OECD-EC high-level expert workshop series Productivity Policy for Places

The innovation productivity paradox

Raquel Ortega-Argilés, University of Birmingham,
R.OrtegaArgiles@bham.ac.uk

Philip McCann, University of Sheffield Management School,
p.mccann@sheffield.ac.uk

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When we examine the relationships between innovation and productivity, we see many paradoxical features. In general, we know that innovation fosters productivity growth but productivity growth is not always observed in the same setting or context as the origin of the innovation, and the transmission linkages between innovation and productivity are often much more complex. These linkages are neither necessarily direct nor are they linear, and in some cases, they can even be negative, depending on the various innovation-related constraints, facilitators and inhibitors. Moreover, it is increasingly understood in recent years that geography shapes and is shaped by the relationships between innovation and productivity, and many different regional features influence these patterns. This synthesis paper tries to unpack these different elements and to identify the innovation drivers, facilitators, constraints and inhibitors, and to understand which of these elements, or combinations of elements, are most likely to operate in different settings or contexts. This allows us then to assess how these combinations of elements shape the links between regional innovation and regional productivity, and to clarify that many of the apparent innovation-productivity paradoxes in reality just reflect the heterogenous outcomes of complex processes, many of which are becoming even more complex.

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DISCLAMER

This paper was prepared as a background document for an OECD-EC high-level expert workshop on "Productivity Policy for Places – Innovation-Productivity Paradox" held virtually on March 3 and 5. It sets a basis for reflection and discussion. The background paper should not be reported as representing the official views of the European Commission, the OECD or one of its member countries. The opinions expressed and arguments employed are those of the author(s).

ABOUT THE OECD-EC HIGH-LEVEL EXPERT WORKSHOP SERIES ON PRODUCTIVITY POLICY FOR PLACES

The workshop is a part of the five-part workshop series in the context of the OECD-EC project on "Productivity Policy for Places". The five workshops cover the following topics: (1) Innovation-Productivity Paradox; (2) Productivity in the Private Sector; (3) Public Sector Productivity; (4) Inclusive Productivity? and (5) Productivity and Resilience.

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. The financial contributions and support from DG REGIO are gratefully acknowledged.

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1 Introduction

Over recent decades our economies have become transformed by the advent of new information and communications technologies (ICTs) which have transformed almost all areas of our lives and certainly all areas of commerce. These started to appear within most parts of the OECD economies during the 1970s and accelerated rapidly throughout the 1980s and onwards. The growth in the 'weightless' economy (Quah 1999; Varian 2001, 2018) led to a fundamental transformation of how many parts of the global economy worked and with it, the roles and occupations, and activities undertaken by people in their working, home and leisure environments. Yet, the economic impact of these societal transformations appeared to be somewhat less than might have been expected, and this is a critical ongoing feature of the 'innovation-productivity paradox'. As Nobel Laureate Robert Solow (1987) put it, "*You can see the computer age everywhere but in the productivity statistics*", and the point still holds after more than thirty years. Indeed, the fact that such enormous technological transformations were not associated with dramatically increased productivity growth is still the case, even after the subsequent invention of the internet and work on these seemingly paradoxical issues continues today (Acemoglu, Autor, Dorn, Hansen and Price, 2014; Wolf 2018).

On the other hand, one of the issues in which modern technological change does appear to have played a role in is in terms of the growing partitioning of the incomes and wealth of different groups in society, and this is also the case in terms of geography and regions. This partitioning appears to be related to the fact that information technologies change how modern economies operate on many different levels, with some sections of society benefitting more relative to others, and this also appears to be the case for regions. In general, these new features of the knowledge economy are argued by Haskel and Westlake (2018) to be characterized by 'the four *Ss*': namely that knowledge is *Scalable*, knowledge incurs *Sunk costs*, knowledge displays *Synergies*, and knowledge provides and benefits from *Spillovers*. In terms of regional productivity, each of these features, either individually or in combinations, will play a different role, in some cases fostering regional productivity convergence while in other cases driving regional productivity divergence.

When we examine the relationships between innovation and productivity, we see many paradoxical features. In general, we know that innovation fosters productivity growth. However, productivity growth is not always observed in the same setting or context as the origin of the innovation, and the transmission linkages between innovation and productivity are often much more complex than is often realised. These linkages are neither necessarily direct nor are they linear, and in some cases, they can even be negative, depending on the various innovation-related constraints, facilitators and inhibitors. Moreover, it is increasingly understood in recent years that geography shapes and is shaped by the relationships between innovation and productivity, and many different regional features influence these patterns. It is therefore essential to unpack these different elements and to identify the innovation drivers, facilitators, constraints and inhibitors, and to understand which of these elements, or combinations of elements, are most likely to operate in different settings or contexts. This allows us then to assess how these combinations of elements shape the links between regional innovation and regional productivity, and to clarify that many of the apparent innovation-productivity paradoxes in reality just reflect the heterogenous outcomes of complex processes, many of which are becoming even more complex.

On top of the previous generations of information and communications technologies, the coming years are likely to see an acceleration in the take-up of new advanced digital technologies, spurred on by the COVID-19 pandemic shocks. Digitalisation is currently taking place at some 25 times the pre-pandemic rate (*Financial Times* 2020), and in just a few months, the COVID-19 pandemic has spurred digitalisation by a matter of 3-4 years (McKinsey Global Institute, 2020). Increased digitalisation will likely be disruptive of many existing innovation processes (Neirotti and Pesce 2019), potentially spurring new open-innovation systems and further blurring the boundaries between manufacturing and service innovations (OECD 2018a; Gal, Nicoletti, Renault, Sorbe, and Timiliotis, 2019).

Encouragingly, the issue of regional productivity has been gaining in importance in recent policy debates, and especially in the years following the shock effects of the 2008 global financial crisis. The last decade has seen the productivity growth of many countries slow down or even stall, while at the same time interregional disparities within many countries have widened. In many parts of the OECD, decades of interregional productivity convergence (Barro and Sala-i-Martin 1992, 1995) suddenly shifted to an environment of interregional divergence in spite of the ICT revolution, also leading to a widening of pay divides within countries. However, the regional dimension of the productivity slowdown has been largely neglected in many of the current debates on productivity (Sena 2020). A vast body of literature looks at individual firms, industries, countries and does not consider the sub-national and local level variations in productivity performance. These types of productivity analysis that omit the spatial dimensions of productivity generally consist of studies that try to explain the levels and growth in firm-level and industry-level productivity, both by examining changes within and between firms and sectors (Tsvetkova, Ahrend, Oliveira-Martins, Lembcke, Knutsson, de Jong and Terzidis, 2020). Importantly, as well as failing to uncover the role which regions play in underpinning productivity growth, these non-spatial approaches also miss out on the opportunities associated with measuring productivity across several geographies which may enable us to test the relevance of a number of explanations for the productivity slowdown by using discontinuity design or other techniques (Sena 2020).

Yet, in order to examine these issues in spatial and regional terms, our discussion in the second section and after this short introduction will examine how productivity as a phenomenon for analysis and measurement is understood in a non-spatial setting, and then in the next section will consider the ways in which geography and place shape and are shaped by productivity-generating processes. The reason is that regional productivity is intrinsically related to local features, such as the regional skills profiles and industry structures, as well as to inter-regional issues around knowledge spillovers and the diffusion of knowledge and technology between places. Understanding how the role of production factors and sectoral structures, alongside knowledge spillovers, are considered in a non-spatial setting, is first essential in order to identify then the role which geography and place play in these processes (McCann and Ortega-Argiles, 2016).

2 Productivity and innovation: Definitions and measurement issues

Productivity measurement

In a non-spatial setting, most of the discussions on the productivity slowdown tend to focus on aggregate national or sectoral indicators such as GDP per capita, GVA per hour worked total factor productivity (TFP) or multi-factor productivity (MFP)[1]. However, there is no unique measure of productivity. Productivity can be proxied as labour productivity (output per hour worked), capital productivity (output per unit of capital stock) or total factor productivity (TFP) (a weighted sum of outputs divided by a weighted sum of inputs). Each of these measures has its advantages and disadvantages and differs in usefulness depending on availability and use. However, these headline indicators are at a high-level, in that they capture the outcomes of numerous interacting influences and processes. In many ways, productivity can therefore appear as a vague concept, in that it refers both to efficiency but also market structure and market power, and as such, these discussions can sometimes appear too opaque to the public and can easily be misunderstood. This is also reflected in policy debates because appropriate policy implications and recommendations also depend on the different sources of productivity growth or productivity decline (Grifell-Tatjé, Lovell and Sickles 2018).

Table 1. Headline indicators of productivity growth or decline

<table>
<tr><td rowspan="4">Aggregate national or sectoral indicators</td><td colspan="2">GDP per capita</td></tr>
<tr><td colspan="2">GVA per hour worked</td></tr>
<tr><td colspan="2">GVA per worker</td></tr>
<tr><td colspan="2">Total Factor Productivity (TFP)</td></tr>
<tr><td rowspan="3">Micro measures</td><td>Labour Productivity</td><td>Output per hour worked</td></tr>
<tr><td>Capital Productivity</td><td>Output per unit of capital stock</td></tr>
<tr><td>Total Factor Productivity</td><td>A weighted sum of outputs divided by a weighted sum of inputs</td></tr>
</table>

Source: Authors' elaboration.

Headline indicators often do not succinctly reflect these nuances in a manner that can be easily communicated. Building up the argument from its constituent elements in a non-spatial setting and then translating it into an explicitly spatial setting will help us better understand what is particular and unique about the spatial and regional productivity debates from more general non-spatial discussions.

[1] The terms TFP and MFP are typically used interchangeably, and the nomenclature is largely a matter of preference, although in some instances MFP differs from TFP in those inputs such as energy, infrastructure and qualitative differences in factor inputs are normally not accounted for in official statistics, as would strictly be required in genuine TFP measures.

In very general terms, we can decompose and attribute output growth to three components (Farrell 1957):

- Input growth or changes in economies of scale (movements along a path on the production frontier);
- Efficiency change, movements towards the production frontier (technical efficiency change and allocative efficiency change);
- Technological progress – shifts of the production frontier.

The Farrell (1957) framework also allows us to distinguish between changes in technical efficiency and allocative efficiency (Kumbhakar and Lovell, 2000), whereby technical efficiency refers to the relationships between inputs and outputs, while allocative efficiency refers to the relationships between factor inputs. In this general context, economists traditionally refer to Total Factor Productivity (TFP) when discussing productivity based on neoclassical models of economic growth, whereby total output growth is decomposed into a weighted sum of input growth rates and a component that cannot be explained by changes in inputs over time, often known as the 'Solow residual' (Kumbhakar and Lovell 2000; Abramovitz 1956; Solow, 1956). Empirically, the measurement of TFP has been operationalised by estimating a production function with the regression residual (i.e. the change in output which cannot be explained by input growth) being interpreted either as TFP or as technical change (Kumbhakar and Lovell 2000; Sena 2020). This identification between TFP and technical change implies that productivity improvements arise from technical progress, although this is very unrealistic given that it is based on the assumption that all firms are efficient and operate on the technology frontier (Kumbhakar and Lovell, 2000). However, evidence has shown that many firms are located in the long tail of the productivity distribution (Hwang, Lee and Zhu 2016; Andrews, Criscuolo and Gal 2015), and if firms are inefficient, it is essential to quantify the effects of potential drivers of output variations among firms and industries other than a technical change. Among many other factors, these may include differences in firms' learning by doing, managerial practices as well as the poor diffusion of new technological knowledge (Kumbhakar and Lovel, 2000; Hwang et al., 2016). All these possible factors have the potential for improving TFP by allowing firms to improve their efficiency and move closer to the technology frontier. In other words, TFP measurements contain the effects of different processes. Moreover, the measure of TFP as a residual from a regression model does not allow us to take into account the nature of competition across product markets as well as the possibility that firms can operate on portions of the production functions which exhibit non-constant returns to scale (Saint-Paul, 1997; Kumbhakar, Ortega-Argilés, Potters, Vivarelli and Voigt 2013; Kumbhakar, Parmenter and Zelenyuk 2018). In other words, TFP of itself cannot be the final measure of productivity since it also comprises a range of different process and structural issues and must instead be interpreted as an index of the aggregate scale of these interacting issues on overall productivity.

