either as a standalone explanation or as a further contributor to innovation in others. As early as the end of the nineteenth century, John Stuart Mill described that "the labour of (James) Watt…was undergone…in the prospect of a remuneration from the producers" (Mill, 1890, p. 68[22]). Inventors themselves openly expressed their belief in this view of innovation. Mokyr (1990, p. 248[23]) quotes James Watt on his appreciation of the patent system: *"[…] an engineer's life without patent was not worthwhile"*. Despite its simplicity however, this assertion fails to nullify the possibility that inventors would have continued to work under a different institutional environment that would provide them with the necessary inputs to carry on their work. Departing from the necessity of returns from inventions, Schmookler (1966[24]) supports the view that invention is similar to any other economic activity and, as such, is pursued for gain (1966, p.206).

16. Both views, the "science-driven" and the "profit-driven", seem to have some merit as drivers of innovation. The key distinction overseen so far is that these incentives drive different types of innovation. When risks are low and returns are high – usually in the case of incremental innovations – then the profit drivers appear to suffice for driving innovation. When uncertainty and risks are high, longer time horizons are needed for technologies to evolve. Especially for GPT innovations, the market driven approach may be inadequate and public or private guarantees might be preferred.

17. A vast empirical literature has investigated the determinants of innovation at the firm level. While not always conclusive, it suggests that the level of competition, firm size, and being an exporter are each important determinants of the quantity and quality of innovation. At the local or regional level, on which we focus here, a supporting set of institutions and agglomeration economies appear to be key. It is also worth emphasizing that some technological domains appear more prone to fast progress than others and technological proximity to fast-improving technologies are also important determinants of technological progress.

2.3. Technology and labour markets

18. The adoption of new disruptive technologies, often leads to a displacement of production inputs like labour and infrastructure. In fact, the Industrial revolution was characterized by this massive substitution process (Hounshell (1985[25]), Mokyr (1990[23]) Goldin & Katz (1998[26])) and this trend has continued ever since. Over the past century, economists have argued that technological adoption may increase incomes, but labour inputs will shrink as workers will gradually become redundant (Keynes (1930[27]) Leontief (1983[28]) Heilbroner (1965[29])).

19. The invention of the transistor and later the computer, expanded the scope of this substitution as information processing allowed for a much wider set of functions to be automated (Bresnahan, 1999[30]). Apart from the set of tasks that they generated, information processing capabilities marked a significant qualitative change in the job market. In the nineteenth century investments in high technology capital led to an increase in the demand for labour that could perform routine information processing tasks and complement the work of the machines, as seen in the rapid rise of the clerking occupation at that time (Chandler 1977; Goldin and Katz 1995). Computerization on the other hand, introduced the capacity to augment or entirely substitute routine information processing tasks. This process pushed the labour force to shift from routine to non-routine cognitive tasks that could not be substituted by machines but could be complemented by their use.

20. During the first decade of the twenty-first century, computers were largely unable to substitute workers in carrying out cognitive tasks that required flexibility, creativity, generalized problem-solving, and complex communications (Bresnahan, 1999[30]). As the computer scientist Winston (1999[31]) noted: *"The goal of understanding intelligence, from a computational point of view, remains elusive. Reasoning programs still exhibit little or no common sense. Today's language programs translate simple sentences into database queries, but those language programs are derailed by idioms, metaphors, convoluted syntax, or ungrammatical expressions"* (Autor, Levy and Murnane, 2003[32]).

21. Until recently, these non-routine cognitive tasks remained unaffected by computers. Methodological improvements in artificial intelligence combined with the lower cost of computer resources have made it possible to automate some of these tasks. For example, autonomous vehicles can replace professional drivers and robots making and receiving calls can replace employees in call centres. In spite of these capabilities, the empirical evidence has so far shown that new technologies have generated new demand for human labour in tasks that were previously unknown. From 1980s onwards in the US, employment growth has been greater in occupations with new job titles (Lin (2011[33]), Acemoglu & Restrepo (2018[34])). In fact, this trade-off between automation of existing tasks and creation on new ones lies at the heart of the labour impacts of technology: as long as humans have a comparative advantage in new and complex tasks this process can continue *ad infinitum* (Acemoglu and Restrepo, 2018[34]).

22. To understand the impact of technological disruption further, labour economists have introduced various modelling frameworks. Zeira (1998[35]) showed that technological innovations are not adopted everywhere, but only in countries with high productivity. This process amplifies the heterogeneity in the levels of productivity across countries. This view can possibly be expanded to include regional disparities in skills and technology adoption. Autor, Levy, & Murnane (2003[32]) suggested that the automation of routine tasks leads to increased inequality in the U.S. labour market. Acemoglu & Restrepo (2018[34]) depart from a job-based view of labour inputs and, instead, adopt a task-based framework. In their model they link factor prices and the range of tasks allocated to factors. With more automation, the capital shares increase while labour shares and wages decline. Similarly, the creation of new tasks (that cannot be automated) leads to increased employment.

23. The regional dynamics of this technology-mediated transition are subtle and can have different effects across the labour market and the economy. The breadth of tasks that may be affected by recent advances seems to be quite broad too: Frey & Osborne (2017[36]) estimated that 47% of all occupations in the US are prone to automation. The OECD reports similar estimates, showing that about half of all workers will need to "adapt to the new environment" alluding to high risks of their existing task automation (OECD, 2018[37]). A key concern is that fast automation may increase inequality and reduce welfare. In spite of the positive impacts of an exogenous automation shock on welfare the impact on employment can offset these effects when labour market frictions are present (for example with spatial disparities or other constraints in the labour supply choices of workers). Moreover these frictions may actually encourage further automation and lead to a further drop in employment (Acemoglu and Restrepo, 2018[34]). These "robot productivity" effects can be mitigated by redistribution policies that narrow their consequences for unskilled and younger workers (Sachs, Benzell and LaGarda, 2015[38]).

3. Technology and local development

3.1. Tacitness, cumulativeness, and disruptive technologies

24. The intrinsic properties of knowledge make spatial heterogeneity a key moderator of its diffusion and use. While, in theory, information has a zero marginal cost and is a public good, knowledge is often considered tacit, situated, localized, and developing through communities of practice (Amin and Cohendet, 2004[39]). Disruptive technologies tend to be more radical especially in their early stages of development, and thus based on knowledge that is more often tacit. The literature (Cowan, David and Foray, 2000[40]) has emphasized that knowledge is not necessarily intrinsically tacit or codified, but is codified when it is articulable and there are incentives to codify it. By affecting the knowledge base of an industry and its key players, disruptive technologies such as machine learning may not only affect the degree to which knowledge is articulable but also the degree to which articulable knowledge is codified. These changes in the nature of knowledge within an industry can translate into a reorganization of knowledge networks within and across clusters.

25. As well as this, in a specific domain and as long as a dominant paradigm persists (that is, as long as there as there is no disruption), knowledge is cumulative in the sense that new knowledge builds on existing knowledge, giving to incumbents a competitive advantage that can contribute to spatial inequalities. While path dependence implies a continued advantage along a trajectory, it also generates a vulnerability to paradigm changes (Dosi, 1982), explaining simultaneously place-specific long persistent successes and fate reversals at last, and suggesting stages in the technology life cycles as major determinants of optimal policy.

3.2. Geographic concentration and agglomeration economies

26. To understand how geography matters for economic development, Cronon (1991[41]) contrasts first nature (genuinely natural, such as climate) and second nature (human-specific) regional differences. Natural environments do matter, through their effects on transport costs, disease burdens, and agricultural productivity or more indirectly as a partial and non-deterministic cause of self-reinforcing and intertwined processes that eventually determine development - typically technology and institutions. Well-known examples include the natural resource curse (Sachs and Warner, 1995[42]) and the distinction between extractive and inclusive institutions (Acemoglu, Johnson and Robinson, 2001[43]), and have led to an ongoing debate in the development literature about whether or not "institutions trump geography" in explaining development (Rodrik, Subramanian and Trebbi, 2004[44]).

27. The earliest economic models that incorporated space gave a limited role to technology and mainly considered location decisions under fixed transportation costs. Krugman (1991[45]) generated a renewed interest in economic geography by showing that strong enough economies of scale or low enough transportation costs can induce a regime where cumulative causation leads to the concentration of manufacturing in a single region. Empirically, there has been an accumulation of evidence on the spatial concentration of economic and innovative activities (Ellison & Glaeser (1997[46]) Jaffe, Trajtenberg, & Henderson, (1993[47]) Audretsch & Feldman (1996[48])). Usai (2011[49]) and Kogler,

Essletzbichler, & Rigby (2017[50]) describe a very high and fairly persistent patenting intensity dispersion across European regions. In terms of labour productivity, the OECD (2018[51]) observed that in the last two decades within-country regional inequality has increased whereas regional inequality, at the level of the OECD, has decreased thanks to significant catch-up from poor regions in Eastern Europe, Chile and Mexico.

28. To explain agglomeration patterns, a classical distinction in the literature is between “Marshallian’’ (intra-industry or specialization) and “Jacobian” (inter-industry or diversity) externalities. Marshallian externalities arise because firms in similar activities share common specialized inputs (especially human capital). If input production features economies of scale, or if thicker input markets improve matching efficiency, firms have an incentive to locate close to firms in the same industry. Moreover, in the spirit of Arrow (1962[52]), Nelson (1959[53]) and Romer (1990[4]), since knowledge is not fully appropriable, it generates positive externalities. But a firm’s knowledge is more likely to be useful to firms of the *same* sector, and will flow more easily if firms are close in space, whether through market interactions or not (specific channels of localized knowledge flows include employee mobility, markets for technology, or formal university-industry collaborations (Breschi and Lissoni, 2001[54])). In contrast to Marshallian (specialization) externalities, Jacobs (1969[55]) suggested that diversity provides higher knowledge spillovers. Large cities, with their diverse set of occupations, make possible the cross-fertilization of ideas and knowledge recombination, leading to higher innovation.

29. Establishing the relative importance of each type of Marshallian externality is delicate because they all predict intra-industry agglomeration (Duranton & Puga (2004[56]), Carlino & Kerr (2015[57])). However, explaining the co-agglomeration of pairs of industries by their proximity in terms of the three types of Marshallian externality (input-output linkages, demanding labour from similar occupation, or patenting in similar technological categories), Diodato, Neffke, & O'Clery (2018[58]) found that labour market pooling is the major determinant of agglomeration, and has increased at the expense of value chain linkages over time.