Table 2. Decomposition techniques for measuring productivity

Decomposition techniques	**Main characteristics**
SFA – Stochastic Frontier Analysis	Differ in the way they envelop the data and construct a frontier and the Stochastic noise differences in the assumption of the characteristics of the technology
DEA – Data Envelopment Analysis – Linear Programming	
RDD – Regression Discontinuity Design for Longitudinal or Cross-sectional Data	Measure the causal effects of interventions (e.g. environmental subsidy) on output, productivity, efficiency.
Shift-share Decomposition Techniques Analysis	Allows for the separation of the within-output growth and productivity effects in the data at any level of analysis (firm, sector, region)

Source: Authors' elaboration.

For this reason, and in overcoming these limitations, various decomposition techniques of the residual-based measure of TFP have been developed which aim to distinguish between the specific sources of efficiency gains associated with technological progress, changes in technical efficiency and economies of scale, and these techniques also better facilitate comparisons between different businesses, industries (Grifell-Tatjé et al., 2018) and countries. Institutions such as the Conference Board have calculated the relative contribution of different factors to GDP growth, namely labour composition (which measures hours worked adjusted for skills composition), non-ICT capital, and ICT capital, mainly at the national and sectoral level (see for example for the case of Ireland, Irish National Competitiveness Council 2017).

In terms of techniques for measuring productivity and its components, the frontier analysis offers a variety of techniques that allow us to measure TFP at industry and firm levels and then decompose it into its key components. The most widely used techniques are based on econometrics (Stochastic Frontier Analysis or SFA) and linear programming (Data Envelopment Analysis or DEA), and they differ in the way they envelop the data and construct the frontier (Kumbhakar and Lovell, 2000; Hwang et al., 2016). Some differences can be found in the way stochastic noise and technology are treated by the two techniques, but one key advantage of the linear programming technique is that unlike SFA it provides disaggregated information such as producer-specific measures of technical change, slack and efficiency peers as well (Hwang et al., 2016). Each measure can be aggregated at the industry or sector level, and these new measures can be used for policy purposes.[2]

The measurement of the components of productivity growth also faces what is sometimes known as the ‘mismeasurement hypothesis’ (Mokyr 2014; Alloway 2015; Feldstein 2015; Hatzius and Dawsey 2015; Smith 2015). This relates to the fact that some aspects of the modern economy, and in particular the intangible and information economy, are very hard to measure and value, especially in the context of how national accounts are balanced (Coyle 2014, 2017; Haskel and Westlake 2018; Brynjolfsson, Rock and Syverson, 2017; Ugur and Vivarelli 2020; Riley, Rosazza-Bondibene and Young 2015; Riley, Rincon-Aznar and Samek 2018; Oulton, Rincon-Aznar, Samek and Srinivasan 2018). In this context, Haskel and Westlake (2018) talk in terms of a capitalist economy operating without capital. The measurement of the contribution to the economy of the digital world is especially difficult, even though, and to some extent, precisely because, digital technologies affect so many different aspects of our society (Atkinson and McKay 2007; Katz, Koutroumpis and Martin Callorda 2014). More fundamentally, however, the intangible and information economy is intrinsically related to processes of innovation and the way that innovation drives productivity. While TFP has traditionally been considered as the best measure of productivity, some innovation studies (Ortega-Argiles and Moreno, 2009; Ortega-Argiles Moreno and Suriñach 2005; Aboal and Garda, 2016; Aboal and Tascir, 2018; Peters Riley Siedschlag Vahter McQuinn, 2018; Bartelsman et al. 2017, 2019) consider that the TFP is not necessarily caused by technological change, because it also contains a variety of non-technological factors.

As well as changes in the nature of capital, a further challenge for growth analysis is that there appears to be a long-run decline in research productivity in many advanced economies (Huggins and Izushi 2020), and there is a range of evidence that suggests that over time the ability to innovate is becoming more difficult (Jones 2009; Bloom et al. 2017). The fact that many industries go through innovation lifecycles suggests that one argument is that the more knowledge is created, the more difficult and costly it becomes to add to that knowledge (Machlup 1962), until the point at which the whole field is transformed by new major and radical technological breakthroughs (Griliches 1990; Utterback 1994; Henderson and Cockburn 1996). This long-run decline in research productivity challenges many of the assumptions underlying endogenous growth models (Huggins and Izushi 2020; Romer 1990; Grossman and Helpman 1991; Aghion and Howitt 1992; Jones 1995a,b; Kortum 1997; Segerstrom 1998; Young 1998; Howitt 1999; Laincz and Peretto 2006).

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[2] For a survey on the measurement of TFP see van Beveren (*Journal of Economic Surveys*, 2012)

Innovation and productivity

Innovation is a complex multidimensional phenomenon that is heavily influenced by many other aspects such as the nature of the local economy, path dependency, international competition, the quality of government, and financial conditions. These concepts and their measurement, as with the concept of innovation itself, have significantly evolved in recent decades. Many analyses have attempted to explain the complexity and heterogeneity of innovation activities and also the non-linearities in their relationships with productivity performance, and these analyses have attempted to proxy the links between innovation and productivity with a series of quantitative as well as qualitative approaches. In general, some of these studies consider that labour productivity may be a better measure of productivity than TFP because it reflects not only the use of labour but also how efficiently labour is combined with other factors of production. For this, they use augmented regional production function approaches, including measures of both knowledge-related and non-knowledge-related factors ranging from patent counts to data on cultural embeddedness and the role of brokering actors, co-creation spaces, etc. Probably the largest single group of research papers use the number of patents as an objective measure of innovation, in that while patents are an indicator of the rate of invention, it is also a crucial precursor to innovation (Roberts 1988). More recent studies, however, have concluded that it is not only the quantity but also the quality of the patenting activity and have tried to define and measure the quality of patents by looking at legal, commercialisation and 'societal' outcomes (Higham, de Rassenfosse and Jaffe 2020). Indeed, some patenting activity is actually designed to discourage (Bessen and Meurer 2008; Jaffe and Lerner 2004) or even block innovation (Shapiro 2010; Hall, Helmers and von Graevenitz 2015). Meanwhile, other papers use different measures focusing on the importance of the interactions between agents to develop innovation based on agent-based models (O'Sullivan and Strange 2018) in order to help to identify the role which aspects such as embeddedness, relatedness, connectivity, absorptive capacity or knowledge diffusion play in innovation processes. Recent advances also include linking the economics literature on intellectual property rights protection to innovation (Hall and Sena 2017).

Taken together, there is an extensive body of evidence and analysis which argues that there is a positive and significant relationship between innovation and productivity at the firm and national levels (Mairesse and Sassenou 1991; Hall and Mairesse 1995; Harhoff 1998; Lotti and Santarelli 2001; Huergo and Jaumandreu 2004; Parisi et al. 2006; Ballot et al. 2006; Hall et al. 2010). Moreover, at the country level, technologically advanced countries are more likely to engage in innovation rather than imitation (Vanderbussche, Aghion and Meghir, 2006). Empirical evidence to date suggests that the impact of R&D expenditures on a firm's productivity is more marked in high-tech sectors than it is in their low-tech counterparts (Verspagen 1995; Stiroh, 2002; Tsai and Wang 2004; Ortega-Argiles Piva Potters and Vivarelli 2010, 214, 2015; Ortega-Argilés Potters and Vivarelli 2011; Kumbhakar et al. 2015). Moreover, at the sectoral level, using US data the depreciation of R&D has recently been found to be higher than has traditionally been assumed at approximately 15% (Li and Hall 2020), although it also varies across industries. The empirical challenges associated with the interdependencies of innovation inputs by isolating the effects on innovation and productivity have been partially solved in the past by applying two-stage knowledge production function models often referred to as CDM (Crepon, Duguet and Mairesse, 1998) models, and the original CDM model has inspired many subsequent analyses (Ugur and Vivarelli 2020). Many of these analyses are developed at the country level using microdata from R&D surveys, such as the Community Innovation Survey (Hong, Oxley and McCann 2012), in order to evaluate either the relationship between R&D and innovation and simultaneously the relationship between innovation and productivity. In the short run, the disruptions associated with the implementation of innovations may actually decrease productivity (Crowley and McCann 2015), although in the long run innovation and productivity are broadly positively related. However, the various papers identify several sources of the heterogeneity in the evidence base, including variations in measurement, model specification and estimation methods. (Ugur and Vivarelli 2020), but the broad principle holds that innovation drives productivity, although the ways that this plays out in different firms, sectors and countries may differ. Selfselection is an important issue (Halpern and Muraközy, 2012; Aboal and Garda, 2016; Aboal and Tascir, 2018; and Tello, 2015) and another issue is the potentially confounding effect of market power in the innovation-productivity relationship (Máñez, Rochina-Barrachina and Sanchis-Llopis 2015; Baum, Lööf, Nabavi and Stephan 2017). In general, R&D-active firms have higher levels of productivity, and a firm's exporting status is also a compliment, but the positive effect of R&D on productivity becomes slightly smaller when market power is controlled for (Máñez et al. 2015). At the same time, some recent studies which estimate the productivity effects of firms' non-technological innovation features such as marketing innovation (Aboal and Garda, 2016; Aboal and Tascir, 2018; Peters Riley Siedschlag Vahter McQuinn, 2018), broadband connectivity (Bartelsman, Falk, Hagsten and Polder, 2019); and innovations in resource planning, customer resource management and supply chain management (Bartelsman, van Leewen, Polder 2017); find that these may be larger compared to the effects of those process or product innovations which require sustained investment in R&D (Ortega-Argiles and Moreno 2009; Ugur and Vivarelli 2020). In other words, innovation is both a technological and non-technological phenomenon, and as such, needs to be understood from different perspectives.

Table 3. Firm innovation and productivity indicators

Firm determinants – control variables	Innovation Inputs	Innovative Output	Firm Performance
Firm Size (sales, turnover, employees, employment growth) Sectoral Affiliation (Pavitt's taxonomy, Schumpeter Mark I, Schumpeter Mark II) Competition – market power, market share, market concentration, market regulation Diversification indexes Ownership structure (private, public, foreign,) Managerial ability – managerial practices (subsidiary firms, multi-establishment firm, diversified firm) Human capital (labour quality, type of workers) Capacity of utilisation Physical capital intensity Industry price indexes Firm price indexes	R&D expenditures Non-R&D based innovation activities expenditures Purchase of outside services Purchase of machinery, equipment for innovation activities Industrial design for new products Marketing expenditures Education for innovation activities Human capital resources: Highly educated employees Engineers Administrators Average work experience Cooperation with outside partners Sources of knowledge	Patents Citations Licenses Trademarks Models of use/utility models, copyrights, among others Process innovation Product innovation Sales devoted to new products Qualitative indicators: Sources of innovation Technological changes User demand	Value-added per employee Output per hour worked Sales per employee, revenue (sales) per worker Profit before depreciation Profit after depreciation Sales margin in level Employment growth Exporting activity

Source: Authors' elaboration based on Ortega-Argiles (2013).