30. A second difficulty in empirical research surmounted in recent years concerns the sharp distinction between Jacobian and Marshallian externalities, which rests upon the idea that we can classify pairs of firms as belonging to the same sector or not. The strict differentiation between inter- and intra-sectoral spillovers has proven to be of limited utility, and a lot of effort has been devoted to developing and evaluating measures of relatedness, using three main approaches. The first approach considers that sub-industries are similar if they belong to the same industry (Frenken, Van Oort and Verburg, 2007[59]). The second approach builds on the idea that co-occurrence indicates relatedness, and measures relatedness by how often two industries are found together within a region. The last approach assumes that two industries are related if they have the same inputs and/or provide inputs to the same industry (Essletzbichler, 2015[60]). Despite this diversity in measuring relatedness, differences in geographic and time spans, methodology and the studied outcome, it is becoming increasingly clear that economic development proceeds by branching, starting from specific areas of the knowledge space and developing from there along specific branches.

31. A few studies have looked more specifically at breakthrough or emerging technologies. Castaldi, Frenken, & Los (2015[61]), using patent data on US states for 1977-99, found that related variety increases innovation but unrelated variety increases breakthrough innovation (measured as very highly cited patents). Evangelista, Meliciani, & Vezzani (2018[62]) studied European regions specialization in Key Emerging

Technologies (KETs)[1], and found that such specialization increases regional growth, especially in backward regions. Montresor & Quatraro (2017[63]) found that being specialized in KETs increases the likelihood of entering new technological domains, though it mitigates the effect of relatedness on the probability of branching. This relates to Petralia, Balland, & Morrison (2017[64]), who found that relatedness matters more for developing than for advanced economies using country-level data.

32. Economic geographers have long argued that local labour markets conditions determine how firms and ultimately regions adjust to changing conditions (Clark, Gertler and Whiteman, 1986[65]). A literature on regional resilience, although concerned with shocks in general and not specifically with disruptive technologies, argued that a number of factors can improve adaptability, including a strong system of innovation (see below), good infrastructure, skilled and entrepreneurial workforce, and a "patient" financial system (Christopherson, Michie and Tyler, 2010[66]). While it has been suggested that a diverse economic base improves resilience, Delgado, Porter, & Stern (2015[67]) found that regions with a strong cluster specialization resisted better to the Great Recession in terms of employment growth.

33. Disruptive technological change has the potential to affect dramatically regional agglomeration because of its interactions with all types of agglomeration forces. A typical example would be a technology that creates a substitute for a specific type of input, thereby eliminating these types of Marshallian externalities for the region in which the old input producers are localized, and creating new externalities for the region where the new input suppliers are developing. Similarly, it is conceivable that a disruptive technology makes a specific skill irrelevant, thus lowering the thickness of the associated specialized labour markets. Knowledge spillovers (whether Marshallian or Jacobian) can also be affected by disruptive technological change in a number of ways. New technologies may change the structure of technological interdependencies, thereby changing the very definition of industries and thus the potential for spillovers between firms. It is therefore essential to move beyond a Marshall vs Jacob distinction and instead attempt to describe regional economies at the fine-grained level of firms featuring different and changing levels of proximity in an evolving techno-economic space.

3.3. Regional innovation systems

34. After Freeman's (1989[68]) definition of the National System of Innovation as "the network of institutions in the public and private sectors whose activities initiate, import, and diffuse new technologies", an emerging literature (Lundvall (1992[69]), Nelson (1993[70])) started to map the diversity of innovation actors (private corporations, government, universities), the complexity of their relationships (procurement, specialized supply, "horizontal" services, inter-firm R&D collaboration, etc.) and how differences between countries lead to different outcomes.

35. For instance, Freeman (1995[71])'s comparison of Japan and the USSR revealed striking differences in the organization of knowledge creation and diffusion activities. Japan exhibited a higher share of its R&D taking place at company level and strong integration of R&D, production and import of technology at the enterprise level, strong user-producer and sub-contractor relationships, as well as better innovation incentives and

[1] KETs as identified by the EU are nanotechnology, micro and nanoelectronics, photonics, advanced materials, biotechnology and advanced manufacturing systems. The KET observatory provided a match between KETs and international patent classification codes.

an exposure to international competition. The comparison between then-emerging Latin America and South-East Asia also showed that Latin American countries had a deteriorating education system, lower R&D, lower Foreign Direct Investment, weak linkages between science, technology and industry, a slow development of infrastructure for the high-tech sectors, and as a result, poorer innovation outcomes. The chapters by Nelson and by Freeman in Dosi, Freeman, Nelson, Silverberg, & Soete (1988[72]) contrast the US and Japan National Innovation Systems, with the US marked by University-Industry collaboration and strong funding from their defence budget, and Japan instead developing inter-firm collaborations, often orchestrated by the ministry of international trade and industry. The lack of military-driven funding and the focus on electronics in post-war Japan is often cited as a reason for Japan's tremendous success in the consumer electronics market.

36. Moreover, the institutional and behavioural underpinnings of inter-firm relationships determine the emergence, diffusion and impact of disruptive technologies. The obvious example here is the Silicon Valley "cluster". While there are antecedents (such as the Industrial districts of Alfred Marshall, the growth poles of François Perroux, and the similar analysis of Gunnar Myrdal), it is from a few influential contributions in 1980-90s (Saxenian (1991[73]), Porter (1990[74])) that a larger literature emerged on clusters and localized knowledge spillovers. The identification of interactive forms of learning and increasing recognition of the role of formal and informal institutions led to the idea of Regional System of Innovation. Cooke (2001[75])'s list of conditions and criteria for successful regional innovation systems include the availability of regionally determined (public or private) finance, investment in infrastructure, both hard (transport[2] and telecommunication) and soft (universities, technology parks) infrastructure, a culture of innovation, cooperation and networking.

37. Overall, the Systems of Innovation approach puts learning processes at the centre of attention, taking a holistic perspective and identifying institutions and interactions (networks) as key substrate for knowledge growth (Edquist, 2013[76]). It is relevant here because it highlights the key role of institutions, and one of the most disruptive aspects of disruptive technologies is that they bring about a need or an opportunity for institutional change, in the broad sense of social norms, laws and regulations, standards and routines.

38. Yet, as noted by Boschma & Frenken (2006[77]), the innovation systems literature tends to be mainly institutional but ultimately its treatment of technology-related issues should rely on the analysis of technologies and their specificities. Pavitt (1984[78])'s taxonomy and the theory of sectoral innovation systems (Malerba, 2002[79]) proposes that sectors have particular knowledge bases (e.g. strongly appropriable or not) and modes of innovation (e.g. internal or external) that determine their industrial dynamics and organization, even though a wide variety of firm behaviour exists within sectors (Leiponen and Drejer, 2007[80]).

[2] The relationship between regional development and transport infrastructure is controversial. Crescenzi & Rodríguez-Pose (2012[174]) evaluated the returns to kilometres of motorways across 120 regions in the EU during the period 1990-2004, and found little evidence of an effect of own infrastructure or neighbour's infrastructure on regional growth once R&D capacity, local social conditions, and migration are controlled for.

4. Disruptive technologies

4.1. The history of disruptive technologies

39. The very long-run history of technology starts a few million years ago with the first deliberately made tool as yet discovered, a river cobble with pieces broken off (Headrick, 2009[81]), from which Homo *Habilis* takes his name. Homo Erectus developed multipurpose hand axes and fire, and eventually Homo Sapiens made various stone tools for different purposes. Archaeologists date the origins of cultural evolution to roughly 70,000 years ago, with the emergence of art, religion, and ocean navigation. The period 10,000-3,000 BCE is classified as the Neolithic and produced agriculture and animal domestication for which tools were especially adapted, as well as melting.

40. These early developments are sometimes tied to specific regional characteristics that helped them diffuse across similar environments (like the key inputs necessary to produce them, or the environment to support them), and in other cases they appeared "quite independently" in several places (Headrick, 2009[81]). Diamond (1998[82]) provided a forceful and influential account of the role of geography on development. People in the Fertile Crescent not only benefitted from the availability of wild wheat and barley, but from the animals that were domesticated: sheep, goats, cattle and horses, which could provide meat and muscle power. It is often emphasized that sedentary populations were less well-fed than hunter-gatherers and suffered from more diseases due to proximity with domesticated animals. However, Diamond (1998[82]) notes that over time this also provided them with the higher resistance to germs that would eventually lead to the very fast decline of American indigenous populations when they became suddenly exposed to European diseases in the 16th century.

41. Classical Antiquity (500 BCE-500 CE) was an era of slow progress (Mokyr, 2013[83]), with the most important innovation being the lever (attributed to Archimedes). Greek and Roman technological developments formed around public civil engineering such as roads, water and sewage systems, including pumps and irrigation systems and heating, while most of these included few machines. In metallurgy, the progress was slow due to the difficulty in reaching temperatures that were high enough for casting iron. In agriculture, most improvements were usually local, with the aim to adapt existing Mediterranean techniques to different environments (soil conditions and crops).

42. The Early Middle Age (500-1150) is characterized by a decline in trade, transportation, and an increase in violence. Yet technological progress was quite important in comparison to the previous centuries. Most notably, the heavy plow made possible the exploitation of heavy and moist clay soils in the plains north of the Alps, which created a higher dependence on animals for traction. This new need was accommodated by the change in land use with the emergence of the three-field crop rotation system (where animals graze and fertilize the unused third). The center of gravity in the 8-12th century was still Mediterranean, with Moslem society more advanced, and developing large libraries to catalog knowledge, especially brought from elsewhere, China in particular.

43. The Late Middle Age (1150-1500) was a period of "slow but inexorable progress", driven by tinkerers and craftsmen. Aside from the windmill and better navigation techniques, high temperature furnaces made cast-iron available in Europe, more than a millennium after China. Important inventions include the weight driven mechanical clock

(late 13th century), the printing press (Gutenberg in 1453), and increased use of chemicals – gunpowder being perhaps the most consequential example.