As well as many different factors influencing firms' ability to produce research and knowledge which can drive innovation, another aspect of the innovation-productivity argument concerns the ability of firms to absorb new knowledge in a manner which allows them to improve productivity. Firm *absorptive capacity* (AC) refers to the "ability of firms to derive a competitive advantage from knowledge from the environment in which they operate" (Harris, Krenz and Moffat 2020 p. 589) even in the situation where R&D is not taking place (Moilanen and Woll 2014). The notion of absorptive capacity is increasingly understood as being critical in determining the ability of firms to adopt new technologies and techniques. It is dependent on many issues, potentially including organisational factors, management processes, labour relations, skills profiles, amongst others. In this regard, Zahra and George (2002) go further and distinguish between *potential* absorptive capacity, which they define as the ability to recognise, acquire and assimilate useful external knowledge, and *realised* absorptive capacity, which they define as the ability to transform and apply acquired knowledge effectively within organisations. This distinction implies that it is not just the behaviour or attitudes of individuals or teams of people that determine absorptive capacity but also structural features of organisations and industries in which they operate that matter. In the decades straddling the New Millennium, the USA appears to have had a better-suited skills profile for adopting and adapting the new information and communications technologies (ICTs) than many parts of Europe (Van Ark, O'Mahony, and Timmer 2008; Ortega-Argiles 2013). Mason, Rincon-Aznar and Venturini (2020) argue that upper-level skills, as well as intermediate technician-level skills, are crucial for firms' absorptive capacity and for translating externally-sourced knowledge into innovative outputs, while the skills profile of the whole economy is critical for making use of innovative outputs (Mason et al. 2020). On this point, recent cross-country analyses using different methodologies and exploiting the Community Innovation Survey (CIS) have stressed the positive effect that firm absorptive capacity plays in the translation of inputs to innovation outputs (Song, Gnyawali, Srivastava and Asgari 2018; Harris and Yan 2019). Principal Component Analyses (PCA) have been used to derive measures of absorptive capacity (Escribano, Fosfuri and Tribo 2009; Kostopoulous, Papalexandris, Papchroni and Ioannou 2011; Moilanen and Woll 2014) proxied by internal R&D expenditure, R&D department presence, training for R&D personnel, the percentage of scientists and researchers of the total firm labour force, for example. As well as using internal features, Harris Krenz and Moffat (2020) generate an index of absorptive capacity from external features associated with access to a range of local information sources and cooperation with different institutions. Among the information used in these analyses can be found information on suppliers of equipment, materials, components, or software; clients or customers; competitors or other enterprises in the same industry, consultants and commercial labs; universities of other higher institutions; and government, public or private research institutes as well as knowledge acquired in conferences, trade fairs and exhibitions, scientific journals and trade and technical publications, as well as professional and industry associations (Harris et al. 2020). The effects of absorptive capacity on R&D and product innovation are positive, although the results vary according to the country concerned.

The internationalisation characteristics of firms also play a role in shaping knowledge flows. Multinational enterprises (MNEs) tend to play a greater role in driving productivity than domestically-oriented enterprises (DOMEs). MNEs are generally more R&D-intensive than DOMEs, and they also typically are better positioned to facilitate global knowledge flows and to improve absorptive capacity (Bournakis et al. 2018; Barrios, Görg and Strobl 2003; Cantwell and Mudambi 2005; Cortinovis and van Oort, 2019). However, the sustainability of FDI-related innovation and productivity gains is subject to the degree of embeddedness of the MNEs within the economy (Haskel, Pereira and Slaughter 2007) with the general conclusion that the more embedded, 'sticky' (Markusen 1996; Benito, Grogaard and Narula 2003) and autonomous in terms of decision-making (Murray, Jalette, Bélanger, and Lévesque 2014) regarding links with local suppliers and joint-ventures (Birkinshaw and Hood, 2000) is the MNE subsidiary establishment within the host country, the more that it will contribute to the home economy in terms of knowledge transfer (Haskel et al. 2007; Iammarino and McCann 2013). Yet, there are some situations in which impact of DOMEs on TFP can sometimes be more crucial than those of MNEs (Altomonte and Pennings, 2009), and this is often associated with cases where domestic MNEs outperform foreign subsidiaries (Higón and Manjón Antolín, 2012). However, the general principle still holds that MNEs tend to contribute more to absorptive capacity and productivity growth than domestically oriented firms and that MNEs can act as key conduits for the global knowledge flows crucially required to drive productivity, especially with new technologies.

In general, therefore, absorptive capacity and knowledge transfer and knowledge diffusion are also linked with the concepts of openness of trade and investment, including foreign direct investments and technology adoption (Griffith, Redding, and Simpson 2009). The ability to access the creation of learning opportunities via trade and FDI does not automatically imply there will be local knowledge spillovers unless the domestic firms have the skills and human capital required to both rapidly absorb the new knowledge and technologies and also to cope with the increase in competition effects (Harris and Robinson 2004).

Within Europe, the results from the cross-country analysis (Harris et al. 2020) show that Germany has the highest mean value of absorptive capacity with the highest proportion of enterprises that do some sourcing of information or cooperation on innovation, but a lower proportion of enterprises that do a lot of these activities when compared to Portugal, Norway and the United Kingdom (Harris et al. 2020). Large enterprises display higher levels of absorptive capacity and are shown below to be more likely to undertake R&D and product innovation. Except for Spain which displays low levels of absorptive capacity, the results show that within Europe there is an East-West split in terms of the levels of absorptive capacity, with Western European countries having generally higher levels (Harris et al. 2020).

Taken together, the evidence suggests that R&D-related activities are indeed critical for enhancing productivity growth by driving innovation processes, although the success of innovation activities depends on the interplay of a range of technological and non-technological issues. Across the different research agendas outlined here, there is broad consensus that knowledge-related research and information technologies and activities are all broadly associated with economic growth at the scale of the firm, the sector, the region or the nation (Katz et al. 2014). However, finding this evidence can, at times, be a major empirical challenge. Technological change of itself does not translate into productivity enhancements, and other social and institutional influences would appear to be critical. Moreover, the context does appear to matter significantly in terms of the ability of firms to absorb and act on new knowledge, as well as their ability to develop new knowledge.

AI and Industry 4.0

The somewhat paradoxical evidence on the economic role played by new knowledge-related research and information technologies on wider economic productivity and growth effects is likely to be reshaped again by the widespread adoption of new artificial intelligence (AI) and so-called Industry 4.0 digital technologies. These digital and AI technologies refer to computer systems based on machine-learning algorithms and chatbots that can sense their environment, think, learn and interact within other components of the technological system and then subsequently take action as a result. This ability to respond to the environment distinguishes AI from the existing generations of the automation of routine tasks.

Until now, the links between robotization and productivity have been rather weak because it is high-productivity large and export-intensive firms which account for the lion's share of robots (Dauth, Findeisen, Suedekum and Woessner 2018; Kock, Manuylov and Smolka 2019) so this raises the question of whether these patterns will change with the new generations of AI and Industry 4.0 digital technologies. In general, it is likely that it will still be the larger and more highly productive firms which will adopt and deploy the new digital and automation more quickly than other type and size-cohorts of firms (OECD 2017; Koch et al. 2019). These same types of large and highly productive export-oriented firms also tend to benefit the most from both network externalities (Goldfarb and Trefler 2018) and global connectivity (McCann and Acs 2011; Iammarino and McCann 2013) via their higher ability to exploit better access to data (Cockburn, Henderson and Stern 2018) and knowledge flows.

Some commentators argue that these new generations of technologies offer significant opportunities for productivity growth (Brynjolfsson and McAffe 2014; Frey and Osborne 2017), although their impact on productivity and employment will depend on the extent to which AI complements different levels of human capital, something which at present is somewhat unclear (Ernst, Merola and Samaan 2018). There are some arguments to suggest that AI may be relatively more complementary of particular types of higher-skilled activities (Agrawal, Gans and Goldfarb 2017; Felin and Zenger 2018; Malone 2018), but whether this will lead to significant job-displacement or job-creation impacts is as yet unknown. Estolatan, Geuna, Guerzoni and Nuccio (2018) shed light on the unequal growth effects on robots for industrial applications combining information from company press releases, news articles, peer-reviewed journals and trade and industry reports from different OECD countries. Their analysis concludes that the development of AI has triggered new waves of technological investments in robots and the establishment of a worldwide market at the core of Industry 4.0. Although both the demand and supply of robots continues to be concentrated in a small group of countries - China, Japan, the US, Germany and Italy - multi-million dollar programs have been launched at the global level with the support of research centres and universities. While in manufacturing the intermediate demand for robots from car makers is pivotal, there is also now a dramatic expansion of human-machine and machine-machine interaction in the healthcare and medical sectors, and in logistics. The results suggest that there may be a need for more regulation to ensure that the positive effects do not remain uneven.

Returning to the so-called ‘Solow Paradox’, Brynjolfsson et al. (2017) argue that time lags have in all likelihood been the major explanation for innovation-productivity paradox because numerous other complementary innovations need to be developed and adopted in order for information and digital technologies to have the full impacts, which means that time lags can be long. This was probably the case with earlier generations of information and communications technologies (ICTs) from the 1970s and ‘80s which built on a combination of mainframe, mini and personal computing, as well as the internet-based transformations from the 1990s onwards. Logic might dictate that there may be similar effects associated with the take-up of Industry 4.0 digital technologies, with only slowly-growing and slowly-observed effects on overall productivity (Cowan 2011; Gordon 2018; Nordhaus 2015; Bloom, Jones, van Reenen and Webb 2017). On the other hand, many observers argue that these changes have the potential to be particularly pervasive and profound (Brynjolfsson et al. 2017; Ezell 2018; McKinsey Global Institute 2018, 2019; Szczepanski 2019; Elia, Margherita and Passiante 2020; European Union 2020).

Regional technology and productivity growth

Many of the issues outlined above have direct corollaries and implications at the regional and local scales, although some of the issues are manifest in somewhat different ways. Already, three decades ago (Cohen and Levinthal 1990) the interrelations and interdependencies between firms and locations which shape absorptive capacity were being emphasised (Griffith, Redding and Van Reenen 2004; López-Bazo, Requena and Serrano 2006). High levels of local investment are typically required to sustain world-leading R&D. Similarly, local human capital plays a dual role in improving regional absorptive capacity, because a more skilled workforce improves both the production capabilities and the production possibilities of the region including the implementation of technologies, while at the same time also increases the attractiveness of the region as a location for investment (Castellani and Pieri 2013), as nowadays acknowledged in many empirical growth models (de La Fuente 2011). However, these stylised facts are not automatically applicable in every region.

While the generally positive links between R&D, innovation and productivity hold for advanced technology regions, this is not necessarily the case in converging countries and regions. Filipetti and Peyrache (2017) show that for fast-growing EU regions, a technology gap reduction was driven via an increase in endogenous technological capabilities, which was indeed a significant source of growth. Yet, if a region is a long distance away from the technology frontier, this does not necessarily imply faster labour productivity growth rates. This is because, for many such regions, productivity growth is mainly driven by capital accumulation while the technology gap remains unaffected (Filippetti and Peyrache 2015). The reason is that not all innovative activity is of the same quality, and some of the new middle-income countries and regions remain far behind the international technology frontiers (Crescenzi, Pietrobelli, and Rabellotti, 2014; Dunning and Lundan, 2009). These insights are corroborated by multilevel regression models (Webber, Min Hua and O'Leary 2019) and non-parametric approaches based on three decades of European regional data across different spatial scales without relying on the mean reversion assumption underlying beta-convergence models. Webber et al. (2019) find that different groups of European regions experience very different long-run growth trajectories which are heavily shaped by the national trajectories, but which also display features which are quite distinct from national trends.