44. The Renaissance and pre-industrial period (1500-1750) was an age of discoveries and instruments, but the gap between technical design and (still manual) craftsmanship was often too wide, as illustrated by the several thousand pages of devices designs found in the Da Vinci notebooks that could never be built, let alone lead to large scale productivity improvement. There was notable progress in agriculture (the "New husbandry"), peat and coal started to be used and major improvements occurred with blast furnaces and mining. Overall, 1500-1750 is more famous for its scientific rather than its technological achievements. The Arabs introduced algebra from India, and Fibonacci introduced Arab numerals in Europe in 1202. Algebra diffused slowly but helped with the creation of double entry bookkeeping in the mid-14th century. Despite a lack of Great Inventions, society became permeated with technology and a culture of knowledge, with books starting to make the diffusion and accumulation of knowledge possible.

45. This period has a direct regional interest, as the industries started to move out of the cities, where salaries were higher, to rural areas where winters could be spent in non-farm activities. The rise of the nation states led to active industrial policies, that benefited engineers and inventors through direct subsidies, pensions, patent or monopoly rights, and support for scientific societies. In the early Renaissance, Italian city-states are at the center of gravity, but in the Northern Renaissance that followed, the pace of development accelerated in the Low Countries and London. Dutch dominance in shipbuilding, coupled with emerging capitalist institutions (multiple share ownership and stock exchange), helped Holland prosper through the spice trade. According to Misa (2013[84]), an often-cited reason why the Netherlands did not dominate in the next period is that it lacked significant coal production.

46. The (first) Industrial Revolution (1760-1830) started in Britain, and has been studied intensively. We limit ourselves to three remarks. Firstly, while this was a period of very rapid and profound technological change, it was not one of impressive growth in real wages, at least initially (Allen, 2009[85]). Secondly, there was a great interdependence between the technologies. In textile manufacturing, the mechanization of spinning was the most significant but other stages of the cotton industry saw important progress and fueled a culture of invention. Precision instruments and machine tools made it possible to transform steel and iron into any shape, and were decisive for inventions such as Watt's steam engine. The steam engine was used mainly to pump water out of flooded coalmines and coal in turn was used for steam engines and furnaces. Thirdly, geography played an important role. Mokyr (2013[83]) notes that the slow diffusion of steam power in some places can be explained by improvements in the efficiency of waterpower, such as the breast wheel and the water turbine. Misa (2013[84]) studied British cities during the first industrial revolution, and describes their different paths: while London had a multidimensional growth, the other cities were fairly specialized, with Manchester's single system of cotton factories, or Sheffield's high quality steel which helped maintain a network of small specialized workshops.

47. The later nineteenth century (1830-1914) is often separated from the previous period because of accelerated developments, more science-based and more prone to increasing returns (economies of scale from large fixed costs in plants, learning-by-doing, network technologies, and purely technical factors e.g. in the chemical industries). Steel was one of the major developments, becoming affordable and of improving quality. Improved steel-making processes also reflected progress in the understanding of the nature

of matter, with German scientists publishing important chemistry books in the 1840s, and systematizing the science-based discovery of artificial dyes in the second half of the 19th, leading the way for the development of fertilizers and the invention of plastics. The development of the chemical industry in Germany in this period, driven by the creation of technical universities, is often taken as example of the role of local institutions in technological development.

48. Electricity had been known since the 18th century, and discoveries such as its lighting capabilities, the electric motor and the dynamo were made, but *"from the mid-1840s on, the earlier enthusiasm about electricity as a source of cheap energy waned"* (Mokyr, 2013[83]). The first uses of electricity were in the telegraph, which developed along railways due to their safety and for the practical reasons of infrastructure engineering. In 1860's and 70's the arc lamp became practical and affordable and started to replace gaslighting in factories, railway stations, etc. Many electric applications had been invented or vastly improved in the late 19th century (electric streetcars, the modern lightbulb, electric motor, telephone) and the battle between direct (Westinghouse) and alternating (Edison) current is a prominent example of the importance of standards. In transport, besides the "meteoric growth of railroads", steamships had to compete with redesigned sailing ships attaining great performance, the bicycle was invented and refined, and most importantly the internal combustion engine appeared. The late 19th century is also associated with the "American System of Manufacturing", developed gradually after the Civil War and characterized by mass production and interchangeable parts. Gordon (2017[12]) documented the impact of new technologies of food production, distribution, preservation and preparation on living conditions, carefully distinguishing between the North and South and describing how cooling and transport technologies changed the American diet and the spatial organization of agricultural production. The second half on the 19th century is also marked by a shift of dominance from Britain to Germany where the chemical industry and techno-scientific institutions developed hand in hand and the US, with the high demand for railways and the telegraph as well as the American System of Manufacturing.

49. The development of solid-state electronics can find its origin in the wartime effort to develop high frequency radar (Misa, 2013[84]), where the state organized collaboration between MIT, Bell, Westinghouse, GE, Sylvania and Dupont. Bell Labs (Shockley, Brattain, and Bardeen) built the first transistor shortly after the war. Shockley moved to his hometown (Palo Alto) to start a company, which had a major spinoff (Fairchild semiconductors), which itself had many spinoffs including Intel. In 1959, both Texas Instruments and Fairchild joined transistors on a single wafer, creating integrated circuits. All demand was originally for military purposes. A similar narrative of state-sponsored large R&D labs collaborations suits the development of digital computing and networks early developments.

50. What do we learn from history? Firstly, that technological change has very long-run effects, and these are almost impossible to predict. Secondly, the most profound technological transitions such as the first industrial revolution occur because a set of mutually supportive technologies emerged. Finally, despite significant hysteresis, over the long run, the centre of gravity does shift.

4.2. New disruptive technologies

51. At the centre of modern disruptive innovations are digital technologies. Semiconductor research and vast circuit integration gradually led to the development of higher computational capacity, faster memory chips and vast storage increases. These

changes spurred higher data processing capabilities in a wide range of sectors. In return, these improvements have fuelled an increase in data creation and reinforced the need for faster and more reliable computing facilities. Advances in software technologies have made possible a widespread adoption and use of personal computers and mobile devices. Through real time connectivity, the development of fixed and mobile communications networks drastically changed the modus operandi of these devices at high speeds in many regions around the world.

52. As a result, in the past two decades, billions of people have been enabled to process information and these capabilities underlie the progress in almost every sector of science, bringing about catalytic changes to the economy. Traditional businesses have been disrupted and new business models have emerged. The global economy has witnessed the rise of companies that provide digital services (online search, software, hardware, social media, e-commerce and others) and populate all top five places in company valuations, replacing other traditional leaders across sectors (finance, petroleum, chemicals)[3]. In fact, only one of these digital disruptors was in the top-5 list in 2009[4].

53. Digital technologies cover a very broad range of options that can be used in various contexts. The use of common information exchange protocols (like the TCP/IP) has largely enabled this ecosystem to emerge and led to significant price reductions that fuelled adoption rates. One of the first disruptions in digital technologies was the shift from vast mainframes to the personal computer. Until then, information processing was expensive and the code was proprietary. In the early 1980s, the drop in silicon chip prices coupled with the first attempts to standardize computer operating systems led to the first decentralization of information processing. This process continued with further improvements that affected the breadth and quality of use (hardware, software and the user interface) and was redefined by the use of narrowband internet connections (late 1990s and early 2000s).

54. Mobile technologies evolved in parallel, but were mainly focussed on telephony services in the early days of the first analogue network generation. The launch of second-generation networks produced digital networks, the first "data" exchange services in the 1990s being the short text messages (SMS). As network coverage expanded and mobile networks transitioned to IP networks (with voice and video data being transferred over IP), the integration among devices became straightforward. A direct implication of this change is the launch of the Internet of Things as a network of physical devices that connect to the Internet and exchange data. It is estimated that there will be 30 billion IoT devices in 2020 (Nordrum and others, 2016[86]). The range of applications that this common information exchange has enabled is broad, including connected vehicles, smart home applications, wearables, remote monitoring/management and connected health applications. These are broadly based on electronic sensors that record an attribute of interest and transmit this information though a common interface. In some cases, the IoT devices can become actuators, thus responding to specific local or remote signals conditional on a set of instructions or remote management commands.

55. Examples of digital disruptions include the substitution of high-street retail activity with e-commerce and digital marketplaces (originally introduced by Ebay and Amazon), the use of platforms to connect buyers and sellers for transport (Uber, Lyft), accommodation (AirBnB), work services (Peopleperhour, Amazon Mechanical Turk) and

[3] https://www.statista.com/statistics/263264/top-companies-in-the-world-by-market-value/

[4] *Financial Times* Global 500–based list is up to date as of December 31, 2009

others. Some of these services have brought upon significant impacts on local markets, either by the drop of high-street retail, the pressure on transportation and accommodation professionals (taxi drivers and hotel owners) and the increase in unemployment due to the off-shoring of certain occupations.

56. IoT applications can be used for monitoring transport, industrial or energy generation infrastructures and prevent conditions that may compromise safety, increase risks or costs (Gubbi et al., 2013[87]). Other applications of the IoT include improvements in agricultural monitoring through sensing and data analysis, predictive maintenance and control systems for manufacturing operations (Tan and Wang, 2010[88]), environmental monitoring for changes in atmospheric conditions, soil and water quality and warning systems for natural disasters such as wildfires, earthquakes or tsunamis (Tan and Wang, 2010[88]). Further implementations can be used for smart city management (transportation, traffic, safety) and energy management for buildings or regions. At the individual level, IoT applications can help with medical care and health monitoring (Internet of Medical Things, Gatouillat, Badr, Massot, & Sejdić (2018[89]), Topol (2015[90])) as well as elderly or disabled population care (Demiris and Hensel, 2008[91]).