Regions, skills and employment

One of the issues which distinguished regions' growth ability is the ability of regions to access and absorb knowledge flows. Mason et al. (2020) demonstrate that multi-factor growth is positively related to previous increases in innovation, while Badinger and Tondl (2005) and Dettori, Marrocu, and Paci (2012), among many others, provide empirical evidence for the positive effect of intangible assets, including higher human or technological capital, on innovation and regional growth in Europe. Higher skills can enhance a region's absorptive capacity and help lagging places close technology gaps with frontier regions (Bernard and Jones 1996; Cameron, Proudman, and Redding 2005; Benhabib and Spiegel 1994). Abreu (2020) points out that in terms of the links between skills and productivity, most of the research literature examines measures of formal schooling (Hanushek and Woessmann, 2011; Islam, Ang and Madsen 2014; Barro and Lee 2015). Yet, in terms of the links between innovation and productivity, a key distinction is between cognitive skills, such as numerical, verbal, and problem-solving skills, and non-cognitive or 'soft' skills, which include personality traits, self-efficacy, attitudes to risk and resilience (Abreu 2020; Payne, 2017). There are potentially many complementarities between cognitive and non-cognitive skills, but these cannot be mapped directly, and local innovation systems may require relatively more non-cognitive skills than another economic environment (Almlund, Duckworth, Heckman and Kautz 2011).

Where successful, the local employment gains in knowledge-intensive activities can translate into more comprehensive regional employment (Moretti 2012) and productivity gains, if the appropriate skills and supply chain linkages are locally evident. Confirming this based on an augmented knowledge production function on a sample of European regions, Charlot, Crescenzi and Musolesi (2015), show that at least 20% of the regional population should possess tertiary education in order for local R&D expenditures to have the maximum effects on patenting intensity. However, exactly how regions acquire and develop the right mix of skills is still a difficult challenge. Regional imbalances in skills are a function of different mechanisms including the rates at which young people enrol in vocational (Mason et al. 2020), further and higher education institutions (Krueger and Kumar 2004), as well as the proportion of graduates moving to larger and more prosperous cities and regions with better labour market opportunities (Faggian and McCann 2008; Venhorst, Van Dijk and van Wissen 2011; Ahlin, Andersson and Thulin 2014)._There is a large amount of research on migration and spatial sorting arising from cognitive skills, but very little research on the sorting of non-cognitive skills (Abreu and Venhorst 2018), so precisely how these innovation-conducive environments develop is still unclear.

At present, we know very little about how the new technologies will impact on employment and wage distributions, although there are major concerns about these issues (Frank, Autor, Bessenc, Brynjolfsson, Cebriana, Deming, Feldman, Groha, Loboi, Moroa, Wangk, Younk and Rahwana 2019; Nambisan, Wright and Feldman 2019). There are already pervasive effects of automation in the distribution of wages per occupation (Terzidis, van Maarseveen and Ortega-Argiles 2017; Terzidis Brakman and Ortega-Argiles 2019; Terzidis and Ortega-Argilés 2021). We know that during the last two decades, the interaction between processes of globalisation and technological change have led to growing income polarisation with increases in the shares at the upper and lower tails of the income distribution and declines in the middle of the income distribution (Terzidis et al., 2017; Terzidis and Ortega-Argilés, 2021). These wage polarisation effects have regional and spatial implications, but these spatial implications also differ between countries. The available evidence suggests that there no simple and generalisable geographical pattern to these changes (Terzidis and Ortega-Argilés, 2021). Moreover, there is no evidence of any link between skills-mismatches and job polarisation in terms of regional productivity.

We currently know very little about the potentially adverse effects of innovation on the distribution of income and wages, or the job-displacement effects of innovation in different regional contexts (Lee, 2016; Lee and Rodriguez-Pose, 2013; Evenhuis et al., 2021). These gaps represent analytical and empirical weaknesses and are in part, because much of the literature on these topics first emerged during the 1990s and 2000s, decades during which unemployment was low in most OECD economies, and growth was steady and stable. In contrast, the macroeconomic conditions during the last decade since the 2008 global financial crisis have been fundamentally different from the two earlier decades, and the COVID-19 pandemic is likely to increase the challenging macroeconomic conditions. However, untangling the potential local employment, skill-loss or wage-scarring effects associated with regional innovation shocks during periods of rising unemployment and weak demand is much more complicated, because it is difficult to assess the extent to which the impacts are micro-local or macro-national in scale. Moreover, these issues are likely to be exacerbated in the COVID-19 context (Jackson and Ortego-Marti 2020) both due to the likely rising employment shocks along with the fact that human capital decay rates tend to be associated with skills levels (Ortego-Marti 2017).

Regions, innovation and inward investment

For regions which are economically strong and highly connected, the widespread presence of MNEs alongside high human capital provides further opportunities to maximise interregional and international connectivity (McCann and Acs 2011). However, their presence also helps to maximise the region's absorptive capacity. Indeed, as we have already seen, one of the key arbiters of the exploitation and transfer of intangible assets is inward foreign direct investment (FDI). At the regional level, there is already an extensive literature on the economic impact of FDI on host regions (Iammarino and McCann 2013), which focuses on the productivity gains induced from the technological and managerial superiority of MNEs. These mechanisms are explained by new trade theory (Markusen and Venables, 1998) and endogenous growth models (Aghion, Howitt, Brant-Collett and García-Peñalosa, 1998) which demonstrate how MNEs improve the growth performance of the host economies via the transfer of intangible assets such as technological know-how (Barrell and Pain, 1999). Moreover, FDI can play an important role, not only in facilitating interregional as well as international knowledge flows but also in terms of building regional absorptive capacity (Ortega-Argilés et al. 2015; Iammarino and McCann 2013). These regional gains can be grouped under three possible channels (Bournakis, Papanastassiou and Pitelis, 2019): (i) imitation gains related to technologically mature products and processes, which are superior to those of local firms; (ii) skills acquisition gains, where MNEs invest in specialised human capital in order to implement their business projects and competition; and (iii) export spillovers, which promote the improved performance and international expansion of local firms (Bournakis et al. 2019).

At the local and regional scale, the effectiveness and sustainability of these three MNE-related knowledge enhancement processes will depend on how embedded the local MNE technologies are in the regional economic structures (Haskel, Pereira, and Slaughter 2007; Benito, Grogaard, and Narula 2003; D'Adda, Guzzini, Iacobucci and Palloni, 2019; Bedreaga, Ortega-Argiles and McCann 2018) in terms of their fit with local supply linkages (Birkinshaw and Hood, 2000) and skills profiles (Castellani and Pieri, 2013). In general, these various mechanisms are enhanced the greater the extent of R&D that MNEs undertake locally is, the more decision-making discretion the subsidiaries have (Murray, Jalette, Bélanger, and Lévesque 2014), and the more R&D-intensive these firms are. When these conditions are in place, MNEs tend to contribute more to regional productivity growth than domestically-oriented enterprises (DOMEs), although these effects also depend on the country of origin of the MNE subsidiary (Bournakis et al. 2019). As such, inward FDI can potentially provide various mechanisms for enhancing regional absorptive capacity (López-Bazo et al. 2006; Kramer et al. 2011). However, the experience of lagging regions may be different, as they are often better able to absorb the intangible assets of DOMEs more readily than MNEs, given that MNEs' strategies may not always be aligned to the needs of host regions (Bournakis et al. 2019). Moreover, depending on their parent-subsidiary relationships, subsidiaries from different countries of origin can have different business strategies, which in turn can make the contribution of foreign firms to the local economy more varied (Gelübcke 2013). In other words, FDI of itself may not always facilitate regional knowledge transfers and improve regional absorptive capacity, because other issues are also relevant, of which the local share of highly educated workers appears to be critical. Yet, exactly how these different types of regions will respond to the new forms of technologies coming on stream, many of which are spearheaded and heavily deployed by MNEs, is at yet largely unknown.

Innovation and geographical features

Some geographical conditions may inhibit the enhancement of local innovation systems. In this regard, many analyses that study the relationship between innovation activity and regional productivity consider the importance of framework conditions to explain the differences in their effects. Recently, this approach has been used to explain what the literature has called 'left-behind' places (Rodríguez-Pose 2018). As Rodríguez-Pose and Wilkie (2016) argue, there are major innovation divides between geographically core and geographically peripheral regions. This is in part because peripheral and remote regions often do not display the types of skilled labour force required to develop and sustain a strong local innovation system. In addition, they often lack the types of institutional and governance settings necessary for innovation promotion (Rodríguez Pose, 1999, 2001). In addition to these structural and institutional gaps, many geographically peripheral regions are also susceptible to distance decay effects (Varga, 2000; Acs, 2002; Moreno, Paci and Usai 2005; Sonn and Storper, 2008; Rodríguez-Pose and Crescenzi 2008) in that they are typically beyond the spatial limits of the rapidly-changing knowledge flows emanating from core cities and regions. Geographically peripheral areas are thus often seen to be less capable of both generating and absorbing new knowledge. On the other hand, it may be the case that innovation in peripheral areas may take other forms than patents and the more classic innovation forms of new products and processes and may relate to various social or lifestyle innovations. Many of these disparities can also be partly explained by the fact that local development and local innovation are not the same thing (Shearmur 2016).

However, as Rodríguez-Pose and Wilkie (2016) also illustrate, there are also many examples of lagging-behind regions in the world that managed to take the lead, among them Asian Dragons, Flanders, the South of Germany or Las Vegas, while there are also other formerly prosperous regions that lost their leadership positions because their economic trajectories were not sustained, such as the cases of Detroit, Charleroi or Katowice. As such, framework conditions are directly linked with regional renewal possibilities, and some regions are able to reinvent themselves through industrial, technological or institutional transformations, while others seem to be incapable of these transformation processes (Balland 2016; Hidalgo et al. 2018; Balland, Boschma, Crespo and Rigby 2019). These processes of new path development are now very much understood as 'multi-actor approaches' (Hassink, Isaksen, Trippl 2019) because there are so many different moving parts which interact to build a regional innovation system. Moreover, these are becoming even more complex when we consider the new digital systems of innovation and entrepreneurship (Nambisan et al. 2020; Elia et al. 2020; Sussan and Acs, 2017).

Regions and new technologies

In terms of future regional trajectories and transformations, there is some evidence that recent technological advances such as artificial intelligence, digital technologies or automation and robotization will not only affect regions differently (OECD 2018a,b), but in many cases, it will be the regions which are better and more rapidly able to adopt these technologies which will gain more of their long-run productivity and employment benefits (McClure, 2017; Muro, Whiton, Maxim and Hathaway 2017; Muro, Maxim and Whiton 2019; Muro 2019). Even though previous generations of information and communications technologies (ICTs) allow for communication independent of location, in reality, they have not led to a so-called 'death of distance' (Castells 1989) and interregional equalisation processes, but if anything the opposite. These technologies have tended to reinforce the primacy of already richer and larger areas (Horrigna and Wilson, 2002; Tranos, Reggiani and Nijkamp 2012; Tranos 2016), because the majority of digital connections have been made over very short distances (Gaspar and Glaeser 1997; Krings, Calabrese, Ratti and Blondel, 2009). Moreover, this digital primacy may become longlasting. For example, Tranos, Kitsos and Ortega-Argiles (2020) use novel, geolocated data about the volume of online content from the Internet Archive to approximate the active engagement with digital economic activities. The paper, using longitudinal panel data econometric models, finds significant positive and long-lasting effects of online content creation in 2000 on subsequent regional productivity levels up to sixteen years later. In other words, technological advances in digital technologies can display very long-run hysteresis effects at the local and regional scales, and this implies that those regions which today are less able to absorb the new technologies may be at a much longer-run disadvantage than the short term take-up challenges imply.