57. A major disruptor that was caused by digital information processing and advances in computer science is Artificial Intelligence (AI). Unlike the passive sensing capabilities and actuation that we discussed for digital communications, AI turns computers into intelligent agents that "perceive their environment and take actions that maximize its chance of successfully achieving their goals" (Poole, Mackworth, & Goebel (1998[92]), Russell & Norvig (2016[93])). The basic principle rests with the establishment of a goal function and the learning process achieved by the repetition of specific patterns or behaviours and their reward or punishment by the goal function (Domingos, 2015[94]). Models can be "trained" over large datasets to optimize their performance vis-à-vis their goal function. AI models rest on a classifier that links inputs to outputs. To build those classifiers AI models use a range of statistical techniques like Decision Trees, Neural Networks, Bayesian techniques and other kernel methods (like Support Vector Machines). The interest of AI applications in the innovation process is key, as models can be used to substitute humans in a variety of cognitive tasks, thus reducing the time and effort to learn and innovate. The generic nature of AI is enabled by the computational capabilities and the underlying data structures. A well-defined "problem" can be approximated as long there is enough representative information that allows the models to have human-like outcomes in their quest for accurate classification. Self-driving cars are a great example; once autonomous cars can navigate in open (real or natural) environments and compare their performance with humans this will signal their potential integration in everyday activities.

58. Apart from AI, the finance sector has also been affected by digitization. Since 2008 when the Bitcoin paper was published (Nakamoto, 2008[95]) the evolution of cryptocurrencies based on the blockchain model have formed a parallel financial network that can provide a significant degree of anonymity for its users and a decentralized transaction mechanism that offsets the necessity of a centralized banking infrastructure for peer-to-peer (crypto-)currency exchange. While the technical specifications of this system are in some cases advantageous, requiring a consensus from network nodes through a public ledger that records every transaction, the actual applications of this framework have been scarce so far. In theory, reducing transaction costs for financial transactions can increase welfare but the broader benefits from a blockchain system (for contract management, a digital currency, or other data protection applications) have been largely unproven. Still, this technology represents a promising system that could become integrated or substitute current financial and data networks.

59. Manufacturing has also been dramatically affected by the advent of digital disruptors. First by the use of robots in industrial facilities that have been growing over the past decade and are expected to double in 2020 from the 2008 figures worldwide. This rise in automation leads to an increase in production capacities and enables a better control for the end products. Software improvements and motion technologies allow robots to integrate with humans in factories with significant implications for the types and number of jobs created in the future[5]. Apart from the use of robots in the production process, manufacturing has been affected in its core design phase by digitization. The Additive Manufacturing technologies break the entire manufacturing process into layers that originate from a 3D computer aided design and integrate all further steps by adding layers of plastic, metal, concrete or even human tissues. Relying on data from the 3D design, this process automates some delicate and accurate processes enabling engineers and users to create objects for Rapid Prototyping and parts or entire objects through 3D printing (Direct Digital Manufacturing). These new capabilities showcase the changes in the manufacturing industry that can affect both the locational and organizational aspects that are common in current industrial plants.

60. Another major aspect of technological disruption can be found in the area of personalized medicine through the evolution of genomics. The underlying hypothesis is that different individuals have unique variations of the human genome. While most of these differences are not directly reflected by an individuals' health, this DNA variation can reveal genetic mutations that influence diseases such as cystic fibrosis or cancer (Lu et al., 2014[96]). Apart from DNA sequencing, the analysis of the RNA can further help identify the RNA molecules linked to specific diseases, providing a broader understanding of a person's health (Battle et al., 2014[97]). These tools can lead to a transformation of healthcare provision. The use of predictive technologies and dynamic systems biology can help evaluate health risks and design methods to help patients mitigate risks and treat it with precision that is "tailor-made" to each individual.

61. Further integration of computational methods in other sectors have led to significant developments in computational chemistry, which aims to model the complex structures and properties of molecules. These findings can be used for laboratory synthesis of new materials and further analyse the experimental information including the position and source of spectroscopic peaks. This automated process can also lead to predictions for the possibility of unknown molecules and explore new reaction mechanisms within them. Given the high complexity of the underlying mechanisms, these methods can vary from rough approximations to high accuracy. This trade-off is linked to the computational resources required for each experiment as they increase rapidly with the size of the system (one molecule, a group of molecules or a solid) being studied (Cramer and Bickelhaupt, 2003[98]). The development of computational chemistry allowed for the creation of chemical databases where researchers can store new experimental information and search for existing findings. This systematic information has also helped create new computational approaches for the synthesis of new compounds and designing molecules that have well defined characteristics in their interactions.

62. A key issue for digital infrastructures is their need for efficient energy usage. All electronic sensors, network components and complex machines require energy to measure, actuate, transmit and complete more complex tasks. Combining this necessity with global

5 https://ifr.org/downloads/papers/IFR_Robots_and_the_Workplace_of_the_Future_Positioning_Paper.pdf

climate change policies (like the Paris Agreement in 2015) makes the use of renewable energy central in the scientific and industrial sphere. The progress made in this area has already disrupted the prices and supply of fossil fuels. Three dimensions will be discussed. The first relates to energy generation and the substitution of fossil fuels with renewable resources that have a zero carbon footprint and are not subject to scarcity. The second is linked to the efficiency improvements that (digital) accurate measurements and information exchange (through electronics or new materials) can provide thus reducing the overall needs in a global environment where developing countries are quickly in need for more energy. The third is linked to minimizing the energy storage requirements. The latter is often achieved on a large scale (at the electricity grid level) with the use of individual information and economic or behavioural techniques for custom demand management.

63. In 2016, energy from renewables accounted for an estimated 18.2% of global total final energy consumption, with modern renewables representing 10.4%[6]. The focus on electricity generation from renewables overshadows other important sectors. In particular, heating and cooling represent almost half of final energy use (48%) and transport one third (32%) while electricity covers the remaining 20%. In these core areas, fossil fuels are still predominantly used. The increase in the use of electric vehicles and the introduction of new infrastructure for heating and cooling can significantly help disrupt this market.

64. Improvements in efficiency of energy use appear in almost every sector. Policies in Europe and other countries have introduced tax schemes that promote energy efficiency at the country/industry (Emissions Trading Scheme) and individual level (energy certificates for buildings and electric appliances; vehicle's carbon emissions). Apart from the fixed improvements in energy efficiency, advances in electronics (like responsive thermostats, motion detectors, etc.) have allowed for further improvements in efficiency by sensing the occupancy levels in buildings or public spaces and adjusting the related energy consumption (for heating/cooling or lighting) accordingly. Other electronics have been utilized in new vehicles to improve their energy efficiency in various ways (turning the engine off in prolonged stops, using lower friction materials for new tyres, using turbochargers to utilize the wasted pressure and energy from the exhaust gases, etc.).

65. The last part in energy efficiency involves the use of behavioural interventions aimed at lowering greenhouse gas emissions (GHGs). Energy consumption has a strong periodicity that evolves around human lives and thus shifting loads to off-peak times is critical. To achieve this, electricity companies have introduced daily variations in tariffs. More recently, the use of smart meters and smart plugs have been shown to decrease overall consumption by more than 10% and shifting this consumption into lower demand tiers (Alberts et al., 2016[99]). The use of smart grids and intelligent devices that can manage electric loads independently can have a significant impact in this area. Moreover, inducing an energy conservation behaviour can also affect the emissions and nominal consumption levels.

66. The future of technology is impossible to predict, but findings in research labs indicate a great promise in quantum computing. Unlike current computers that represent information (data) into bits of two distinct states (0 and 1), quantum computers use qbits that can be in superpositions of states – the fundamental principle of quantum mechanics. In theory, large-scale implementations could solve problems much more quickly than current computers. Beyond this, they can tackle problems that are not practically feasible to solve with existing computational capacity. These changes can redefine computational

[6] http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf

limits and provide the basis for a further step towards new knowledge frontiers that could resemble the previous phases of digitization.

4.3. Predicting disruptive technologies and their impact

67. Technological change is a particularly difficult subject for forecasters. Breakthrough discoveries are sometimes serendipitous, and interdependencies between technologies make it difficult to predict technologies in isolation. However, path dependencies largely constrain technological development and routine innovation behaviour along a trajectory creates persistent patterns that make prediction possible.

68. Before the second half on the 20th century, anticipating future technology was essentially the domain of science fiction. According to Ayres (1969[100]), *"the first major forecasting effort by a panel, the 1937 study by the Natural Resources Committee of the National Research Council, was a very sober and responsible document which missed virtually all of the major developments of its decade, including antibiotics, radar, jet engines, and atomic energy"*. In the 60's, with the acknowledgement of the importance of technology in strategic matters and the continued formalization of research in large R&D laboratories, governments, academics and corporate institutions started to engage in more formal Future-oriented Technology Analysis. This term is used here to mean all activities aimed at predicting future states of the world that depend on technology, conditional or not on actions being taken, and aiming or not at optimizing decision-making of these potential actions.

69. We briefly discuss three broad categories. For more complete reviews, see e.g. Ciarli, Coad, & Rafols (2016[101])

4.3.1. Trend extrapolation: Moore's law and diffusion curves

70. Perhaps the earliest tool of quantitative technology forecasting was trend extrapolation. When monitoring the performance of a technology, such as the record speed of aircraft, often a clear trend appears. Martino (1993[102]) describes how in the 1930's and 40's propeller driven aircraft speed was increasing at a small rate, and, by contrast, the jet engine started with a lower performance but had a faster rate of improvement that eventually led it to overcome propeller performance. At an aggregated level, merging these individual technologies produces "envelope curves" that tend to have an exponential trend. The most well-known of all performance curves is Moore's law.

71. Recent work on performance curves has shown that while many technologies feature an exponential trend (a fixed average rate of progress), their rate is very different. Koh & Magee (2008[103]) documented that energy technologies for instance, improved much slower than information technologies. Farmer & Lafond (2016[104]) evaluated the extent to which these trends are good enough for prediction, and found that modelling these curves as autocorrelated geometric random walk with drift produces prediction errors as large as expected by the model. This does not mean that prediction is always precise, but it means that prediction intervals at different prediction horizons can be constructed and tend to be reliable.

72. Performance curves are very similar to experience or "learning" curves. While performance curves show an exponential improvement in time, experience curves show that cost falls (or performance improves) by a constant factor for every doubling of experience. Originally observed by Wright (1936[105]) for the cost of airplanes, experience curves became popular in the aftermath of World War II and have since been observed in

many domains. Experience curves often appear stable enough to lead to sensible predictions, if uncertainty in parameter estimates and future shocks are taken into account (Lafond et al., 2018[106]). However, in practice it is difficult to separate the effect of experience from other effects, and experience itself captures a great deal of other effects that take place along the deployment of a technology, not just learning-by-doing as some early studies suggested.