This would suggest that regions with an existing and strong ICT-base and knowledge advantages in terms of absorptive capacity are likely to be those same regions which are most able to rapidly adopt, adapt and deploy these new digital technologies in diverse ways across their regional economic structures (Shearer and Shah 2018; UNCTAD, 2019). Expertise in artificial intelligence (AI) already tends to concentrate around the major R&D and ICT hubs displaying the infrastructure and highly-skilled labour markets (Tsvetkova et al. 2020; Goldfarb and Trefler, 2018; Klinger, Mateos-Garcia and Stathoulopoulos, 2018). Moreover, we know that large and more productive firms tend to be those which most rapidly adopt new technologies and that these firms also tend to be located in prosperous cities and regions (Behrens, Duranton and Robert-Nicoud, 2014). In other words, the scale of regional exposure (Dauth et al. 2018) and resilience to these new waves of technological shocks (Kitsos et al. 2019) will also depend on the existing regional industrial structures, with certain regions being less exposed to automation than others only by way of the portfolio of economic activities undertaken locally. On the basis of the previous evidence and also the diverging technological growth trajectories of regions in recent years (Atkinson et al. 2019) it is difficult to see how these new generations of technologies will lead to another era of interregional convergence rather than bolstering the current processes of interregional divergence evident in many countries.

Having said this, it is important to remember that one of the features of new generations of technologies is that under certain conditions they do have the power to change the nature of growth trajectories and policy-thinking needs to consider what might be appropriate and possible in different contexts. For example, while we know that improving absorptive capacity is essential for the catching-up process of lagging regions, an important issue regarding policy is whether the same level of support should be provided for both internal in-house R&D and external outsourced R&D (Watkins and Paff, 2009). In the empirical literature, these two forms of R&D have generally been found to be complements rather than substitutes in the production of innovations, although this is not always the case. At the regional level, external out-sourced or even off-shored R&D is less likely to build absorptive capacity than locally-based internal R&D. As such from a policy perspective, there are strong arguments that imply that support for internal R&D will tend to have a greater effect on the long-run performance of the recipient firm and the region in which it is located than R&D which is out-sourced. On the other hand, in order for many R&D-intensive locally-based firms to deepen and widen their regional knowledge impacts, it is essential they become more effectively engaged with local suppliers and customer firms, and this would be especially so if the firm is an MNE subsidiary with a parent in another country. The development of such locally-embedded linkages may itself require the encouragement of R&D out-sourcing to other local firms. As such, any policy support should also be provided to improve the breadth and depth of firms' external networks so that firms can exploit their absorptive capacity (de Jong and Freel, 2010; Harris and Yan, 2019), especially at the local level wherever possible.

Techniques for examining innovation and growth

In order to map and understand the new waves of technological change washing over regions we can exploit various new empirical research techniques. As with many earlier approaches, many of these techniques (Glass, Kenjegalieva and Paez-Farrell 2013; Glass, Kenjegalieva and Sickles 2014, 2016) are still largely based on production frontier concepts. Both Stochastic Frontier Analysis and Data Envelopment Analysis techniques are quite suitable for the analysis of productivity growth in local areas. Indeed, they have been extensively used for this purpose and have allowed us to compare the sources of productivity growth among localities (Sena 2020; Glass et al., 2013, 2014, 2016). Recent empirical developments in the measurement of efficiency using stochastic frontier analysis also allow us to control for possible spatial dependency among the units under analysis which can be regions or localities, and to explore the mechanisms that push a region below or towards the frontier and eventually to create clusters of regions characterised by persistently high or low TFP (Glass et al., 2013, 2014, 2016). This set of techniques is particularly suited to the analysis of the OECD regional databases that have data on TL2 and TL3 regions, thereby providing different types of spatial data and at different geographical levels.

The novelty of these techniques, however, is that they allow us to measure productivity and its drivers in such a way that different clusters of low productivity regions can be identified as well as the economic forces that appear to push them into different directions. Similarly, multilevel and non-parametric approaches (Webber et al. 2019) allow us to decompose different regions into common groupings according to their different growth trajectories. These various approaches exploiting regional growth and productivity differences can therefore provide much-needed granularity into our empirical estimation and understanding of the nature of the links between innovation, productivity and growth both at the regional level and also at the national levels. Unfortunately, however, the current debates on the measurement of productivity largely neglect the regional dimension, instead focussing largely on the computation of the national accounts (Sena, 2020).

Yet, exploiting differences at the regional level in order to deepen our understanding of both regional and national productivity growth processes tends to be very data-intensive. Examining innovation, growth and productivity at the sub-national level requires comparable and detailed longitudinal data on localities in order to analyse how firm-level productivity effects interact with other external and local influences (Sena 2020). Often this takes the form of cross-sectional data, but wherever they are available, longitudinal analyses based on surveys or business registers, or linked employer-employee data can better allow us to extrapolate meaningful productivity growth trajectories.

A very large literature has developed on the empirical analysis of regional innovation and R&D activities based on the analysis of patent data. From international evidence garnered across many OECD countries, these lines of research broadly confirm that R&D activities and patenting are highly correlated geographically (Cozza, Paci and Perani 2012). However, in order to understand the geography of innovation and its links with productivity in particular regions and countries, it is necessary to be more specific, and here the use of patent data can often pose serious challenges. Fortunately, we nowadays have a better understanding of the weaknesses of using patent counts or patent application counts as indicators of regional knowledge-related or innovation-related activities. Using patent data for these purposes at the regional level typically faces the difficulty of associating them with a particular place, and it requires assumptions in order to operationalise the data (Cozza and Schettino 2015). For example, identifying where the inventor or the applicant according to the firm is located is often difficult, as is identifying where the firm's R&D department is located. Sometimes the patent data is only linked to the headquarters of the firm but not to the actual place where the research has been conducted or undertaken, and this is especially problematic when discussing the vast number of important patents held by multi-plant or multinational firms.

However, the complex nature of innovation processes means that the measurement of innovation in space cannot be based on just one indicator. Most of the measures that we use are based on combinations of employees, firms, and plants that also evolve and interact with each other. Analogous evidence from entrepreneurship systems (Szerb et al. 2020) suggests that a holistic evaluation of the effects of regional innovation activity on regional productivity would involve a complex computational process, given the likely interdependencies between these different types of innovation inputs.

In recent years various other new methodological approaches or data sources have been used in the evaluation of innovation activity in regions (Sena 2020). For example, machine-learning techniques have been applied to survey data to proxy the innovation activity of regional firms by constructing new variables that take information for a series of inputs and outputs and classify innovators in space (Gandin and Cozza, 2019; Nuccio and Guerzoni, 2019). Nuccio and Guerzoni (2019) evaluate the effects of big data in market competition, by looking at the risk of entry barriers, price discrimination and potential for technology improvement. Gandin and Cozza (2019) show the feasibility of predicting innovator firms using the Community Innovation Survey by applying a supervised machine-learning approach on a sample of Italian firms. Using an integrated dataset of administrative records and balance sheet data, which is designed to include all easily accessible and informative variables related to innovation, a random forest algorithm is implemented to obtain a classification model aimed to identify firms that are potential innovation performers (Gandin and Cozza 2019). The model is able to identify three-quarters of firms with patents and is also able to identify the role of many of the classical predictors of innovation potential and performance discussed in the literature, such as firm size, sector belonging and investment in intangible assets (Gandin and Cozza 2019). These new types of empirical techniques, therefore, hold out the prospects of a better understanding of regional innovation and productivity relationships.

As we will see shortly, there is now also a whole host of new empirical techniques based on entropy and network frameworks which are nowadays widely used in examining regional innovation systems, and these throw different and new light of the relationships between innovation, regions and productivity.

3 Increasing regional productivity performance through innovation: Regional location factors

Until now, the discussions of innovation and regional productivity have focused on the role played by knowledge accumulation and technological change, as mediated via knowledge spillovers and knowledge flows in different sectoral and spatial settings. However, much evidence nowadays indicates that many non-technological issues are also critical in shaping regional innovation and productivity growth, and the research suggests that the four main groupings of non-technological influences on regional innovation and productivity are: regional cultural and creativity factors; the nature and scale of regional infrastructure and public investments; the nature and quality of regional institutions and governance; and finally, the policy context. However, these issues also all need to be seen in the context of major societal challenges we currently face, namely the COVID-19 shocks and the climate change emergency.

Regional cultural and creativity influence

The notion of 'embeddedness' has various meanings, one of which is regarding the scale of the economic linkages and the longevity that a firm has in its locality. However, another notion of embeddedness refers to how economic activities are facilitated, inhibited or constrained by a firm's social relationships with other local actors and institutions (Granovetter, 1985; Zukin and DiMaggio, 1990; Hess, 2004). Local innovation systems involve many different actors including company managers, technical and technological specialists, legal institutions, funding bodies, researchers, employees, labour organisations, entrepreneurs, university and research centres, technology transfer organisations (TTOs), R&D managers and R&D users, all of whom interact with each other in many different and overlapping ways and local cultural norms will shape how these actors interact and are incentivised to interact (Fligstein, 2001). Attitudes to risk-taking differ markedly between places (Szerb et al. 2020) and the ways that people interact are often a non-conscious process (Fligstein 2001) based on local cultural norms and communities of practice. These local cultural norms are often heavily shaped by the organisational culture of locally-dominant employers or sectors (Klepper, 2007). The entrepreneurship ecosystems approaches have also been expanded to encompass digital ecosystems (Sussan and Acs, 2015; Nambisan 2017; Nambisan and Baron 2019; Elia et al. 2020)

These local cultural norms (Spigel 2016) can act either as a bridge or a barrier to other innovation and knowledge environments. Local innovation environments which are culturally open are more likely to access and absorb new knowledge from other innovation environments than local innovation environments which are culturally relatively closed. By 'open' and 'closed', here we refer to the degree to which local entrepreneurial and innovation environments are welcoming and conducive to new entrants and to new ideas from other places, whereby entrants could be variously either people, firms or institutions. These issues underscore the fact that, as Wostner (2017) has argued, the technological and structural transformations underpinning innovation systems are not just about changes in the economy, but more fundamentally about how whole societies function in terms of developing the trust relations essential for risk-taking. This is because the collaborative relationships essential for innovation depend on having the right atmosphere for fostering personal motivation, engagement and activation (Wostner 2017).

Some local economic systems are dominated by local incumbent firms or institutions which tend to inhibit the inflow of new people or ideas. In contrast, other local economic environments are less dominated by any particular grouping, and as such, are more susceptible to new ideas and risk-taking initiatives (Chinitz 1961). These cultural differences can also shape either individual or collective behaviour (Huggins and Thompson 2019; Tabellini, 2010; Tubadji, 2013), and this is important in social terms because innovation is as much a collective process as it is an individual process.

The differences in the cultural openness of local environments, and especially relating to commercial and business practices, has been a key element underpinning the widespread research on creativity (Florida 2002, 2005; Wolfe et al. 2008; Wolfe 2016). Culturally open local social and commercial environments tend to attract talented and creative workers who are vital to driving local innovation (Bain 2016; Blake and Hanson 2005). This is in part because innovations are generated both by cognitive analytical and problem-solving skills as well as non-cognitive skills, and it is in these non-cognitive skills also embodying aesthetic and artistic senses as well as the ability to synthesise different forms of knowledge, where creativity becomes so crucial (Bain 2016). As such, innovation processes in creative places are built on a combination of analytical-deductive, synthetic-inductive (Boix-Domenech and Soler-Marco 2017) and symbolic-aesthetic (Asheim, Boschma and Cooke 2011a) knowledge supported by the appropriate physical and social and economic infrastructure (Asheim, Lawton-Smith and Oughton, 2011b). This social and economic infrastructure includes creative services industries (Boix-Domenech et al. 2014) made up of activities such as publishing, audiovisual, radio and TV, software, architecture and engineering, research and development, advertising, design, photography, and arts and entertainment (UNCTAD 2010). These creative services industries can contribute to the local innovation system and enhance local productivity (Boix-Domenech et al. 2017) in three different ways. Firstly, they provide inputs to other local industries; second, they can generate vertical and horizontal knowledge spillovers in the local economy, and third, they can improve the aesthetic and heritage aspects of the local environment which in turn can improve the attractiveness of a locality for other inward entrepreneurs and financiers. There is now a wide body of evidence that demonstrates that creativity is associated with regional growth, although, as with other aspects of the innovation-productivity relationships, at present, the causality relationships are still somewhat unclear.