73. A second major branch of trend extrapolation concerns diffusion. A large literature has found that the diffusion of technology, in terms of the share of the population having adopted the technology, tends to follow S-shaped curves. There is a large literature describing different forms of S-shaped curves, and discussing how they emerge. A typical aspect of theories of diffusion is that there are different kinds of agents, with different propensity to adopt. While a rich sociology of adoption behaviour exists (Rogers, 2010[107]), a simple distinction between those who adopt independently and those who adopt because others have adopted leads to a fairly good description of most diffusion patterns (Bass, 1969[108]). Yet there is still a great potential for more sophisticated attempts at understanding how behavioural patterns influence the shape of diffusion curves. Young (2009[109]) in particular distinguishes between contagion (epidemic diffusion), social influence (conformity), and social learning, where people observe their peers and revise their cost-benefit analysis accordingly. The latter, which is somehow more satisfying as a premise for human behaviour, can lead to more complex patterns of diffusion with slow diffusion early on and sharp accelerations.

74. Besides imitation and learning behaviour, a very large literature has looked at how diffusion is affected by the structure of social networks (Cowan, 2005[110]). The details of the diffusion process matter, so it is difficult to draw generic conclusions. However, it appears that several network properties influence diffusion. For instance, networks with a very heterogenous degree distribution (that is, with a few “hubs” having a very large number of connections) can facilitate diffusion (especially the contagion-like diffusion) because once the innovation has reached the hub, it can reach everyone. Another important insight is that “small world” networks can promote diffusion. Small word networks feature a high degree of clustering, (friends of an agent tend to be friends with each other), which has important implications for influence, and yet they have a short average path length, so that no part of the network is very far from any other – the so-called 6 degrees of separation.

4.3.2. Experts: From Delphi to superforecasters and prediction markets

75. Quantitative techniques such as trend extrapolation rely heavily on data and on the continuation of existing trends and may need to be complemented when constructing scenarios for the very long run. A complementary approach that has been historically popular is to seek expert opinion, for instance through structured interaction groups such as workshops.

76. The Delphi method was originally developed at RAND to extract the opinion of a group of experts while limiting expert biases. Typically, during a Delphi session, experts are asked to forecast an event. Then responses are aggregated and given back in distributional form to the participants so that they can update their predictions. Experts’ responses stay anonymous. This method aims at taking advantage of the good aspects of the group (wisdom of crowds in repeated interactions) while avoiding the bad ones by removing reputational effects (through anonymity) and detrimental group dynamics (by structuring interactions tightly).

77. There is continued interest in the aggregation of expert opinions. Foremost amongst them are advances in behavioural economics and psychology that are improving our ability to design structured interactions that remove some known types of bias. Experts biases include overconfidence, anchorage, unwillingness to back down from the publicly announced positions, peer effects, bandwagon effects, the desire to look cautious, overcompensating past errors, being limited to one's own area, incorrect calculations, common information, herding, vested interest, etc. Better understanding these biases can help designing questionnaires or interaction structures that limit *ex-ante* or correct *ex-post* these biases. For instance, recent expert elicitation studies include an explicit process of expert debiasing (Bosetti et al., 2012[111]).

78. Secondly, progress has been made using ICTs to aggregate opinions of much larger populations. A prominent example is the work of Tetlock (see Tetlock & Gardner (2016[112])), who first found a negative relationship between experts' fame and accuracy, a result that tended to discredit expertise, but then found that in forecasting competition some experts consistently beat others. While this research (The Good Judgement Project) is currently oriented toward political science, going forward it is likely that these methods can be used fruitfully in technology forecasting. Like technological change, political events forecasting is complicated by an important degree of relationships between different events, an important degree of randomness, and an important degree of performativity/reflexivity (the chance of an event happening can be modified in response to the forecast itself).

79. Recently, progress in machine learning and artificial intelligence have led to a number of expert surveys, to evaluate the likelihood that these techniques would reach a given capability at a given horizon (Frey & Osborne (2017[36]), Grace, Salvatier, Dafoe, Zhang, & Evans (2018[113]), Müller & Bostrom (2016[114])). These results have proven very useful, by being instrumental in raising awareness of the current and potential future progress in these areas and helping researchers and policy makers identify specific areas where disruption is likely to be more intense, and when.

4.3.3. Big data and networks

80. Digitization creates vast amount of data, and it is likely that this will improve our ability to monitor and anticipate technological trends. Here we describe a few examples of recent research using Big Data and networks to predict emerging technologies using patent data. Of course, not everything is patented[7] and biases are well known, such as the lack of patenting in services, patent trolling, etc. Patent data is however public, easy to collect, and very rich in the sense that it contains a lot of metadata (inventors, assignees, citations to other patents or scientific literature, classification codes, different types of text, etc.). Rather than summarizing the vast existing literature, we discuss briefly three emerging research directions.

81. A first trend is to map patent data as innovation networks for predictive purposes. For instance, Acemoglu, Akcigit, & Kerr (2016[115]) constructed networks between patent categories using citation data, and found that levels of patenting activity predicted using activity in an upstream (cited) category was correlated with actual patenting in the future.

[7] Apart from patents, other mechanisms that help create, share and use new knowledge are open source systems. There licensing requirements – if in place – are seldom strong enough to guarantee monopoly rights but focus mainly on attribution for creators (see the Creative Commons Licensing) with the exception of the Open Data Commons "share-alike" approach.

82. A second trend starts from the idea that innovation networks are in a sense too static, because the number of nodes (technological domains) is given, whereas it seems important to try to predict radically new domains. One issue here is to define what an emerging technology is, and some recent studies have suggested that since patent classifications are often updated, it may be possible to consider new technological categories as new domains and look for patterns that pre-date the update of classification systems (Érdi, et al (2013[116]), Lafond & Kim (2017[117])).

83. A final branch of emerging literature also holds the potential to detect new domains or topics, but focuses on using text as data, often leveraging recent development in machine learning and natural language processing. Some studies attempt to develop better classification systems (Bergeaud, Potiron and Raimbault, 2017[118]), while others develop indicators of patent quality and novelty (Kelly et al., 2018[119]) or similarity (Arts, Cassiman and Gomez, 2017[120]).

84. Overall, there is a great potential for this literature to deliver new insights, and while it is limited on patents, the methods that it applies and develop (networks, text mining, text.) can be useful for other indicators of innovation once good datasets will be developed.

4.3.4. Global trends

85. Technological change and its regional impacts are affected by other trends that are both very important and to some extent predictable.

86. Ageing is a very important trend, because it is fairly predictable, and will have massive consequences on public finance, work and careers, and the structure of demand for goods, services, technologies, and places. When thinking about regional innovation policy, regions should consider the age structure of the population, their intrinsic attractivity for retirees in terms of physical geography, and their ability to provide services, including medical. An important point that is not currently being studied is that population ageing affects the supply of skills and abilities. It is known, specifically, that fluid intelligence (e.g. computing, reasoning and creativity) peaks in the early 20's but crystallized intelligence (encyclopaedic knowledge and social intelligence) keeps improving with age for a long time. Because productivity at certain tasks depends differently on these abilities, and because different tasks will be affected by automation, task-level supply and demand will be vastly affected by the twin forces of automation and ageing, but they are rarely studied together (Lewandowski et al., 2017[121]). Moreover, it has been suggested that longer life will lead to fundamentally different career paths, away from the traditional study-work-retire path and towards careers punctuated by several periods of learning and transition (Gratton and Scott, 2016[122]). This suggests that disruptive technologies and ageing work together to push away from linear career paths, making it even more important to develop life-long learning formal and informal institutions.

87. Climate change is probably the greatest Grand Challenge currently faced by humanity, and the alarmingly slow speed at which transition to a low carbon society takes place makes it increasingly clear that certain regions will face the dramatic consequences of it, including natural disasters, changing agricultural constraints, floods and sea level rise, and discomfort from temperature variations. Regional innovation policy should seek to understand and best take advantage of the technological transition that will take place. As energy, transport and land use systems will need to be fairly radically changed, this is a great threat for current leaders of the old paradigm and a window of opportunity for new entrants.

88. Among many issues that the rise of populism creates for innovation policy, the slowdown in trade and migrations are perhaps the greatest; considering the mobility of skilled workers and exposure to international trade tend to be seen as positive determinants of innovation. Voting differences between regions of different level of development and culture of innovation are striking (Rodríguez-Pose, 2018[123]), and call for leader regions to help national or supra-national attempts to reduce inequality.

5. Innovation Policies

89. In this section, we review the literature on innovation policy and discuss what may need to be added or amended to deal with the opportunities and challenges specific to *disruptive* technologies. We first discuss the fundamentals of innovation policy (rationale, instruments and evaluation), then discuss regional and finally broad-based innovation policies.

5.1. Innovation policy: rationale, instruments, and evaluation

90. In the post WWII era, innovation policy thinking evolved from a desire to rationalize STIs policies through better R&D data to a broader view of innovation as an interactive process and innovation policy as strongly linked to human, social and environmental considerations (Lundvall and Borrás, 2005[124]). In this subsection we review innovation policy rationales, instruments and evaluation with a focus on the specific challenges posed by disruptive technologies.

5.1.1. Innovation policy rationales

91. The classical justification for innovation policies is simply that positive knowledge externalities lead to a lack of appropriability of individual efforts, and thus to an under-supply of innovation efforts (Arrow (1962[52]), Nelson (1959[53])). This argument is used for justifying subsidizing private R&D, enforcing intellectual property rights, and the public production of knowledge in basic research. However, in this framework, “picking winners” strategies are seen as unproductive and policy should be limited to “horizontal” policies, such as neutral subsidies, general education, and favouring a culture of innovation and entrepreneurship.

92. In an innovation system framework, another rationale emerges under the broad label of system failure: the nature of technological change, in particular path dependence and lock-in, suggests that if the conditions change the system will not be able to get out of lock-in without an external intervention. Due to technological and innovation systems having many inter-related parts, there is a clear risk of coordination failure when the need of transitioning from one system to the other is needed. Transitioning requires the simultaneous, coordinated shift of focus, strategy and knowledge base from suppliers, R&D collaborators including universities, training centres, consumers, and supporting institutions. In this context, there is a strong role for policy in creating clear expectations, through foresights and technology roadmaps, standards and regulations, and public procurement.

93. Disruptive technological change provides another rationale for public policy. Disruptive technologies may displace existing workers, firms and institutions. While the “destructive” part of creative destruction is often inevitable in the long run, short and medium-run policies to accompany technological transitions can reduce the negative consequences of abrupt transitions. To the extent that disruptive technologies are negatively affecting social capital, they are lowering the positive externalities emerging from it. The market left to itself is unlikely to factor in these effects, and public intervention may thus appear legitimate.

5.1.2. Innovation policy instruments

94. Edler & Fagerberg (2017[125]) distinguish fifteen innovation policy instruments, which may be broadly grouped as R&D and invention support, policies to provide skills, technical, financial and foresight services, entrepreneurship and innovation culture policies, policies to support networks and collaboration, procurement and demand policies, and standards and regulation. Often these policies are supply-oriented, but demand-side policies have received renewed attention recently. Mazzucato (2015[16]) in particular emphasized the role of the state and procurement in the development of historically major technologies. These instruments are also often "horizontal", aiming at improving conditions and framework for innovation, independently of the sector or company, and thus are less biased than "picking winners". However, vertical innovation policies, clearly focused on developing a specific sector or technology, have been revived in recent years.

95. Innovation policy instruments specifically directed towards managing disruptive innovation, includes policies aimed at generating radical innovations, policies interfering with diffusion, either by accelerating, slowing or affecting the conditions for diffusion, and policies aimed at mitigating the impacts. We will come back to the latter in Section 5.3.

5.1.3. Innovation policy evaluation

96. Edler, Cunningham, Gök, & Shapira (2013[126]) produced a major review of the literature on innovation policy evaluation and found that generally, immediate effects are as expected but wider effects are more uncertain. Significantly, they found that context matters, interactions with other policies, conditions for implementation, existing technical, scientific and economics capabilities, financial markets, and cultural factors in particular.

97. Building upon the disappointing lack of clear results in innovation policy evaluation, Bravo-Biosca (2016[127]) argues for the development of experimental innovation policies. Recent years have witnessed the fast and prominent development of randomized control trials (RCTs) in development economics, and a case can be made that some aspects of innovation policies may be well evaluated by conducting randomized pilot studies. Clearly the limitations of RCTs (Deaton and Cartwright, 2018[128]), such as the lack of external validity due to the specificity of each context, apply forcefully in the case of innovation. Some aspects of technological change, such as the long-time scale for evaluation or the interaction of the targeted mechanism with other dimensions may well just make the innovation policy problem too complex. This is particularly so for disruptive technologies, for which the number of cases is low, the risks associated with randomization are high, the interactions with other socio-economic dimensions and policies are difficult to apprehend (see Section 5.3), and the effects are well understood only in the long run. Yet, there are surely some low hanging fruits, such as randomizing the marketing of SMEs innovation support programmes to increase participation rates. Regardless, RCTs provide fresh perspectives for thinking about innovation policy design and evaluation, and it is likely to matter for regions if nation states decide to test different pilot programmes in randomly selected homogenous regions.

5.2. Regional innovation policy

98. In the EU, the first regional policies appeared in 1993-94, and were essentially horizontal (Foray, 2014[129]). While cluster policies inspired by Porter (1990[74]) were debated but found too hard to put in place, a gradual move toward policies for regional innovation systems took place around 2000-2006, based on the recognition that different

regional policies may be appropriate for different regions, leading to the concept of place-based innovation policies (McCann and Ortega-Argilés, 2013[130]). Since the outcomes of innovation policy depend on the context, it follows that innovation policy design should be adapted to the specific challenges and context of the territory in which it is applied (Autant-Bernard, Fadairo and Massard, 2013[131]).

99. McCann & Ortega-Argilés (2013[130]), building on a dense review of regional innovation policies and experiences, propose the following distinction between challenges faced by different regions. World-class performing regions should focus on strengthening public-private partnerships, attracting global talents and fostering networks. Regions with a focus on industrial unemployment should instead attempt to increase the number of firms engaged in innovative activities, diversifying activities, and developing networks and external collaborations. By contrast, regions with a focus on services and public sector R&D should try to better exploit and commercialize research, develop public-private links and encourage entrepreneurship.

100. This recognition that one-size-fits-all policies are inappropriate in the context of regional innovation was the starting point of what became known as Smart Specialization Strategies (S3). Quoting from Foray (2014[129]), *"The notion of smart specialisation describes the capacity of an economic system (a region for example) to generate new specialties through the discovery of new domains of opportunity and the local concentration and agglomeration of resources and competences in these domains"*. There are three major and most distinctive aspects of S3, on which we comment in light of our concern with disruptive technologies.

101. The first is that S3 target specific sectors at a semi-aggregated level. Recognizing the need to concentrate resources because of agglomeration economies, economies of scale and economies of scope in knowledge production, the basic idea of S3 is to develop "distinctive and original" domains of specialization that should be relatively precise - a few "innovation microsystems" associated with specific niches, allowing even small regions to find their share of the knowledge economy. Depending on the initial state of the region and its targeted specialization, this can be a transition (new markets thanks to new technologies in old domains), modernization (use of new technologies in old domain), diversification (economies of scope make it clear that entering a new sector will be profitable), or a radically new domain, with no links to previous ones. This targeted specialization echoes closely the idea of managing disruptive technologies, as helping the transition of old domains affected by new technologies and promoting new specialization in domains where a window of opportunity arises.

102. The second aspect is that S3 insist on letting entrepreneurial discovery (in the Hausmann & Rodrik (2003[132]) sense) be the principal source of information. The principle that discovery of what to invest in is driven by entrepreneurs "allows a clear-cut distinction between smart specialization and older policy style that involved centralized planning methods for identifying priorities". This process is aimed at not only ensuring a better-informed specialization, but also at building up public-private partnerships and networks in the early stage of the implementation of the policy, where vertical areas of specialization are decided. While *ex-ante* all firms have a chance to be part of a S3, in the end only the firms that are innovating in a smart specialization area should be supported. An issue arising in the case of disruptive technology is that the interests of various actors may be more misaligned than in the case of "smoother" technological change. As noted by Schot & Steinmueller (2018[133]) "the resistance to change of existing incumbent networks benefitting from the current systems can be very strong". This caveat notwithstanding,

when the objective is to manage disruptive technologies, the focus of collective learning from the entrepreneurial discovery process should be on identifying threats (disrupted sectors) and windows of opportunities, but also on understanding the reorganization of the networks of technological interdependencies, a task that may require significant capabilities not always available locally.

103. Finally, in contrast to the idea that policy should be long-run, stable and reduce uncertainty, Foray (2014[129]) advocates evolving prioritization (while making it clear *ex ante* that support is limited in time). After about 5 years, new activities are no longer new and more information has emerged from other part of the system. Policies should be renewed. It is crucial to avoid subsidizing long-term assets, and subsidize only new activities, to avoid a conflict between competition and innovation policies. S3 should support early stage activities, where coordination problems such as the need for simultaneous large-scale investment are important. Choosing the right niche is critical, and the criteria to do so include the plausibility of becoming a leader/excellent follower in the niche, the proximity to market (vs fundamental research), that the new domain is rich in innovation and spillovers that can stay in the region, and that it requires the right number of partners (too few implies little impact, too many may not be possible for the region). From the point of view of managing disruptive technologies, additional criteria would include that the disruptive impacts of the new specialization be limited, or understood within a broader strategy of reconversion; that the new specialization addresses a specific need for reconversion that has arisen from disruption in a another sector (for instance by reusing displaced assets or providing new job opportunities for specific skill categories that have been displaced) and that the new specialization contributes to building a knowledge portfolio that is sufficiently diverse yet coherent for the region to be resilient to future disruptions. An example provided by Boschma (2015[134]) is to favour a mix of industries that have high skill relatedness, so that workers can transition from one to the other, yet have limited supply chain relationship, so that they are not affected by the same external shocks.

5.3. Broad-based innovation policy

104. The fact that innovation policy interacts with other policies, and that innovation may create or help to solve social problems or grand challenges is widely recognized (Edler and Fagerberg, 2017[125]), and many have called for “responsible research and innovation” through better governance principles. A definition of broad-based innovation policy provided by Edquist et al. (2009[135]) is one that encompasses wider societal benefits as its objectives, emphasizing coherence between policy objectives. Here we briefly discuss the intersection of innovation policy with environmental and with social policy.

105. Innovation policy should be seen as a major instrument of environmental policy, and vice-versa. For instance, in the context of climate change, establishing a fair price for natural capital, e.g. using carbon taxes, is regarded as a major policy instrument through its ability to generate induced innovations (Hepburn, Pless and Popp, 2018[136]). Similarly, as environmental norms and regulation may stimulate innovation (the Porter hypothesis), procurement is a key tool of niche creation to help technologies cut costs in the early part of their learning curve, and feed-in tariffs have been widely used to promote renewable energy technologies. Environmental innovation policy is concerned with managing disruptive technologies by nature because it aims at creating and implementing technologies that would displace existing solutions that are no longer desirable. A large amount of work on the issue of Transition Management already exists (Markard, Raven

and Truffer, 2012[137]), and inspires new framings of innovation policy, such as the idea of Transformative Change (Schot and Steinmueller, 2018[133]), where there is a clear concern with policy coordination failure (across policy domains and governance levels), directionality failure (in terms of technical options limited to the boundaries set by incumbents), tentative governance and experimentation.

106. A second policy field that interacts with innovation policy is social policy. Innovation is implicitly a force that creates dispersion; creating something new literally means creating a gap, a distinction between the innovator and the rest. Recent trends in regional inequality, partly driven by the labour market effects of technological change, translate into a geography of discontent (OECD (2017), Rodríguez-Pose (2018)). As a result, promoting innovation without compromising societal cohesion is a major challenge. Symmetrically, social policy thinking emphasizes the role of innovation policy. For instance, the first proposal in Atkinson's 15 proposals on *"what can be done about inequality?"* is *"encouraging innovation in a form that increases the employability of workers and emphasizes the human dimension of service provision"*.