Public investments and regional infrastructure

At the regional scale, productivity-enhancing investments in fields such as transportation, education and R&D tend to be positively associated with productivity. In contrast, public expenditures in areas such as income support or social welfare support tend not to be associated with productivity growth (McCann 2016). However, the specific lines of causality between public investment and productivity are still largely unclear, and this is mainly the case for transportation (Docherty and Waite 2020) and energy infrastructures. In many ways, the reason is that large-scale infrastructure investments are not amenable to standard cost-benefit analysis (CBA) types of analysis if the installation itself changes many parts of the local, regional or national economic system (Docherty and Waite 2020). This problem is particularly acute in the case of network infrastructures. In the case of major transportation infrastructure investments, there is currently no clear pattern as to the relationship between investments and regional productivity growth, other than a very general understanding of there being a positive relationship in certain contexts (Docherty and Waite 2020). Instead, each investment of this type has to be considered on its own merit, and often in an environment of limited information.

This is also broadly the case with new information and communications infrastructure investments and Docherty and Waite (2020) explain the major difficulties in any attempts to accurately capture the economic impacts of new digital connectivity accurately. First, assessments of these impacts tend to be based on proxy measures such as the capacity of the broadband infrastructure or the number of customers signed up with internet service providers; second, experience suggests that digital activity is constantly and rapidly changing both regarding the levels and use of digital services, thereby diminishing the relevance of some of these proxies; third, as with many major infrastructure and network investments, there may well be reverse causality or two-way causality between digital activity and productivity; fourth, changes in ICT usage may be associated with other equally major changes in areas such as management, production or marketing activities, again complicating any causality relationships; and finally, there may be key thresholds in the quality of digital connections beyond which digital infrastructure-innovation-productivity relationships may exhibit highly non-linear relationships (Docherty and Waite 2020).

In addition to problems of assessment and evaluation, infrastructure investments are often also subject to political (Vasilev 2013), or economic rent-seeking, and these forms of rent-seeking can be especially harmful to innovation-related activities (Murphy et al., 1993). Moreover, local and regional economies with a significant public sector presence and public sector wage premium may also face distortionary effects on the allocative systems underpinned by financial markets due to problems of the ‘crowding out’ of local investment (Persson and Tabellini, 2000; Vasilev, 2013) from the private sector. A combination of rent-seeking and these types of distortionary investment effects can lead to the wasting of resources and hamper regional growth.

There is some evidence from regional policies of waste and inappropriate public investment allocations in transport infrastructure investments (Rodríguez-Pose and Fratesi 2004). However, broader empirical evidence suggests that this is not necessarily a major problem and that transport investment operate largely as intended (Ferrara et al. 2017). Indeed, in some cases such as the UK, the country’s most productive regions are also those with the largest share of public sector investments, especially in education and research (McCann 2016). These various observations suggest that the relationship between local public investments and local entrepreneurial private-sector investments, therefore, depends largely on whether the activities underpinned by the public investments are broadly complements or substitutes for each other and what specific forms these investments take.

Institutions and governance

There is now a large literature on the role played by institutions in economic development, and institutions come in a variety of forms which are generally classified into ‘hard’ and ‘soft’ institutions. *Hard institutions* tend to be organisations and modes of conduct which are characterised by formal legal definitions and a legal basis, such as companies, universities (Beer, McKenzie, Blazek, Sotarauta and Ayres 2020), educational institutions, research centres, banks and finance houses, market exchanges, regulatory bodies, tax codes, social insurance systems, chambers of commerce, trade unions and labour organisations, as well as systems and procedures of exchange, disclosure, as set out in legal contracts and enforceable regulations, including intellectual property rights (Henrekson and Sannadaji 2011). In contrast, *‘soft’ institutions* tend to be those informal norms, conventions and roles which, although they have no formal legal basis, are very powerful in terms of shaping how individuals and organisations interact. Well-designed and effective institutions, including financial institutions (Demetriades and Law, 2006), are supportive of entrepreneurship and innovation by correctly aligning incentives and constraints (Boettke and Coyne, 2009; Kibler et al., 2014) to encourage risk-taking in a manner which is socially constructive (Storper, 2013; Baumol et al., 2009).

During the 1980s and 1990s, almost all of the research was on the role played by national and international institutions in shaping growth, and the great majority of the analysis was on *hard formal institutions*. In contrast, during the last two and a half decades an extensive literature has emerged examining the role played *soft institutions*, and also on the roles played by local, regional and national institutions in fostering local innovation and shaping regional productivity and growth trajectories (Huggins and Izushi, 2020). A key finding of this literature is that these issues differ markedly between places, and at the regional scale institutions and governance really do matter for productivity growth. The institutional set-up also includes questions of financing and how the regional financial systems interact with the national financial system (Klagge and Martin, 2005*;* Hutton and Lee, 2012; Cortinovis et al., 2017; Mayer, McCann and Schumacher 2021). In particular, both the structure and the quality of institutions play a key role in shaping local productivity growth and interregional productivity growth differentials, and there are two major aspects to this.

Firstly, countries with more devolved and decentralised governance systems, including financial systems (Mayer et al. 2021; Wójcik, 2009) tend to exhibit more equal patterns of regional productivity growth across the whole country and are less dominated by any particular city or region (Carrascal-Incera, McCann, Ortega-Argiles and Rodriguez-Pose 2020). In contrast, countries with highly centralised governance systems tend to display highly unbalanced regional growth patterns. Moreover, neither highly unbalanced nor balanced regional growth patterns offer any national productivity advantages (Carrascal-Incera et al., 2020). As such, countries with highly unbalanced regional growth trajectories incur serious social problems, without any associated economic advantages (McCann 2020; Rodríguez-Pose 2018).

Secondly, the quality of both national and local institutions also matters crucially for the fostering of regional productivity growth (Rodríguez-Pose, Ganau, Maslauskaite and Brezzi, 2020). A higher quality of local governance institutions enhances all aspects of local and regional economic development, including innovation (Rodríguez-Pose and Di Cataldo 2015; Hussen and Çokgezen 2020), growth (Rodríguez-Pose 2013), regional resilience (Ketterer and Rodríguez-Pose 2018) and wellbeing (Ferrara and Nistico 2019). Indeed, a combination of good formal and informal institutions at the local scale are likely to play a positive role in the fostering of local entrepreneurial ecosystems (REDI; Acs, Szerb, Ortega-Argiles, Aidis and Coduras 2015; Sussan and Acs, 2017; Szerb, Ortega-Argiles, Acs, Komlosi 2020; Elia et al., 2020), innovation and growth (Caragliu and Nijkamp, 2015; D'Agostino and Scarlato, 2015). Yet, exactly how these regional innovation systems operate also depends on the local regional spatial and industrial settings (Prenzel, Ortega-Argiles, Cozza and Piva 2018) as well as the complementarity of all of the local innovation inputs (Crescenzi, Gagliardi and Iammarino 2015; Crescenzi 2020). Yet, whether economic development encourages the building of good institutions, or whether good institutions are a precursor to innovation and economic growth is still unclear, since the human agency is involved (Huggins and Izushi 2020; Fagerberg 2017).

Regional economic policy

In the last two decades, there has been a wide-ranging international debate regarding the effectiveness of space-blind versus place-based policies (Barca, McCann and Rodriguez-Pose 2012), and in recent years much of the intellectual and empirical momentum has been moving away from space-blind thinking and towards place-based approaches. In terms of innovation and productivity, there is evidence that if well-designed, place-based policies do work broadly as intended (Ferrara, McCann, Pellegrini, Stelder and Terribile 2017). There are sometimes challenges associated with the fact that the performance of specific programmes and projects depends on them being the appropriate mix of top-down and bottom-up elements (Crescenzi and Giua, 2016 and 2020) which dovetail with the mix of local endowments (Sotiriou and Tsiapa 2015) and display a balanced basket of investments (Di Cataldo and Monastiriotis 2020) which ensure congruence with regional socioeconomic needs (Crescenzi, Fratesi and Monastiriotis 2017). This includes issues of financing and policy prioritisation (Wostner 2017). However, questions regarding absorptive capacity are also relevant here. Sometimes, regions are not sufficiently able to use the financial resources made available by the policy due to absorptive capacity problems on the part of either or both the local private and public sectors (Driver and Oughton, 2008).

Societal challenges: COVID-19 and the climate change emergency

In addition, each of these issues raised here are likely to be impacted by the two major societal challenges facing all regions at present, namely the shocks associated with the COVID-19 pandemic and also the climate change emergency.

Regarding COVID-19, in regional terms, the immediate shocks have been most keenly felt in sectors such as travel and tourism, hospitality, creative and cultural industries, along with certain areas 'high-street' retail. Obviously, regions specialised in these sectors are likely to be the most adversely impacted in the short term, but the long term regional effects are likely to differ somewhat from these immediate sectoral impacts. In the medium and long-term, as economies slowly come out of the crisis in response to new vaccines, there will still be profound shocks to our economies, some of which will be longlasting, and different regions will be impacted on in different ways by these shocks, of which there are two major types.

Firstly, the crisis is leading to major global capital shocks, and these capital shocks are likely to impact on regions in terms of increased differences in capital pricing (McCann and Ortega-Argilés 2021). In particular, the radical uncertainty brought about by the COVID-19 crisis means that required yields on all financial investments in economically weaker places are likely to rise higher, relative to more prosperous places. To the extent that this happens in real estate markets, supported indirectly also by quantitative easing, this will mean that the costs of capital, along with any collateral requirements for business investment loans, will fall in more prosperous places relative to less prosperous places (Daams McCann Veneri Barkham Schoenmaker 2020). In terms of the regional innovation system, all local investors aiming to foster innovation will face increased costs relative to more prosperous locations, although the adverse effects on small and medium-sized enterprises (SMEs) searching for investment capital (Mayer et al. 2021) underpinning innovation activities will be incredibly difficult, as will be the effects on local real estate investors (McCann and Ortega-Argilés 2020). These capital shocks are therefore likely to weaken the SME-based local innovation systems in lagging regions relative to leading regions, especially where SMEs also use local real estate equity at collateral. This will almost certainly lead to further interregional divergence.

A second effect relates to commuting behaviour. The COVID-19 crisis has permanently shifted the extent to which people will work from home post-crisis, and this may also change the spatial configurations of regional innovation systems and their links with regional productivity. In particular, a lowering of commuting frequencies to major core city centres will be likely to increase the geographical hinterlands of prosperous cities and potentially out-compete the local hinterlands of less prosperous cities. It may also increase the extent to which people search for more home-based work and lifestyle changes, which may include developing more locally-based innovation activities in more peripheral locations, although the capital pricing effects just described will probably work against this. However, the balance between these various issues is still to be seen as the crisis and post-crisis period progresses.

The other major issue shaping regional innovation systems is the climate change emergency. The COVID-19 crisis has delayed the implementation of many of the agreed actions in the 2016 Paris Accord, as states try to encourage output and employment to recover as quickly as possible in the aftermath of the pandemic shutdowns. Of necessity, responding to climate change must be an innovation-led process, but how this will impact on regions differs very much. In many countries, many of the regions which are the most exposed to climate change risks are also those same regions which will be the most adversely affected by climate change mitigation measures, due to a greater presence of carbon-intensive and carbon-extensive activities in the industrial fabric (McCann and Soete 2020). In contrast, many of the OECD's more prosperous regions are relatively more specialised in lower carbon-intensive activities and also in those same knowledge-related activities and infrastructures, which will spearhead climate change innovations. As such, finding ways to ensure that climate change agenda does not increase disparities between regions is crucial in order to ensure societal engagement and buy-in to the agenda. In other words, finding ways to help these regions both enhance and also reorientate their innovation systems toward climate change mitigation innovations would therefore appear to be paramount, in order to avoid climate change agenda also increasing interregional inequalities. This will also require a significant rethink of policy settings (McCann and Soete 2020).