107. A point of note is that innovation policy includes diffusion policy and as such can have a direct effect on reducing productivity and wage differences. For instance, rising wage dispersion in OECD countries has been tied to rising dispersion in firm-level productivity (Andrews et al., 2016[138]). Ensuring that laggard firms catch up or that their workforce can be reallocated to more productive firms is a means of reducing wage inequality without using direct transfers.

108. Zehavi & Breznitz (2017[139]) conceptualize distribution-sensitive innovation policies into four different types: supporting directly traditional industries in which productivity levels do not support fair wages, specific disadvantaged areas, specific disadvantaged groups such as minorities and improving inclusion by supporting specific consumption abilities – for instance directing innovation toward making affordable products for disabled persons.

109. OECD (2017[140]) studied a wide range of inclusive innovation policies specifically for digital technologies, noting that the low marginal cost typical of these technologies in principle can allow better prices or easier access for all, in E-commerce, E-learning, E-health and E-government. Public education, digital literacy and access to infrastructure remain key policy targets, but more specific challenges also emerge, such as the question of bias in training AI algorithms. As far as promoting territorial inclusiveness is concerned, it is suggested that boosting productivity directly, instead of R&D *per se*, can help narrow-down interregional disparities more efficiently.

6. Managing disruptive technologies at the regional level

110. In this paper, we have seen that that the drivers and consequences of innovation are varied, changing over time, changing from one technological domain to another, and subject to chance and self-reinforcing mechanisms (Sections 2, 3 and 4). Yet, the rationales for innovation policy are strong, and we do understand some patterns in technological development that can be useful for policy design (Section 4).

111. In this section, we take stock of what we have reviewed above and attempt to formulate a framework that lists the characteristics of technologies and regions that would determine how specific technologies will affect specific regions, and how policy can respond to these challenges and opportunities.

6.1. Technology characteristics

112. Throughout the paper, we have highlighted the tremendous heterogeneity between technologies. Here we list some key characteristics and then attempt to discuss how "flexible" these characteristics are, in terms of the potential for technology policy to change them (here we think of policies as more likely to be designed and implemented at the national or supra-national level). A summary can be found in Table 1.

113. ***Dependence on infrastructure.*** As emphasized by Perez (2003[141]), each technological revolution is associated with an infrastructure network. However, infrastructure is often local, so infrastructure-dependent technologies will have a more local effect. As an example, while the "digital divide" in terms of access to broadband remains important, disruptive technologies in energy and transport may appear even more infrastructure-intensive than digital technologies. The dependence of a technology on an infrastructure is generally difficult to change by policy intervention.

114. ***Need for local adaptation.*** Some technologies simply cannot work in the same way everywhere. Historically, agricultural technologies are the prime example, with ploughs, horse breeds and plant varieties requiring important modifications to suit local conditions. Transport and energy technologies to a good extent also fit this category. In comparison, digital technologies require little adaptation apart from language and cultural factors. Technologies that require local adaptation often diffuse and progress less fast, precisely because experience cannot be shared, but also offer more promise for laggard regions to engage in "technological dialogue" (Pacey, 1991[142]) and develop specific capabilities to meet their own demand. In general, it is unlikely that the need for local adaptation is a trait of the technology that can be easily influenced by policy.

115. The ***life cycle stage*** determines the type of externalities and windows of opportunities. If a new technology is disruptive, then by definition it is a challenge for incumbents and, as a result, provides a window of opportunities for others. To enter these windows of opportunity, latecomers need a reasonable productive capacity, human resources and locational advantage. Along the life cycle of a technology, windows of opportunity emerge as the industry undergoes changes in knowledge and technology, demand, institutions and public policy (Lee and Malerba, 2017[143]). Advanced regions are well placed to benefit from the next wave of technological development, but there are also many examples of regions unable to reinvent themselves, turning collections of resources into *"communities of inertia"* (Foray, 2014[129]). Duranton & Puga (2001[144]) suggest that

product innovation takes place in diversified cities, and then moved to specialized locations to be mass-produced and innovate in processes. This spatial life cycle determines threats and opportunities. To the extent that the speed of technological development and diffusion can be affected by policy, the life cycle stage is one the most “flexible” traits of a technology.

116. ***Mode of innovation:*** Some technologies tend to progress more through top-down, science driven inputs (the Science Technology Innovation, STI mode), while in others progress is achieved more through bottom-up learning (the Doing Using Interacting, DUI mode, Lundvall (1992[69])). It is well acknowledged that appropriability conditions determine patterns of industrial dynamics and thus affect agglomeration externalities. For instance, if the knowledge base is tacit, communities of practice will develop and the industry may have a strong local dimension (Amin and Cohendet, 2004[39]). Technologies that are intrinsically more based on a DUI mode of innovation will tend to thrive more in regions that have a consumer base. This could be the case, for instance, for health and ageing-related technologies. While the DUI/STI mode or the degree of codification is to some extent an intrinsic property of the knowledge base, some aspects respond to incentives (Cowan, David and Foray, 2000[40]). Typically, a DUI mode of innovation can be fostered by reinforcing knowledge networks using the tools of cluster policy.

117. ***Position in supply chains, value chains and innovation networks.*** Some technologies are more upstream/downstream than others in the innovation network (Acemoglu, Akcigit and Kerr, 2016[115]). This implies a structure of interdependence between regions. Regions focusing on downstream technologies are potentially able to benefit from externalities from innovation in other domains or regions, but this also makes them dependent and thus vulnerable in case the upstream knowledge generation decreases. Examples here include health, where applications of new therapies rely on continuous innovation in pharmaceuticals, and renewable energy where progress in renewable energy has been partly driven by semiconductors and digital technologies. Similarly, the position in the supply chain matters. Technological progress affecting upstream parts of the input-output network will tend to have larger effects (Baqaee and Fahri, 2017[145]). For instance, because all sectors use electricity, technologies that lower energy costs have large effects beyond the energy sector. Finally, technological change can affect different parts of the value chain, from conception, to production, marketing and distribution. This is important because OECD (2018) notes that there is more value added in the upstream (R&D) and downstream parts (marketing), and regions might be specialized in different parts of the value chain. Disruptive technologies could be thought of as those technologies that create a reorganization of these networks, typically by changing the dependence of one sector on another. Thus, apart from creating new disruptive technologies, these networks are fairly stable and policy cannot affect them in the short run.

118. ***Types of agglomeration economies.*** Some technologies might have a “more Jacobian” or “more Marshallian” potential. For instance, some technological ecosystems with very wide applicability, such as all technologies related to digital innovation, could thrive in diverse cities thanks to the good match between the diversity of the city and the large potential applications of the technology. In contrast, more specific technological domains are likely to benefit more Marshallian externalities, such as health technologies thriving in regions with large medical universities producing a pool of specialized workers. While the type of agglomeration economies provided by a technology appears rather inflexible at first, there might be some scope for technology policies to orient efforts towards depth or breadth of a technology. For instance, current national strategies for

Artificial Intelligence discuss both developments of the technology in terms of fundamental capabilities and in terms of "recombining" AI with various applications domains.

119. ***Labour and skill intensity***. Some technologies require few workers or workers with limited qualification, while others are very skill- or labour- intensive. Technology is responsible for up- or de-skilling in many sectors. Automation in manufacturing, transport, but also in less expected occupations is one of the greatest challenges for inclusive innovation policy. Regional authorities should not only try to anticipate what jobs will be lost, but also what jobs might appear, and whether or not the local labour force will be able to transition. In some instances, there might be a potential for policy to favour specific variants of a technology or modes of implementation that are less de-skilling or are more complementary to tasks that are more valued/enjoyed by workers, or easier to retrain for.

120. ***Product, processes or services***. Not all disruptive technologies concern technological physical products (Freeman and Soete, 2009[146]). Many disruptive technologies can take the form of innovative services with a strong local dimension, for instance in health services or in services currently being disintermediated by digital platforms and the "sharing" economy. Also, some technologies are more "material" than others in their inputs, and the degree to which a technology relies on tangible or intangible capital may in turn determine their offshorability, or territorial embeddedness. Similarly, some product innovations lend themselves to the development of an ecosystem of supporting services, or services that are themselves supported by the technology. These services represent a great share of jobs, value added and can be knowledge intensive and non-offshorable. While it seems difficult for policy, for instance, to change a product innovation into a service innovation, encouraging the development of associated supporting services that operate locally may sometimes be possible.

Table 1. Technology characteristics and flexibility for policy interventions

	Reasonably high and/or short term flexibility	Fairly low and/or long term flexibility	Fixed or almost Fixed
Dependence on infrastructure			✓
Need for local adaptation			✓
Life cycle stage		✓	
Mode of innovation	✓		
Network position		✓	
Types of agglomeration effects		✓	
Labour and skill intensity	✓		
Product, process or services		✓	

6.2. Regional characteristics

121. Throughout the paper, we have seen that a consensus exists around the idea of place-based regional innovation policy. Here we try to summarize the main regional characteristics that need to be evaluated and monitored to understand how specific regions will be affected by specific disruptive technologies. We also briefly attempt to evaluate whether a characteristic is flexible in the sense that innovation policy can modify it – see Table 2 for a summary (here we tend to think of policy as regional or decentralized policy, although we do not exclude national policies with regional implementation and effects).

122. ***Leader vs Follower***. On the one hand, advanced regions often benefit from already being leader, because of their knowledge base but also thanks to associated built advantages

such as the availability of finance. On the other hand, really disruptive technologies may open windows of opportunity for catching-up regions that have developed sufficient absorptive capacity (Foray, 2014[129]). In the absence of information asymmetries, the leading regions could benefit from easier access to key inputs and manage to sustain indefinitely their advantages unless some form of labour or capital scarcity exists (Ross and Sharapov, 2015[147]). This would allow them to imitate their followers' successful innovations and avoid the pitfalls[8]. Here there are many historical examples of policy for reducing inequality between leader and advanced regions, the main example in the EU being the Cohesion fund from the European Structural and Investment Fund.

123. ***Knowledge portfolio and industrial structure***. Beyond the leader/follower status on a specific technology, a key factor to consider is the current overall positioning of a region in terms of technological specialization and capabilities. Regional branching is often into related varieties, so existing specializations largely determine the ability to take advantage of current progress in a new domain (Frenken, Van Oort and Verburg, 2007[59]). To some extent, general-purpose technologies are crosscutting domains that open opportunities to all regions and make existing specializations less binding (Montresor and Quatraro, 2017[63]). Another important distinction is between specialization in tradable or non-tradable sectors (whether good or services and whether actually traded or not). The OECD (2018) finds that regions specialized in tradable sectors achieved more catching up, because tradable sectors tend to have higher productivity and productivity growth, and lower reliance on internal demand makes the system more robust to shocks. The premise of Smart Specialization Policies is that knowledge portfolios/industrial structures can be stirred in specific directions by policy intervention.

124. ***Infrastructure***. Regional characteristics that will determine the impact of the disruptive technology include the ability to develop the new infrastructure, the difficulty in getting rid of the old one, if relevant, and the ability of the region to connect to the infrastructure built by neighbouring regions. Market failures are likely to be more important in infrastructure building than in other domains, and as a result, public policies for infrastructure remain not only a major priority for overall development but also a key instrument for ensuring territorial inclusiveness.

125. ***Physical geography.*** While the literature has found that agglomeration and development tend to be driven by human factors rather than physical geography, some aspects of physical geography may matter going forward, especially in link with global trends. Climate change will affect different areas differently, both directly, but also through migration from adjacent areas. Sunny regions tend to attract retirees and the scale of population ageing is such that weather conditions may partly determine the demographics of particular places, and as a result interact with technological development and opportunities, through the type and availability of both workers and consumers. Finally, materials remain important inputs into value chains, and technological breakthroughs or incremental technological change alike can change material requirement and influence local development. Physical geography is probably the least flexible regional characteristics.

126. ***Proximity to other regions***. Regions are not isolated and recent empirical work tends to emphasize that it is important to consider spatial structures to understand the impact of policies (Autant-Bernard, Fadairo and Massard, 2013[131]). As a result, regions

[8] An example is manifested in Amazon's recent practices, to monopolise information from its marketplace for its own benefit: https://hbr.org/2015/10/when-platforms-attack

should consider their strength and weaknesses in link with that of their neighbours (Foray, 2014[129]), considering system-wide implications, and this of course requires significant efforts of policy coordination at national and supra-national level (OECD, 2018[51]). This is particularly true when physical infrastructure plays an important role, as a region can benefit from connecting to a neighbour's network. Physical proximity also matters for migration, including (in- or out-) migration of skilled workers (Miguélez and Moreno, 2015[148]), and thus remains an important regional characteristic to consider. Proximity to other regions is rather inflexible, though we do note the large literature emphasizing the multidimensional (cognitive, organizational, social, institutional) aspects of proximity (Boschma and Frenken, 2010[149]).

127. ***Cities systems.*** Cities are increasingly seen as the engine of growth and technological development through agglomeration economies. Large cities tend to have more managerial and technical professionals, making them less at risk of automation (Frank et al., 2018[150]). Beyond the size of cities that a region may have however, it is their organization that matters. Cities need to be "well-functioning" (OECD, 2018[51]), in the sense that rural areas can borrow agglomeration externalities by benefiting from specialized services, and cities can benefit from rural amenities. Achieving this goes beyond purely urban planning requiring a regional view that acknowledges agglomeration costs and considers wellbeing and not only purely economic indicators. Beyond the urban-rural dichotomy, geographers have shown that it not possible to understand cities growth and the location of activities without reference to systems of cities (Rozenblat and Pumain, 2007[151]). As a result, urban economic and innovation policy should strive to consider cities within their wider sphere of influence, as (physical or otherwise) proximity to other cities influences innovation diffusion and competition. Moreover, some regions have "central place" cities while others have cities part of a "network system" (Hohenberg, 2004[152]). This determines the type of specialization that can be acquired or maintained, with capital cities often being at the advantage of specializing in high value added and non-offshorable services, while cities as part of a network system are specialized in specific parts of the value chain that are at significantly more risk of being disrupted by technological change. There is ample scope and need for urban and regional policy at present, with close-to-market disruptive mobility technologies that can accompany a transition toward better-organized urban hierarchies.

128. ***Population structure and cultural factors.*** Entrepreneurship and innovation capabilities differ in regions depending on the age structure of the population (Maestas, Mullen, & Power (2016[153]), Liang, Wang, & Lazear (2014[154])). Cultural (Florida, 2014[155]) and institutional aspects (Rodríguez-Pose, 2013[156]) are often analysed as major drivers of the success of cities and regions. These aspects have taken a renewed importance recently, with productivity divergence and cultural divergence reinforcing each other, fuelling the emergence of a geography of discontent. Policy here can take the form of social policy and education. Mitigating the "brain drain" is an option but at the expense of the higher agglomeration economies in advanced metropolitan places.

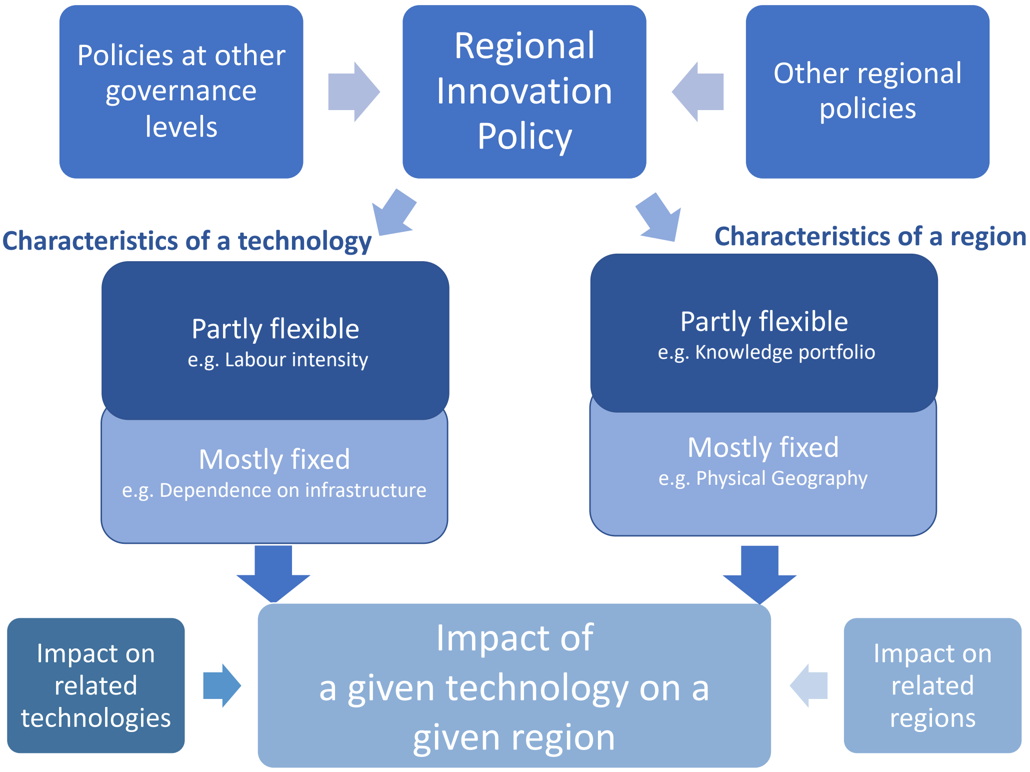
Table 2. Regional characteristics and responsivity to policy intervention

	Reasonably high and/or short term flexibility	Fairly low and/or long term flexibility	Fixed or almost Fixed
Leaders vs Followers	✓		
Knowledge portfolio	✓		
Legacy Infrastructure	✓		
Physical Geography			✓
Proximity to other regions			✓
Cities systems		✓	
Population structure and culture		✓	

6.3. An approach to regional innovation policy for managing disruptive technologies

129. Since there is no one-size-fits-all approach for regional innovation policies, we refrained from suggesting specific instruments and we instead proposed an overall approach to guiding instrument choice. Our key argument in this paper is that innovation policy should be based on evaluating the effects of a specific technology on a specific region – taking into account the characteristics of the region, the characteristics of the technology, interdependencies between technologies, interdependencies between regions, interdependencies between policy fields and interdependencies between governance levels (Figure 1).

Figure 1. An approach to regional innovation policy for managing disruptive technologies



130. We acknowledge that this laudable goal might only be feasible very imperfectly in practice, and we do not have a case study to offer. Yet, we would suggest that this approach can be implemented in 5 steps:

1. Monitoring and benchmarking local characteristics and competencies.
2. Understanding the spectrum of technological capabilities that each innovation provides and how the innovation system can leverage and sustain it throughout its life cycle
3. Assessing technological interdependencies and regional interdependencies (proximity with and dependence on other regions).
4. Identifying the characteristics that are the most flexible given the instruments available at a particular governance level.
5. Assessing continuously vulnerabilities, opportunities, and policy interactions across governance levels and policy fields.

131. This approach suffers from several caveats, and only intends to provide some insights into possible avenues for modernizing innovation policies. Two important limitations are that our lists of characteristics are not exhaustive, and our evaluation of flexibility is only illustrative.

132. Another point to note is that we have articulated our approach around the technology-region pair, arguing that this is the “right” level of analysis. Indeed, we do mean to suggest that each region should run a diagnostic of its own characteristics, and evaluate the impact of each technology first separately, and then accounting for interdependencies

between technologies. However, we do not mean to say that there is no hope for a more general understanding of the regional effects of disruptive technologies. The literature we have reviewed has an important track record of grouping regions or grouping technologies into meaningful classes. An avenue for further research would be to specify these types and attempt useful generalizations.

7. Conclusion

133. In this paper, we have discussed the impact of disruptive technologies on regional development. Summarizing this impact would not do justice to the large heterogeneity observed throughout history: some regions stay dominant and other backwards despite technological change; other places suffer or thrive as structural change takes place.

134. In line with decades of scholarship in this economic geography, we conclude that regional innovation policies should be tailored to the specific challenges faced by each region. In line with the large literature on technological change, we emphasize that different technologies can have vastly different impacts. Combining these two insights helps shed light on the challenges and opportunities offered by the new wave of disruptive technologies.

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