4 Increasing regional innovation: Localised knowledge and innovation impacts

Regions, rather than nations, are an essential scale for understanding innovation processes because of that fact that so many types of knowledge spillovers are very local in nature. These local knowledge spillovers and exchanges can operate between co-located firms as well as between firms and local knowledge institutions such as universities, but the evidence suggests that they tend to be very spatially concentrated (Anselin, Varga, Acs 1997, 2000; Henry and Pinch, 2000). Indeed, the extensive empirical and analytical work over the last four decades means that one of the key principles that modern regional innovation research rests on is that regional productivity growth is heavily shaped by the local conditions for creating, accessing, transferring and exploiting knowledge (Roberts and Setterfield, 2010).

The knowledge-based economy underpins activities and resources aimed at fostering innovation (Romer, 2007), and depends crucially on the ability of knowledge to *spill over* between individuals and firms, thereby resulting in the generation of increasing returns (Roberts and Setterfield, 2010). Vertical knowledge spillovers can occur between customers and suppliers within supply-chains and input-output relationships while horizontal knowledge spillovers can take place between competitor firms, and knowledge spillovers can also occur between institutions and firms (Dachs, Ebersberger and Pyka 2008). Which type or types operate in each specific context depends primarily on the economic structure. Nowadays, however, knowledge spillovers are increasingly understood as being primarily a regional phenomenon (Audretsch and Lehmann 2005; Ó huallacháin and Leslei 2007), and while knowledge is not necessarily a pure public good, in that it can be at least partially excludable via different forms of intellectual property rights (Griliches 1979; Audrestch 2000), the tacit knowledge exchanges facilitated by the spatial clustering of activities can largely overcome many of these constraints. Many local knowledge spillovers consist of externalities that are at least partially paid for (Andersson and Ejermo 2005) by location and land prices (Gordon and McCann 2000), and there is now a large body of evidence that demonstrates that the spatial concentration of activities and the 'buzz' (Storper and Venables 2004) they generate can facilitate agglomeration processes driven by knowledge spillovers (Feldman 1994).

The specific nature and scale of local knowledge spillovers, in turn, depends on the particular array of people and occupations, firms, technologies and commercial relationships operating in the local economy. Where this efficiently takes place, this allows for the diffusion of best-practice and technological know-how rapidly throughout the local economic system and facilitates the generation of locally-specific increasing returns to scale. However, we also know that many regions are not characterised by dense agglomerations and also that knowledge spillovers tend to be spatially constrained and truncated (Anselin et al., 1997, 2000; Acs, Audretsch, Braunerhjelm and Carlsoon 2004; Acs and Plummer 2005). This spatial truncation occurs both because of the relatedness features amongst local firms, practices and technologies, and also because of the effectiveness of local institutions (Acs and Plummer 2005). The fact that knowledge is often truncated spatially means that there is always the danger of local technological 'lock-in'. Therefore, promoting knowledge connectivity (McCann and Acs 2011) via the building of knowledge 'pipelines' in order to tap into knowledge from other non-local regions (Bathelt Malmberg and Maskell 2004) becomes very important.

In terms of innovation, the evidence on the relationship between agglomeration processes and innovation is not entirely clear. In countries such as the USA and South Korea, cities are seen to account for the overwhelming majority of innovations, whereas in other countries, the picture is somewhat more distributed (Fritsch and Wyrwich 2021). While innovation activities related to business services tend to be associated with proximity to cities (Brunow et al. 2020), in many countries large cities do not appear to have an innovation advantage over smaller urban centres or even non-urban areas (Fritsch and Wyrwich 2021). This reflects the fact that knowledge 'distance' and innovation distance are not the same thing as the geographical distance (Boschma 2005) and that many variations in different agglomeration-type geographies can arise even for a single sector (Carlei and Nuccio 2014; Cainelli and Ganau 2018). As such, the relationships between regional innovation, productivity and growth are complex and do not reflect a simple co-location mapping of urbanisation, agglomeration and productivity.

Yet, exactly how these different spatial processes emerge, and how they are related to innovation and productivity growth in different types of regions, is still a matter of debate. Building on much earlier arguments (Marshall 1920; Jacobs 1969), for the last three decades there has been a debate about whether sectoral diversification or specialisation is more conducive for local growth (Glaeser, Kallal, Scheinkman, Shleifer 1992; Henderson, Kuncoro and Tumer 1995), especially in the context of local agglomeration processes in cities. As yet, however, there is still no real consensus as to whether diversification or specialisation is advantageous for enhancing regional innovation, productivity and growth (Beaudry and Schiffauerova 2009; Caragliu De Dominicis and De Groot 2016; De Groot Poot and Smit, 2016; Melo Graham and Noland, 2009) and conceptual debates are still ongoing (Kemeny and Storper, 2015; Santoalha, 2020).

More recently, there is an extensive literature which has developed over the last two decades which examines empirically the extent to which innovation and knowledge creation in the form of diversification and specialisation are important for regional productivity and development. We know that processes of regional industrial transformation and diversification are essential for enhancing regional economic growth and resilience (Lazzeretti Oliva and Innocenti 2019; Rocchetta and Mina 2019), in that regions will be able to mitigate declines in parts of their industrial fabric by facilitating processes of renewal based on movements into new technologies, products and services (Boschma 2011). The evidence shows that regions that are better able to develop new activities overtake those that remain locked into the existing ones (Neffke Henning and Boschma 2011; Balland Jara-Figueroa and Petralia 2020). Yet, the ability of a region to undertake these processes of diversification and renewal is heavily conditioned by the region's existing industrial structure, and the relatedness literature, of which the 'related variety' approach is a key component, has provided new and fundamental twists on the diversity-versus-specialisation debates. This approach is based on the notion that cognitive distance plays a key role in determining the relationships between geography and trade.

The concept of related variety (Frenken, van Oort and Verburg 2007) has changed how scholars think about many aspects of regional economic growth, and this relatedness literature takes a dynamic and historical approach to explain the success of regions in developing new varieties of innovations (Balland, 2016). Related variety indices are an entropy-based construct. The relatedness research agenda examines how regions diversify and evolve rather than asking whether diversity or specialisation is advantageous from a growth and productivity perspectives, an issue about which we have already seen, there is currently no consensus (Beaudry and Schiffauerova 2009; Caragliu et al. 2016; De Groot et al. 2016; Melo et al. 2009). Crucially, the new evolutionary economic geography research field (Boschma and Martin 2010) has demonstrated that the capacity of regions to change and adapt is heavily conditioned and constrained by their existing industrial endowments, skills (Neffke and Henning 2013), input-output linkages (Essletzbichler 2015) and capabilities (Frenken and Boschma 2007; Pike Dawley and Tomaney, 2010)[3].

Technological adaptation processes are conditioned on cognitive proximity between different capabilities, as embodied in specific production routines, skills profiles and institutional settings, and as such, are subject to path-dependency and 'lock-in' effects reinforced by increasing returns and network externality effects (Santoalha 2020). This is because regional capabilities are dependent on existing organisational routines and cognitive proximity in production domains in which a region already has expertise and experience, rather than simply costs alone, as would be the case in neo-classical frameworks. As such, regional diversification opportunities themselves tend to be specialised, in that regional branching (Boschma and Frenken 2018) and diversification around a region's existing areas of specialisation appears to offer the best opportunities for growth and development. Moreover, in many regions, knowledge spillovers and agglomeration effects also tend to be associated with a related variety and cognitive proximity (Frenken et al. 2007; van Oort Geus and Dogaru 2015). As such the process of regional growth evolutions can often be characterised as specialised diversification (McCann and Ortega-Argilés 2015) or alternatively as diversified specialisation (Farhaurer and Kröll 2012)

Another approach to understanding these relatedness features derives from the network-relatedness models of trade (Hidalgo and Hausmann 2009; Hidalgo et al. 2018). These network-relatedness approaches are based on the notion of the product space and in particular the proximity between products in product space, which are in turn determined by the requisite complementary capabilities which span different groups of production activities. In network-structure terms, these complementarities give rise to a trade and production architecture which is unique to each country and is revealed in term of the pattern of sectors in which a country has a relative specialisation. The unique trade-network architecture implies that both the trade opportunities of a country and also its trade-diversification possibilities are heavily determined by the centrality of the country's capabilities, as reflected in its product portfolio, within the broader international trade network structures. In particular, a strong presence in certain sectors, or rather certain combinations of sectors, allows some countries more easily to innovate and develop productivity-enhancing and growth-enhancing lines of activity than others, and these processes themselves may exhibit non-linearities (Patuelli et al. 2006). As a result, some countries and regions are systematically better positioned in product space for adapting to changing circumstances than others, and this means that the ordering of relative prosperity based on trade performance shifts only very slowly.

Similar types of arguments are also made for regions, although in the regional case, the basic Hausmann-Hidalgo logic cannot be applied unchanged. This is because the Hausmann-Hidalgo logic is based on the patterns of exporting by countries, many of which in the developing world only export from a few different sectors. In marked contrast, regional innovation and trade systems are heavily shaped by many different local linkages, many of which do not reflect relative regional trade specialisation patterns (Cicerone et al. 2020), and, moreover, in advanced economies regions produce many different types of products and services. Regional innovation systems are a complex mixture of lots of different types of relationships, some of which are overwhelmingly local, and therefore will not appear in regional trade-related data and others which connect with lots of different local activities even though they are not exporting. When the Hausmann-Hidalgo types of frameworks are redefined and better adapted to the regional context in order to reflect these regional features, then it becomes clear that trade-network structures are indeed also important at the regional level for enhancing both innovation and productivity (Cicerone et al. 2020).

[3] For a review of the literature on relatedness see Whittle and Kogler (2018)

Table 4. Related-variety as a source of knowledge spillovers and local growth (selection of recent works)

Relationship	References
Related-variety-Entrepreneurship activity	Bishop (2012); Colombelli (2016); Guo et al. (2016); Tavassoli and Jienwatcharamongkhol (2016); Basile et al. (2017); Fritsch and Kublina (2018); Content et al. (2019); Ejdemo and Örtqvist (2020); Colombelli et al. (2021)
Related-variety-Productivity	Boschma and Iammarino (2009); Quattraro (2010); Bosma et al. (2011); Falcioglu (2011); Rocchetta et al. (2021)
Related-variety- Growth in value-added	Boschma and Iammarino (2009); Boschma et al. (2012)
Related-variety-Employment growth	Frenken et al. (2007); Boschma and Iammarino (2009); Bishop and Gripaios (2010); Hartog et al. (2012); Mameli et al. (2012); Cortinovis and van Oort (2015); van Oort et al. (2015); Firgo and Mayerhofer (2018); Fritsch and Kublina (2018); Cortinovis et al. (2020)
Related-variety-Economic Resilience	Lazzeretti et al (2019); Rocchetta and Mina (2019)
Related-variety- Green Employment	Barbieri and Consoli (2019); Montresor and Quatraro (2019); Boschma (2021)
Related-variety-Regional Innovation	Tavassoli and Carbonara (2014); Castaldi et al. (2015); Aarstad et al. (2016); Miguelez and Moreno (2018)
Related-variety- New 4.0 digital technologies	Castellacci et al. (2020); Montresor and Quattraro (2017)
Related-variety-International innovation	Ebersberger et al. (2014)
Related-variety-Technological diversification	Santoalha (2020); Boschma, Miguelez, Moreno and Ocampo-Corrales (2021)

Source: Authors' elaboration.

These related-variety and network-relatedness frameworks are broadly complementary to each other. They imply that regional productivity growth primarily takes place in an iterative manner in which regions diversify around existing cores of activities in which they are relatively specialised. Of course, branching and diversification mean that the existing industrial structure is not static in the medium-term long-run, and will itself evolve over time (Neffke et al. 2011). However, the point remains, that a region's technological, skills, sectoral and export (Boschma Mirondo and Navarro 2013) diversification possibilities are neither open-ended nor independent of the existing regional industrial structure.

The widespread existence of these related variety evolutionary processes, however, does not imply that these processes are inherently superior to other diversification processes. There is some evidence that in certain contexts regions that display growth via unrelated variety may be more resilient to certain types of shocks (Frenken et al. 2007), although this tends to be a characteristic of already large and diversified agglomeration centres. Moreover, inward FDI can facilitate either related or unrelated diversification (Neffke Hartog Boschma and Henning 2018; Elekes Boschma and Lengyel 2019; Cortinovis Crescenzi and van Oort 2020), in that foreign-owned firms tend to deviate more from the region's existing average capability profile. However, this deviation tends to be greater in the short run than in the long run and more pronounced in peripheral regions and capital regions (Neffke Hartog Boschma and Henning 2018; Elekes Boschma and Lengyel 2019). Regions with certain characteristics may be better able to grow by both processes of related and unrelated variety than others. Indeed, Xiao et al. (2018) find that relatedness is a more important driver of diversification in regions with a weaker innovation capacity, and that the importance of relatedness decreases as the regional innovation capacity increases. This observation is consistent with the argument that a high regional innovation capacity allows an economy to reinvent itself away from existing industrial structures and systems more quickly, but that such capacity is not widely evident across all regions and in all contexts, thereby underscoring the importance of relatedness for regional growth processes. The uneven geography of innovation that we observe is therefore in part due to regional differences in the capacity to access and exploit new knowledge (Santoalha 2020) as well as differential constraints on regional diversification possibilities due to historical development trajectories.

These network-types of approaches highlight the fact the innovation is, in many ways a system phenomenon, the understanding of which also requires a systemic approach. In the context of entrepreneurship, such an approach has already been demonstrated by the REDI framework (Szerb et al. 2020; Acs et al. 2015), and in an analogous manner, an examination of the features linking regional innovation to regional productivity also call for systemic analytical and empirical approaches. The evidence from systems-type analyses suggests that systems-approaches allow us to focus on the weaknesses in the regional entrepreneurial systems which need to be strengthened, the bottlenecks which need to be released and the missing links in regional systems which need to be bridged or re-connected. Similarly, innovation is in many ways a systems phenomenon, and one which is also often closely allied to entrepreneurship, and therefore at the regional scale entrepreneurship and innovation may well share many common features. Identifying the weaknesses in the innovation system potentially offers an approach to help regions upscale their innovation activities and aspirations.

What is not clear at present is the extent to which the new industry 4.0 digital technologies will change these regional innovation diversification processes or possibilities. Crowley et al. (2021) find that regions which are more densely populated, with higher human capital and more unrelated variety are less prone to adverse automation shocks. There is some evidence (Castellacci Consoli and Santoalha 2020) that the current regional stock of e-skills, in terms of the development and use of digital technologies, can enhance regions' ability to diversify into new development trajectories, and this effect appears to be particularly strong for economically less developed regions (Castellacci et al. 2020). In other words, the new digital technologies potentially hold out the potential for weaker regions to develop their novel catching-up processes, in cases where weaker regions are vital in e-skills. Some more work on the role of key enabling technologies (Montresor and Quatraro 2017) and green technologies (Montresor and Quatraro 2019) on regional technological diversification also shows the importance of policy intervention on the adoption of green technologies and its effects on shaping the knowledge and technological space of European regions.

One possibility is that the new digital technologies may be increasingly associated with 'open' innovation processes (Chesborough 2003) whereby firms are increasingly able to exploit knowledge and ideas from other firms (Dhalander and Gann 2010). Although most of the evidence on these new open forms of innovation has so far tended to discuss these in the context of corporations, large firms and their supply chains, some of the arguments ought to be applicable to regional innovation systems, and especially those dominated by small firms (Laursen and Salter 2006; Perkmann and Walsh 2007; van de Vandre et al. 2009; Spithoven et al. 2013; Vanter et al. 2014; Fristch and Schwirten 1999). Moreover, in terms of regional innovation systems, in many ways, the standard agglomeration-tacit-knowledge-spillover model already proxies an open innovation system, although as we have seen, this model is not applicable to many regions. Therefore, it may be the case that the new generations of digital technologies can better facilitate open innovation systems in more networked types of geographies. However, this remains to be seen, given that the extent to which such open systems may develop will also be subject to complex regulatory and intellectual property issues.

5 Our known unknowns: Challenges in understanding and emerging trends

The literature and research reviewed here point to various issues about which the evidence on the links between regional innovation and productivity is still not settled or is insufficiently conclusive for us to make clear statements.

1. Innovation distribution is differently spatially distributed. The case of the US is an outlier in that so much innovation is concentrated in a very small number of large urban locations (Atkinson et al. 2019). Across the rest of the OECD, the picture is more complex. In many other countries, innovation occurs in mainly urban areas, but is also evident in small cities and rural regions and tends to be more evenly distributed than in the USA (Fritsch and Wyrwick 2021). Yet, why we see these different spatial patterns of innovation is still unclear.
2. In general, there is a positive effect of absorptive capabilities on local innovation enhancement and thereby on regional productivity. However, the important local mediators and moderators which facilitate regional absorptive capacity are still little understood and need to be considered in more detail. Different types of innovation require different types of complementary local skills inputs, which mediate or moderate the relationship between innovation and productivity. However, although higher-level skills are critical, there is no clear consensus on what an optimum portfolio of skills would be to mediate local technology and knowledge spillovers.
3. This is especially the case for the links between foreign direct investment (FDI) and local firms (Rojec and Knell, 2018). Locations all over the world compete to attract FDI in order to access knowledge, technology and boost economic development and FDI can also facilitate either local related or unrelated diversification processes (Neffke Hartog Boschma and Henning 2018; Elekes Boschma and Lengyel 2019). However, although the literature shows a positive impact of FDI on regional economies, little is known about its effect on neighbouring regions and also the types of FDI which generate the largest learning effects (Ascani and Galiardi 2015; Ascani Balland Morrison 2020).
4. The effect of the new digital economy on interregional inequalities in innovation and productivity are as yet unknown (Lee 2016; Lee and Rodriguez-Pose 2013). There are likely to be heterogeneous regional effects in the relationship between creativity, AI, automation and robotisation on innovation and productivity. These effects are likely to be heavily influenced by the presence of knowledge spillovers, and the nature and patterns of local spillovers associated with these new digital technologies are likely to be different in different types of regions with different types of firms. Large global exporting firms are likely to dominate the earlier stages of the new technology-adoption processes, and it is unknown how the take-up of these technologies by other firms will play out. Some of the early evidence regarding the regional effects of AI and digital

technologies points to increasing interregional inequalities, although it is soon too early to be unequivocal on these points.

5. The effects of creative services industries on regional growth and productivity are heterogeneous, and while there is a lot of evidence that these links are broadly positive (Rausell Marco and Albeledo 2011; De Miguel Hervas Boix-Domenech De Miguel 2012; Boix-Domenech and Soler-Marco 2017; Marco Rausell and Albeledo 2014), difficulties in identifying these links remain. This is partly because of the complex social relations which underpin the local embedding of creative activities and partly also because of issues related to their definition and measurement and level of aggregation.
6. The links between regional diversity, specialisation, innovation and growth are still unclear (Beaudry and Schiffauerova 2009; Caragliu et al. 2016; De Groot et al. 2016; Melo et al. 2009), although the ways that diversification takes place locally are becoming clearer. This is the case for technological diversification, as well as skills and export diversification, all of which are closely linked to the notion of relatedness, whereby diversification takes place as an incremental, evolutionary process based around existing capabilities, although these relatedness features may exhibit non-linearities.
7. The effects of different types of infrastructures on regional innovation and productivity growth are still unclear, and this is especially so for large and networked infrastructures. While we know that in general, they are conducive to productivity growth, we do not know the exact ways in which these links work. In part this is due to limited information, as well as the limitations associated with our analytical frameworks and these problems may be particularly acute in the case of the new generations of networked digital infrastructures (Lin and Wu, 2013; Docherty and Waite 2020).
8. With the right mix and quality of inputs and institutions, strong local innovation systems have the potential to generate cumulative causal effects or virtuous circles of innovation and productivity growth, and policy can play a role in this. However, having the right quality and mix of institutions is critical, and this is the case for both formal 'hard' institutions and informal 'soft' institutions. Yet, building such institutions is not straightforward, because these are, by definition, nationally and locally embedded in legal and cultural settings, some of which are not transferable between nations and regions.
9. At present, we know very little about how the new technologies will impact on employment and wage distributions, although there are major concerns about these issues (Frank et al. 2019; UNCTAD, 2019; Nambisan et al. 2019). There are already pervasive effects of automation in the distribution of wages per occupation (Terzidis et al. 2017; Terzidis et al. 2019). During the last two decades, the interaction between processes of globalisation and technological change have led growing income polarization (Terzidis and Ortega-Argilés 2021), but the spatial implications of the job-polarisation processes differ between countries. The available evidence suggests that there is no simple and generalisable geographical pattern to these changes (Terzidis and Ortega-Argilés 2021). Moreover, there is no evidence of any link between skills-mismatches and job polarisation in terms of regional productivity.
10. We currently know very little about the potentially adverse effects of innovation on the distribution of income and wages, or the job-displacement effects of innovation in different regional contexts. Untangling the potential local employment, skill-loss, or wage-scarring effects associated with regional innovation shocks during periods of rising unemployment and weak demand is complex. Moreover, these issues are likely to be exacerbated in the COVID-19 context (Jackson and Ortego-Marti 2020) both due to the likely rising employment shocks along with the fact that human capital decay rates tend to be associated with skills levels (Ortego-Marti 2017).

11. Many of the features of the links between innovation and productivity call for systemic analytical and empirical approaches to innovation and entrepreneurship. Evidence from systems-type analyses of regional entrepreneurship suggests that the weaknesses rather than the strengths of a local innovation system are crucial in shaping the constraints that determine the long run innovation trajectory of a place. Systems approaches allow us to focus on the weaknesses in the regional innovation systems which need to be strengthened, the bottlenecks which need to be released and the missing links in regional systems which need to be bridged or re-connected in order to help local innovation to flourish.
12. The COVID-19 crisis is likely to lead to differential capital shocks, and these capital shocks will impact regions differently in terms of increased differences in capital pricing (McCann and Ortega-Argilés 2020). In terms of the regional innovation system, local investors in economically weaker regions aiming to foster innovation are likely to face increased costs relative to more prosperous locations. In particular, the adverse effects on small and medium-sized enterprises and real estate markets investors will be severe and will almost certainly lead to further interregional divergence. However, at present, we do not know the scale of these likely effects, nor the precise extent to which COVID-induced changes in commuting patterns will reshape hinterlands and market areas.
13. In terms of the climate change emergency, the COVID-19 crisis has delayed the implementation of many of the agreed actions in the 2016 Paris Accord, as states try to encourage output and employment to recover as quickly as possible in the aftermath of the pandemic shutdowns. Of necessity, responding to climate change must be an innovation-led process, but how this will impact on regions is still unclear because many of the regions which are the most exposed to climate change risks are also those same regions which will be the most adversely affected by climate change mitigation measures (McCann and Soete 2020). In contrast, many of the OECD's more prosperous regions are relatively more specialised in lower carbon-intensive activities and also in those same knowledge-related activities and infrastructures, which will spearhead climate change innovations. Finding ways to ensure that the climate change agenda does not increase disparities between regions is crucial.

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